WORKING PAPER

ITLS-WP-15-23

Emission charge and liner shipping network configuration - an economic investigation of the Asia-Europe route

By
Wayne Lei Dai[1], Xiaowen Fu, Tsz Leung Yip[3], Hao Hu,[4] and Kun Wang,[5]

[1] Shanghai Jiao Tong University, China
[3] Hong King Polytechnic
[4] Shanghai Jiao Tong University, China
[5] Sauder School of Business, The University of British Columbia

December 2015
ISSN 1832-570X

INSTITUTE of TRANSPORT and LOGISTICS STUDIES

The Australian Key Centre in

Transport and Logistics Management

The University of Sydney

Established under the Australian Research Council's Key Centre Program.

NUMBER:	Working Paper ITLS-WP-15-23
TITLE:	**Emission charge and liner shipping network configuration - an economic investigation of the Asia-Europe route**
ABSTRACT:	This paper models shipping lines' operational costs and CO2 emissions under alternative geographic network configurations when an emission charge is imposed on operations from Asia to Europe. Our modeling results suggest that shipping firms' network configuration is influenced by emission charge, fuel price, port loading and unloading cost, and demand pattern of cargo transport across different markets. Total emission will be reduced by an EU emission charge scheme. However, if the charge is above a threshold, carriers will reconfigure shipping networks to minimize their costs including emission charge payments. This will offset part of the emission reduction achieved by the emission scheme. As a result, a higher charge does not always lead to a higher emission reduction. In addition, the performance of major ports along the Asia-Europe routes will be influenced in different ways, leading to conflicting views from regional governments. These findings reveal possible market distortions associated with regional emission systems, and highlight the complex effects of international environmental policies when market dynamics are considered.
KEY WORDS:	***emission charge; shipping network; liner shipping;***
AUTHORS:	**Wayne Lei Dai, Xiaowen Fu, Tsz Leung Yip, Hao Hu and Kun Wang**
CONTACT:	INSTITUTE OF TRANSPORT AND LOGISTICS STUDIES (H73) The Australian Key Centre in Transport and Logistics Management The University of Sydney NSW 2006 Australia Telephone: +612 9114 1824 E-mail: business.itlsinfo@sydney.edu.au Internet: http://sydney.edu.au/business/itls
DATE:	December 2015

1. Introduction

Despite the high fuel efficiency of modern ships, the large volume of commodity trade and the rapid growth of the maritime industry make international shipping a major source of carbon emissions. Emissions from the global maritime sector currently account for about 3% of global emissions, and are expected to reach 5% in 2050 (European Commission 2013). The container shipping sector is of particular importance in the maritime industry. Psaraftis and Kontovas (2009) noted that although container ships accounted for 4% of all vessels, they generated 20% of emissions from international shipping in 2007. With continued growth expected in the sector, reducing greenhouse gas (GHG) emission from maritime shipping has been a key challenge to organizations and governments around the world.

Many studies have investigated issues related to emissions and environment control in the maritime industry, covering issues such as shipping operations and technologies (International Maritime Organization (IMO) 2000; Eyring et al., 2005; Corbett et al., 2009; Wang et al. 2009; DNV, 2010; Leonardi and Browne 2010; Fagerholt et al. (2010); Cariou, 2011; Cariou and Cheaitou 2012; Maloni et al. 2013; Yin, Fan et al. 2014), the estimation and calculation of emission volume and costs (Wang et al., 2007; Buhaug et al., 2009; Eide et al., 2009, 2011; Liao et al., 2010, Berechman and Tseng, 2012), and international standard such as the Energy Efficiency Design Index (EEDI) for new ships (IMO 2009; Walsh and Bows, 2012; Zheng et al. 2013). There is also a growing awareness of the business and economic implications of emission control and environment protection measures. For example, Psaraftis and Kontovas (2010), and Yin et al. (2014) noted that although slow steaming decreases emissions and fuel consumption, there are also losses in revenues and transit time. Environment related regulations and measures influence firms' operation, costs and profitability, thus there is a need to explicitly consider market structure and firm competition in the design and valuation of relevant policies. Wang et al. (2015) simultaneously modeled shipping operation, market equilibrium and the determination of shadow prices of emission credits under an open Emission Trading Schemes (ETSs) vs. a maritime only ETS. Their study captures the interactive relationship between liner competition and ETS mechanisms, and demonstrates the needs to model industry and firm behaviors when evaluating environmental policies. Although ship size is a decision variable in many of these studies, shipping networks have been treated as exogenous or fixed, or not explicitly considered at all.

The economic literature on environment protection has been well developed. One important research field is to analyze the effects of international cooperation on environment protection and pollution control. Many studies examined the effects of externalities and the associated free-ride problem, most reached the conclusion that international cooperation is necessary. Hoel (1990) analytically illustrated that if one country reduces its emission unilaterally, other countries are likely to free-ride and the total emissions could increase rather than decrease. Similar conclusions were obtained by Yuen and Zhang (2012) on airline emissions. In the maritime sector, Homsombat et al. (2013) modeled port pollution control in a region, showing the need for competing ports to cooperate in pollution control. Wang et al. (2012) and Lam et al. (2013) further argued that it is important for all stakeholders to be involved in port governance on a wide range of issues including pollution control, even for competing ports in a region. Virtually all studies on emission control and environmental protection have recommended coordinated actions among stake-holders.

In reality, however, limited progress has been made to forge global agreements on environment protection and emission reduction. Few studies have analytically explained why it has been so difficult to agree on mutually beneficial policies. The European Union endorsed the 2008 Climate and Energy Package and has successfully implemented the ETS system for years. However, international maritime transport remains the only transport mode not included in EU's GHG control. Although the EU strongly prefers a global approach led by the IMO, it proposed to adopt a gradual approach to include maritime GHG emissions in its emission reduction framework (EC 2013). The gradual approach involves a system of reporting and verification (MRV) of emissions, definition of emission reduction target, and the application of market based measures (MBM) in emission control. Among others, the MBMs considered by the European Commission include a contribution based compensation fund, a target based compensation fund, and an ETS. The EU 2011 White Paper on Transport further established an emission reduction target of 40% by 2050 compared to the level in 2005 (EU 2011), but such an target is yet to be binding to the maritime industry. The European Commission (EC 2013) concluded that “there is a clear need for all international partners to enter into serious discussions …, The Commission invites the European Parliament, Member States and all stakeholders to discuss the open points identified in this Communication in view of possible future initiatives of the EU for addressing GHG emissions from maritime transport.”

This study aims to contribute to such policy discussions by modeling the effects of imposing emission charges to the maritime sector, with a focus on shipping networks configuration and the associated implications to ports and regional economies along shipping routes. We consider the case when a regional EU emission charge or equivalently a fuel tax is introduced to shipping activities within EU and trips to/from EU ports. This is a more realistic scenario in the short to medium term since a global emission control system seems to be out of reach any time soon. Shipping lines’ operational costs and CO2 emissions are analytically solved and simulated under alternative network configurations and choices of ships. A benchmark / status quo case and three alternative network configurations are developed and calibrated, so that shipping lines’ profits and CO2 emission levels can be compared. Our modeling results for the Asia-Europe route suggest that liner network configuration is influenced by emission charge, fuel price, port loading/unloading cost, and demand pattern of cargo transport across different markets. If emission charge is introduced and if the charge is above a threshold, carriers will reconfigure their shipping networks and thus significantly influence the revenue, connectivity and competitiveness of major ports along the Asia-Europe routes. As a result, non-EU countries will have conflicting views toward such a policy. Significant costs may incur due to unproductive transshipment operations when carriers try to reduce their emission charges, offsetting the benefit brought by regional emission charge systems. These findings highlight possible regulation costs and market distortions associated with regional emission charge systems, and highlight the complex effects of international environmental policies when market dynamics are considered.

The rest of the study is organized as follows. Section 2 introduces the economic model and alternative shipping networks. Section 3 analytically solve the market equilibria under different scenarios, and numerically calibrate the model with observed industry data. The last section summarizes the key conclusions, and discusses the limitations of the current study and possible extensions.

2. Economic model

We consider the container shipping market between Asia and Europe. Since numerous manufacturing bases are located in China, Japan and Korea, Northeast Asia (NE Asia) accounts for a large share of the container traffic to Europe. Trans-Oceanic ships are used to serve major NE Asian ports such as Shanghai, Tsingtao, Busan, Tokyo, and in many cases also Hong Kong and Shen Zhen. These large ships often call the Port of Singapore on their way to Europe, where cargos from Southeast Asia (SE Asia) are consolidated and loaded. For intra-oceanic transport from SE Asia to Singapore, cargos are typically carried with smaller ships. Such a shipping network is illustrated in Figure 1, in which routes served by trans-oceanic ships are presented with large block arrows, whereas routes served by small intra-oceanic ships are presented with solid arrows. Regions are numbered from 1 to 5 for ease of notation, thus that the traffic volume from NE Asia (Area 1) to Europe (Area 5) can be denoted as q_{15} for example.

With the introduction of EU emission charge or fuel tax, carriers are likely to respond strategically in order to alleviate the impacts. For example, shipping firms are expected to lower their operational speeds within the charging zone. In addition, shipping lines may reconfigure their networks. One possible scenario is that instead of in Singapore carriers may consolidate cargos in Dubai right before entering into the EU charging zone, thus that emission charge is imposed on the Dubai-Europe segment instead of the Singapore – Europe segment. Without loss of generality, we consider the case of Dubai which is a leading port in the region but our results should hold if any other port in North Africa or Middle East is considered. Among the possible options, following representative cases are considered in our study:

- Case I—Status Quo: There is no change in the configuration of shipping network as the one depicted in Figure 1. A trans-oceanic ship from NE Asia calls Singapore on its way to Europe. Cargos originated from SE Asia is first delivered by intra-Oceanic ship to Singapore, and subsequently loaded to the trans-oceanic ship operating in the NE Asia – Europe route.
- Case II—Shifting Hub to Dubai: This case is depicted in Figure 2, in which the consolidating hub is shifted from Singapore to Dubai. Trans-Oceanic ships are used as feeder services for cargos from NE Asia while smaller intra-Oceanic ships are used as feeder service for cargos from SE Asia. All containers are reloaded to large trans-oceanic ships which are headed directly from Dubai to EU market. The dotted-lined block arrow denotes a change of ship in the route of Singapore to EU.
- Case III—Shifting Hub to Dubai with intra-Oceanic Feeder only: As depicted in Figure 3, in this case Dubai is used for cargo consolidation. All feeder services from NE Asia and SE Asia are offered by small intra-Oceanic ships.

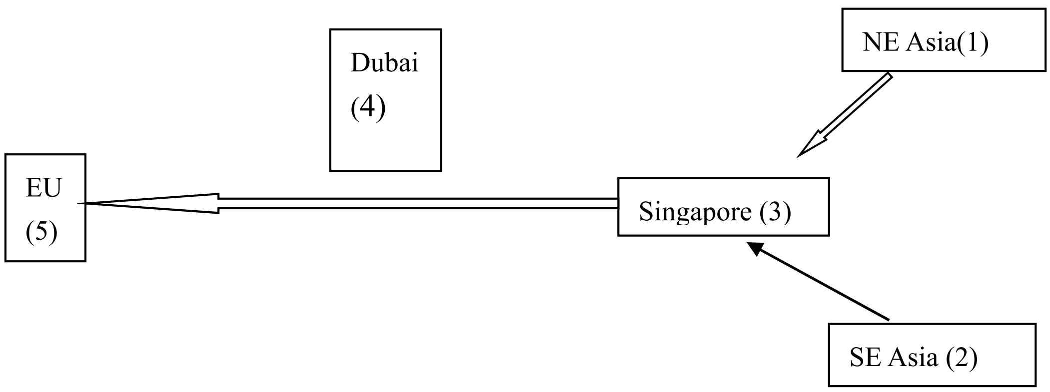

Figure 1. Case I – Status Quo Network Configuration

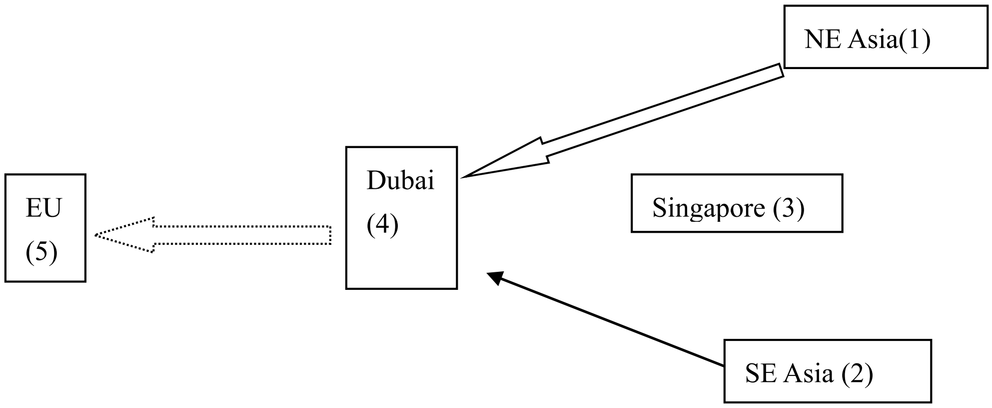

Figure 2. Case II – Shifting Hub to Dubai with trans-oceanic Feeder

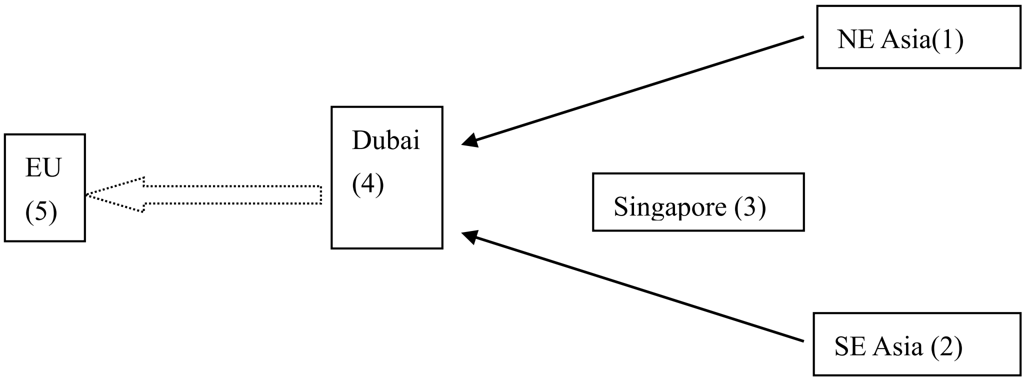

Figure 3. Case III – Shifting Hub to Dubai with intra-Oceanic Feeder Only

For a carrier, several countervailing factors need to be considered in choosing these three options. One important factor is the consolidation and possible logistics cost at a hub. To consolidate traffic at a port, the most prominent cost is the loading and unloading costs which are usually referred to as "trans-shipment cost" in the literature. Without emission charge, container ships can call multiple ports including both Dubai and Singapore without much extra cost, thus only a small proportion of containers are being physically reloaded from one ship to another. However, if emission charge is introduced to bunker fuel for ships entering EU emission charge zone, it is possible that dedicated ships will be used for delivery to EU, in which case all containers will be physically reloaded. If EU imposes strict rules on the origin of production, additional logistics costs, such as re-packing, may incur.

3. Methodology

This section explains the modeling details for the calculation of shipping costs, trans-shipment costs and emission charges. These calculations are necessary for the modeling of shipping companies' operational strategies when an EU emission charge is introduced.

3.1 Model specification

To model shipping firms' operational details in the Asia-Europe route, the following specifications are used.

3.1.1. Fuel consumption and vessel speed:

It has been estimated that the average fuel consumption of marine ships is approximately proportional to the cube of vessel speed, V^3 (Yin, Fan et al. 2014). Therefore, we specify the daily fuel consumption (FC) per vessel as follows,

(1) $$\mathrm{FC} = \delta \cdot \sqrt{\mathrm{U}} \cdot \mathrm{V}^3$$

which is a function of vessel speed *V*, vessel size *U*, and a fuel efficiency parameter *δ*. With fuel price λ, the daily fuel cost *F* (in U.S. dollars) of a ship can be calculated as

(2) $$\mathrm{F} = \lambda \cdot \delta \cdot \sqrt{\mathrm{U}} \cdot \mathrm{V}^3$$

3.1.2. CO2 emission:

Corbett, Wang et al. (2009) concluded that CO2 emission is proportional to fuel consumption. The emission volume measured in kilogram can be obtained by multiplying fuel's carbon fraction (86.4% for typical bunker fuel) and a factor for converting carbon to CO2 (equal to 44/12), and fuel consumption. The CO2 emission for a vessel in a trip is thus calculated as

(3) $$\mathrm{CO2} = (0.8645) \cdot (44/12) \cdot \mathrm{FC} \cdot \mathrm{t} = 3.17 \cdot \delta \cdot \sqrt{\mathrm{U}} \cdot \mathrm{V}^3 \cdot \mathrm{D}/(\mathrm{V} \cdot 24) = 0.132 \cdot \delta \cdot \sqrt{\mathrm{U}} \cdot \mathrm{V}^2 \cdot \mathrm{D}$$

where *t* is sailing time for a trip in days, and *D* is the distance of the trip in nautical miles.

3.1.3. Containership capital and operating cost:

Capital and operating cost of contain shipping can be influenced by many factors such including the type of ship used, insurance policy, repair and maintenance schedule etc. We thus approximate the capital and operating cost per day for a vessel with the following specification

(4) $$K = \alpha \cdot U^{2/3}$$

where α is the capital cost parameter, U is the ship size as defined earlier. Such a specification models economies of scale for larger ship, as cost increases proportionally less than ship size.

3.1.4. Loading / unloading cost at a port

This cost category refers to loading / unloading cost and associated expenses (e.g. warehousing) at a port. The cost in Singapore is denoted as l_s per container and the cost in Dubai is denoted as l_d per container.

For model tractability, it is assumed that after the introduction of emission charge there will be no changes in traffic volumes and shipping prices for containers shipped from NE Asia and SE Asia to EU. The ship size used in trans-oceanic service is assumed to be U=8000 TEU (i.e. Panamax class), and the ship size used in intra-Oceanic service is u=4000 TEU (i.e. Handy class). In addition, it is further assumed that the cargos from SE Asia can be loaded to the trans-oceanic ships without increasing the number of ships in the NE – Europe route. These are clearly simplifying assumptions. In practice, the shipping market has been very volatile as shipping firms optimize operations and react to competition and regulatory policies, and shipping operations are affected both by Europe-Asia cargo flow as well as intra-Asia cargo flow. These assumptions nevertheless allow us to focus on the key issues we would like to analyze. Sensitivity tests are subsequently carried out to validate the robustness of our conclusions.

3.2 Market equilibrium and performance of shipping carriers

With the above model specifications, shipping carriers' optimal operational strategies under alternative network configurations can be identified.

3.2.1. Shipping Carrier's profits and

Use superscript 0 to denote the case without fuel tax, a carrier's profit maximization problem is defined as in Eq. (1), where λ_0 is the fuel price without emission charge / fuel tax. The profit function can be thus specified as in Eq. (5), where D_{ij} is the distance between the port *i* and port *j* as denoted in Figure 1, and cruising speeds V_{13}, V_{23}, V_{35} in different shipping routes are carriers' decision variables.

(5) $$\mathrm{Max}_{V_{13},V_{23},V_{35}}\pi^{0} = P_{15}q_{15} - \frac{q_{15}+q_{25}}{U}\left(F_{13}\frac{D_{13}}{24V_{13}} + F_{35}\frac{D_{35}}{24V_{35}}\right) - \alpha_U U^{\frac{2}{3}}\left(\frac{D_{13}}{24V_{13}} + \frac{D_{35}}{24V_{35}}\right)\frac{q_{15}+q_{25}}{U}$$
$$+P_{25}q_{25} - \frac{q_{25}}{u}\left(F_{23}\frac{D_{23}}{V_{23}}\right) - \alpha_u u^{\frac{2}{3}}\frac{D_{23}}{24V_{23}}\frac{q_{25}}{u} - l_s q_{25}$$
$$= P_{15}q_{15} - \frac{q_{15}+q_{25}}{24\sqrt{U}}\delta_U\lambda_0\left(V_{13}^2D_{13} + V_{35}^2D_{35}\right) - \alpha_U\left(\frac{D_{13}}{V_{13}} + \frac{D_{35}}{V_{35}}\right)\frac{q_{15}+q_{25}}{24U^{\frac{1}{3}}}$$
$$+P_{25}q_{25} - \frac{q_{25}}{24\sqrt{u}}\delta_u\lambda_0(V_{23}^2D_{23}) - \alpha_u\frac{D_{23}}{24V_{23}}\frac{q_{25}}{u^{\frac{1}{3}}} - l_s q_{25}$$

When emission charge is imposed in case I, II and III, the effective fuel price is defined as $\lambda_1=\lambda_0+\chi$, where χ is the bunker price increase, or an equivalent fuel tax due to emission charge. The profit maximization problems of a shipping carrier in different cases are specified below

(6) $$\mathrm{Max}_{V_{13},V_{23},V_{35}}\pi^{\mathrm{I}} = P_{15}q_{15} - \frac{q_{15}+q_{25}}{U}\left(F_{13}\frac{D_{13}}{24V_{13}} + F_{35}\frac{D_{35}}{24V_{35}}\right) - \alpha_U U^{\frac{2}{3}}\left(\frac{D_{13}}{24V_{13}} + \frac{D_{35}}{24V_{35}}\right)$$
$$\frac{q_{15}+q_{25}}{U} + P_{25}q_{25} - \frac{q_{25}}{24u}\left(F_{23}\frac{D_{23}}{V_{23}}\right) - \alpha_u u^{\frac{2}{3}}\frac{D_{23}}{24V_{23}}\frac{q_{25}}{u} - l_s q_{25}$$
$$= P_{15}q_{15} - \frac{q_{15}+q_{25}}{24\sqrt{U}}\delta_U\left(\lambda_0V_{13}^2D_{13} + \lambda_1V_{35}^2D_{35}\right) - \alpha_U\left(\frac{D_{13}}{V_{13}} + \frac{D_{35}}{V_{35}}\right)\frac{q_{15}+q_{25}}{24U^{\frac{1}{3}}}$$
$$+P_{25}q_{25} - \frac{q_{25}}{24\sqrt{u}}\delta_u(\lambda_0V_{23}^2D_{23}) - \alpha_u\frac{D_{23}}{24V_{23}}\frac{q_{25}}{u^{\frac{1}{3}}} - l_s q_{25}$$

(7) $$\mathrm{Max}_{V_{14},V_{24},V_{45}}\pi^{\mathrm{II}} = P_{15}q_{15} - \frac{q_{15}}{U}\left(F_{14}\frac{D_{14}}{24V_{14}}\right) - \frac{q_{15}+q_{25}}{U}\left(F_{45}\frac{D_{45}}{24V_{45}}\right) -$$
$$\alpha_U U^{\frac{2}{3}}\left(\frac{D_{14}}{24V_{14}}\right)\frac{q_{15}}{U} - \alpha_U U^{\frac{2}{3}}\left(\frac{D_{45}}{24V_{45}}\right)\frac{q_{15}+q_{25}}{U} + P_{25}q_{25} - \frac{q_{25}}{u}\left(F_{24}\frac{D_{24}}{24V_{24}}\right) -$$
$$\alpha_u u^{\frac{2}{3}}\frac{D_{24}}{24V_{24}}\frac{q_{25}}{u} - l_d(q_{15}+q_{25})$$
$$= P_{15}q_{15} - \frac{q_{15}}{24\sqrt{U}}(\lambda_0\delta_U V_{14}^2D_{14}) - \frac{q_{15}+q_{25}}{24\sqrt{U}}(\lambda_1\delta_U V_{45}^2D_{45}) - \alpha_U\left(\frac{D_{14}}{V_{14}}\right)\frac{q_{15}}{24U^{\frac{1}{3}}}$$
$$-\alpha_U\left(\frac{D_{45}}{V_{45}}\right)\frac{q_{15}+q_{25}}{24U^{\frac{1}{3}}} + P_{25}q_{25} - \frac{q_{25}}{24\sqrt{u}}(\lambda_0\delta_u V_{24}^2D_{24}) - \alpha_u\frac{D_{24}}{24V_{24}}\frac{q_{25}}{u^{\frac{1}{3}}}$$
$$-l_d(q_{15}+q_{25})$$

(8) $$Max_{V_{14},V_{24},V_{45}}\pi^{\mathrm{III}} = P_{15}q_{15} - \frac{q_{15}}{u}\left(F_{14}\frac{D_{14}}{24V_{14}}\right) - \frac{q_{15}+q_{25}}{U}\left(F_{45}\frac{D_{45}}{24V_{45}}\right) - \alpha_u u^{\frac{2}{3}}\left(\frac{D_{14}}{24V_{14}}\right)\frac{q_{15}}{u} -$$

$$\alpha_U U^{\frac{2}{3}}\left(\frac{D_{45}}{24V_{45}}\right)\frac{q_{15}+q_{25}}{U}+P_{25}q_{25}-\frac{q_{25}}{u}\left(F_{24}\frac{D_{24}}{24V_{24}}\right)-\alpha_u u^{\frac{2}{3}}\frac{D_{24}}{24V_{24}}\frac{q_{25}}{u}-l_d(q_{15}+q_{25})$$

$$=P_{15}q_{15}-\frac{q_{15}}{24\sqrt{u}}\lambda_0\delta_u V_{14}^2 D_{14}-\alpha_u\left(\frac{D_{14}}{V_{14}}\right)\frac{q_{15}}{24u^{\frac{1}{3}}}-\frac{q_{15}+q_{25}}{24\sqrt{U}}\left(\lambda_1\delta_U V_{45}^2 D_{45}\right)$$
$$-\alpha_U\left(\frac{D_{45}}{V_{45}}\right)\frac{q_{15}+q_{25}}{24U^{\frac{1}{3}}}+P_{25}q_{25}-\frac{q_{25}}{24\sqrt{u}}\left(\lambda_0\delta_u V_{24}^2 D_{24}\right)-\alpha_u\frac{D_{24}}{V_{24}}\frac{q_{25}}{24u^{\frac{1}{3}}}$$
$$-l_d(q_{15}+q_{25})$$

Since the optimal cruising speed in our model is determined by vessel size and fuel price, for the benchmarking case 0 (current network configuration without emission charge / fuel tax), we set $\frac{\partial\pi^0}{\partial V_{13}}=0;\ \frac{\partial\pi^0}{\partial V_{23}}=0$, , which lead to the solution of optimal speed $V_{13}=V_{35}=\sqrt[3]{\frac{\alpha_U U^{\frac{1}{6}}}{2\delta_U\lambda_0}}$ for the trans-oceanic ship, and $V_{23}=\sqrt[3]{\frac{\alpha_u u^{\frac{1}{6}}}{2\delta_u\lambda_0}}$ for the intra-Oceanic ship. The optimal cruising speeds for the cases with emission charge can be solved from Eqs. (6)-(8), thus that the optimal cruising speeds are $V_{35}=\sqrt[3]{\frac{\alpha_U U^{\frac{1}{6}}}{2\delta_U\lambda_1}}$, in case I, and $V_{45}=\sqrt[3]{\frac{\alpha_U U^{\frac{1}{6}}}{2\delta_U\lambda_1}}$ in Case II, and $V_{45}=\sqrt[3]{\frac{\alpha_U U^{\frac{1}{6}}}{2\delta_U\lambda_1}}$ in Case III, respectively.

3.2.2. CO2 emission volumes

Based on Eqs. (3), (6), (7) and (8), the total emission volumes for carrying cargoes from Asia to EU can be calculated as follows, where superscript corresponds to the three cases as defined above

(9) $$CO_2^{\mathrm{I}}=(0.8645)\cdot\left(\frac{44}{12}\right)\left(\frac{q_{15}+q_{25}}{24U}\left(FC_{13}\frac{D_{13}}{V_{13}}+FC_{35}\frac{D_{35}}{V_{35}}\right)+\frac{q_{25}}{24u}\left(FC_{23}\frac{D_{23}}{V_{23}}\right)\right)$$
$$=0.132\cdot\left(\frac{q_{15}+q_{25}}{\sqrt{U}}\delta_U\left(V_{13}^2D_{13}+V_{35}^2D_{35}\right)+\frac{q_{25}}{\sqrt{u}}\delta_u V_{23}^2 D_{23}\right)$$

(10) $$CO_2^{\mathrm{II}}=(0.8645)\cdot\left(\frac{44}{12}\right)\left(\frac{q_{15}}{U}\left(FC_{14}\frac{D_{14}}{24V_{14}}\right)+\frac{q_{15}+q_{25}}{U}\left(FC_{45}\frac{D_{45}}{24V_{45}}\right)+\frac{q_{25}}{u}\left(FC_{24}\frac{D_{24}}{24V_{24}}\right)\right)$$
$$=0.132\cdot\left(\frac{q_{15}}{\sqrt{U}}\delta_U V_{14}^2 D_{14}+\frac{q_{15}+q_{25}}{\sqrt{U}}\delta_U V_{45}^2 D_{45}+\frac{q_{25}}{\sqrt{u}}\delta_u V_{24}^2 D_{24}\right)$$

(11) $$CO_2^{\mathrm{III}}=(0.8645)\cdot\left(\frac{44}{12}\right)\left(\frac{q_{15}}{u}\left(FC_{14}\frac{D_{14}}{24V_{14}}\right)+\frac{q_{15}+q_{25}}{U}\left(FC_{45}\frac{D_{45}}{24V_{45}}\right)+\frac{q_{25}}{u}\left(FC_{24}\frac{D_{24}}{24V_{24}}\right)\right)$$

$$= 0.132 \cdot \left(\frac{q_{15}}{\sqrt{u}}\delta_u V_{14}^2 D_{14} + \frac{q_{15} + q_{25}}{\sqrt{U}}\delta_U V_{45}^2 D_{45} + \frac{q_{25}}{\sqrt{u}}\delta_u V_{24}^2 D_{24}\right)$$

With the analytical solutions obtained in this section, we can use real industry data to calibrate our model, so that the market outcomes in real markets can be simulated. These analysis are reported in the following section.

4. Model Calibration and Simulation

We calibrate our model with container operation data in 2007 in the Asia-Europe route. The port of Shanghai and the port of Bangkok are selected as the representative origin ports in Northeast Asia and Southeast Asia. This implies a voyage distance $D_{13} = 2{,}700$ nm and, $D_{23} = 900$ nm to port of Singapore, and $D_{14} = 6{,}600$ nm, $D_{24} = 4{,}800$ nm to Dubai, respectively. The distance from Singapore and Dubai to Europe is about $D_{35} = 10{,}000$ nm and $D_{45} = 6{,}400$ nm, respectively. Sensitivity tests with alternative voyage distances are conducted in following sections for the simulation of alternative origin and trans-shipment ports.

Wang et al. (2015) noted that the capital/operating cost for 8,000 TEU trans-oceanic is USD 2.99×10^7 per year. Bauhaug et al. (2009) suggests that on average one containership sails $\rho = 270$ days on the sea per year. According to equation (4), this is equivalent to $\alpha_U = 59.646\ \mathrm{USD/day \cdot ton^{2/3}}$. Since the same type of ship should have a similar value of α due to technology similarity, we set $\alpha_u = \alpha_U = 59.646\ \mathrm{USD/day \cdot ton^{2/3}}$ for both trans-oceanic (8,000 TEU) and intra-oceanic (4,000 TEU) ships. This specification reflects economies of scale by using large vessels. Notteboom and Vernimmen (2009) assume that an 8000-TEU containership consumes 200 tons bunker per day at a speed of 23 knots, and a 4000-TEU containership consumes 95 tons at a speed of 21 knots. Using equation (1), the fuel efficiency factor δ is calibrated as $\delta_U = 5.813 \times 10^{-5}\sqrt{\mathrm{ton}}/\mathrm{knot}^3$, and $\delta_u = 5.129 \times 10^{-5}\sqrt{\mathrm{ton}}/\mathrm{knot}^3$ (1 TEU=10 tons, Leonardi, J. and M. Browne (2010)).

The directional cargo flow from Asia to Europe is 17.7 million TEUs in year 2007 [1] (Review of Maritime Transport 2008, UNCTAD). As the cargo loading ports cannot be separately identified, it is assumed that among the total cargo flow, 80% is from the NE Asia, with the remaining 20% cargo flow from SE Asia, or equivalently $q_{15} = 14.16$ million TEUs and $q_{25} = 3.54$ million TEUs, respectively. Sensitivity test will be conducted on this assumption. The average freight rate from Asia to Europe is about USD 1,800 per TEU in year 2007 (Review of Maritime Transport 2008, UNCTAD). We assume USD 1,800 per TEU for the Northeast

[1] This year's data is used to be consistent with other financial / cost data used.

Asia, and the freight rate from Southeast Asia to Europe is designed to be USD 1,700 per TEU.[2] Bunker fuel price is about $\lambda_0 = 350$ USD/ton in year 2007 (Yao et al. 2012). The parameter values and sources are collated in Table 1.

Table 1. Parameter values used in model calibration

Parameter	8000 TEU	4000 TEU	Sources and remarks
U	80,000 tons	40,000 tons	Leonardi, J. and M. Browne (2010)
ρ	270 days/year	270 days/year	Bauhaug et al. (2009)
P	1800 USD/TEU	1800 USD/TEU	UNCTAD, 2008
λ_0	350 USD/ton	350 USD/ton	Yao, Ng et al. (2012)
D_{ij}	D_{13}=2,700 nm, D_{23}=900 nm, D_{35}=10,000 nm, D_{14}=6,600 nm, D_{24}=4,800 nm, D_{45}=6,400 nm		UNCTAD,2008; Port.com
V	21.3 knots	19.8 knots	Estimated using the equilibrium equation $V = \sqrt[3]{\frac{\alpha_U U^{\frac{1}{6}}}{2\delta_U \lambda_0}}$ for benchmark case
α	59.646 USD/day· $\text{ton}^{\frac{2}{3}}$	59.646 USD/day· $\text{ton}^{\frac{2}{3}}$	Notteboom, T.E. and Vernimmen, B. (2008)
δ	$5.813 \times 10^{-5}\sqrt{\text{ton}}/\text{knot}^3$	$5.129 \times 10^{-5}\sqrt{\text{ton}}/\text{knot}^3$	Notteboom, T.E. and Vernimmen,B. (2008), Wang et al (2015)
q	17.7 million TEUs		UNCTAD, 2008

4.1 Simulations under alternative network configuration

When fuel emission charge is imposed, shifting trans-shipment activities from Singapore to Dubai will lower emission charges paid by shipping lines, but will increase trans-shipment cost due to loading/unloading operations at a port. A shipping line's profit under different network configuration can thus be regarded as a function of the fuel emission charge equivalent fuel tax $\chi = \lambda_1 - \lambda_0$, and the loading/unloading cost l_s and l_d. We set the benchmark loading cost in

[2] The freight rates used influence the simulated profit but have no effect on a shipping line's network configuration and optimal speed.

Singapore and Dubai as USD 15 per TEU, and the profits for the three cases can be calculated for different fuel tax values as reported in Figure 4.

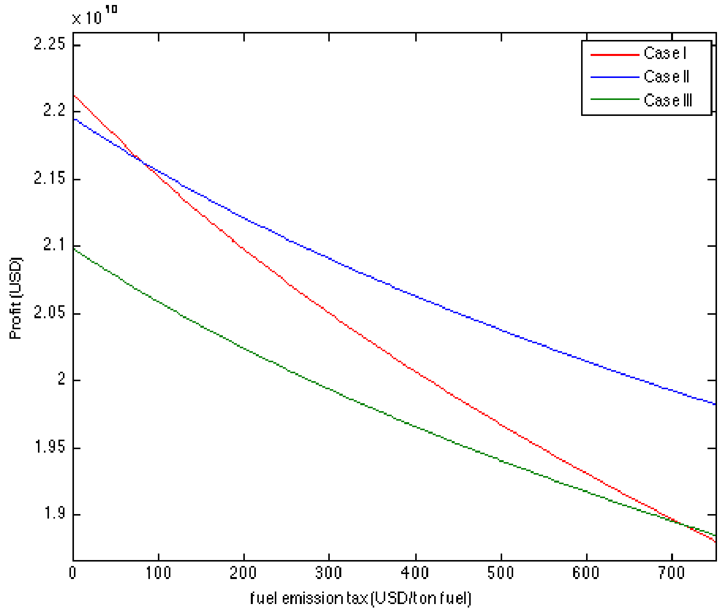

Figure 4. The relationship between shipping line profit and fuel tax ($l_s = l_d = 15\ USD/TEU$)

As expected, shipping line's profits decrease with the fuel tax χ in all the three cases modeled. This is mainly due to the extra expenses related to tax payment. Meanwhile, fuel tax also slows ships' speed from Singapore to Europe or Dubai to Europe (as shown in Figure 5). This requires more ships to be deployed and so increases carriers' operation/capital cost. Most importantly, as shown in Figure 4 there are threshold values of fuel emission tax, $\chi_1 = 80$ USD/ton and $\chi_2 = 709$ USD/ton, at which the profit lines corresponding to Case I, Case II and Case III intersect. As shown in appendix, these threshold values (i.e., χ_1 and χ_2) are unique and the "profit gaps" among the three cases are monotonic functions of χ . That is, the analysis of carriers' network configuration is equivalent to the investigation of the values of χ_1 and χ_2. When $\chi < \chi_1 = 80$ USD/ton, shipping firms achieve the highest profit in Case I, implying that the status quo network configuration is preferred by carriers. When $\chi > \chi_1 = 80$ USD/ton, shipping firms achieve the highest profit in Case II, when trans-shipment activities are shifted to Dubai and trans-oceanic ships are used on the routes of NE Asia –Dubai and Dubai-Europe. That is, when χ is sufficiently high, the benefits to adopt the network configuration in Case II outweighs the additional trans-shipment costs. Compared to the operation and network configuration in Case I, the benefits and costs of Case II are listed as follows

Benefits:

- Direct savings in emission charge / fuel tax due to shorter distance for trips to the EU emission charge zone (i.e., $D_{45} < D_{35}$);
- Indirect savings in ship operation and capital costs for vessels carrying NE Asia cargo q_{15}. This is because traffic volume q_{15} can be carried for a longer distance at a higher speed ($V_{13} = V_{14}; D_{13} < D_{14}$), thus reduces the the number of ships deployed.

Costs:

- Increase in the cargo handling cost due to loading/unloading or re-packaging cost incurred in Dubai
- Increase in ship capital/operation cost for vessels carrying SE Asia cargo q_{25}. Small intra-oceanic ships are less efficient due to smaller size, and they are used for longer distance to deliver cargoes from SE Asia to Dubai.

It is also noted that shipping firms' profits in Case III is always lower than that in Case II. This is because in the Case III, intra-oceanic ships are used to feed NE Asia cargoes to Dubai, which fail to achieve economies of scale of the large trans-oceanic ships. As a result, Case III requires a much higher fuel emission charge ($\chi > \chi_2 = 709$ USD/ton) to allow carriers to achieve higher profits than Case I.

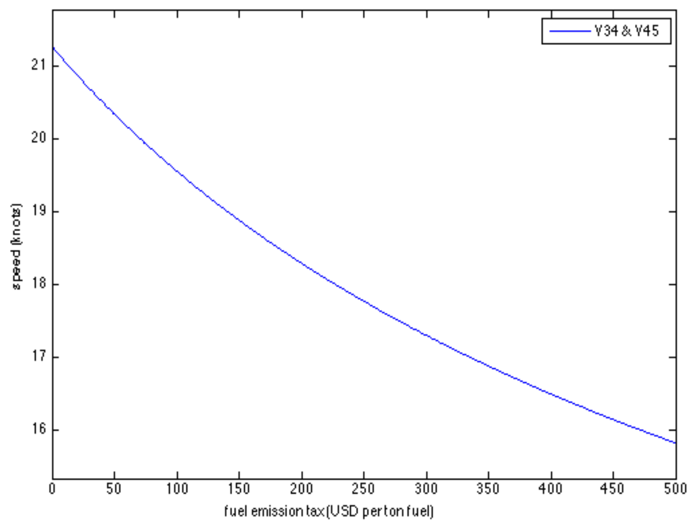

Figure 5. Optimal speed V_{34} and V_{45} with the fuel emission tax χ

Figure 6 illustrates how fuel tax χ and loading/unloading cost l_s $/l_d$ jointly determine threshold values χ_1 and χ_2. Specifically, Area I in Figure 6 corresponds to the outcomes when carriers achieve the highest profits in Case I; Area II correspond to the outcomes when carriers achieve the highest profit in Case II; In Area III, carriers achieve higher profits in Case III than in Case I. The sizes of Area II and Area III increase with χ but decrease with l_s $/l_d$, due to the economic trade-offs discdussed earlier. To sum, if the fuel emission tax is high enough or loading/unloading cost is low enough, shipping lines are more likely to re-configure the network to shift trans-shipment hub from Singapore to Dubai. It should also be noted that for the entire range of l_s $/l_d$ and χ we simulated, Case III has lower profit than Case II. This suggest that the large cargo volume from NE Asia justifies large ships.

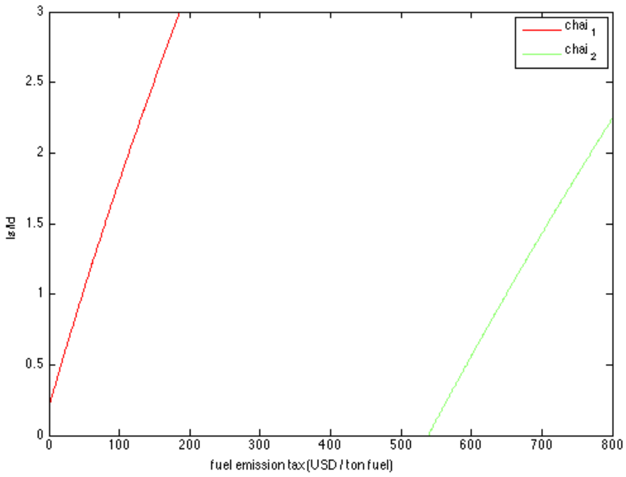

Figure 6. Values of threshold χ_1 and χ_2 for different l_s/l_d and fuel emission χ

Note: it is assumed $l_s = l_d$

Figure 7 reports the effects of different loading/unloading costs in Singapore and Dubai on a shipping line's network configuration. It supports the intuition that with l_s increasing, or l_d decreasing; shipping line is more likely to choose Case II to make Dubai the trans-shipment hub. However, the network configuration choice is more sensitive to l_d than l_s. When trans-shipments activities are conducted in Dubai, all the cargoes, including those from NE Asia and SE Asia, need to be loaded and unloaded to reduce emission charges.

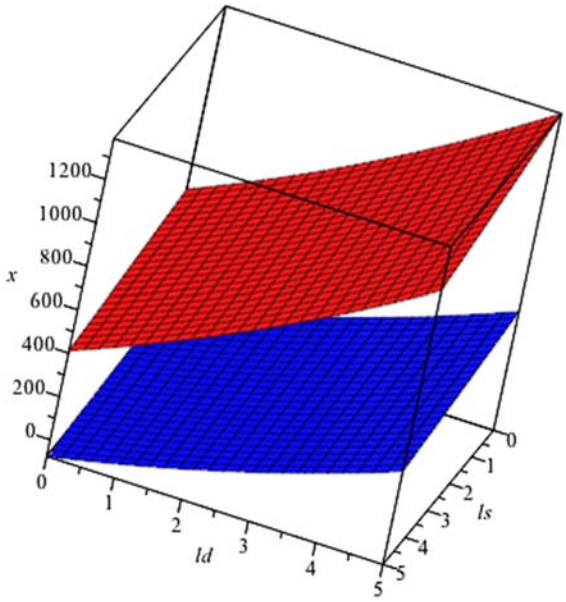

Figure 7. Values of threshold χ_1("Blue" surface) and χ_2 ("Red" surface) with different l_s and l_d

The CO_2 emission volumes for different cases are simulated in Figure 8. The CO_2 emission volumes decrease with emission charge / fuel tax rate χ in all cases, suggesting a regional scheme can still achieve the goal of emission reduction. However, Case II and Case III always generate more CO_2 emissions than Case I. Note if $\chi > \chi_1 = 80$ USD /ton, it is optimal for shipping lines to switch to the operational plan outlined in Case II from the status quo Case I. Such a network re-configuration can reduce the effectiveness of the regional emission scheme. When increasing fuel tax slightly above χ_1, CO_2 emission level will rise as shipping lines reconfigure their network to minimize their cost including emission payments. This finding highlights the importance for policy maker to carefully choose emission charge or equivalent fuel tax, since higher charge does not always yield better emission mitigation results.

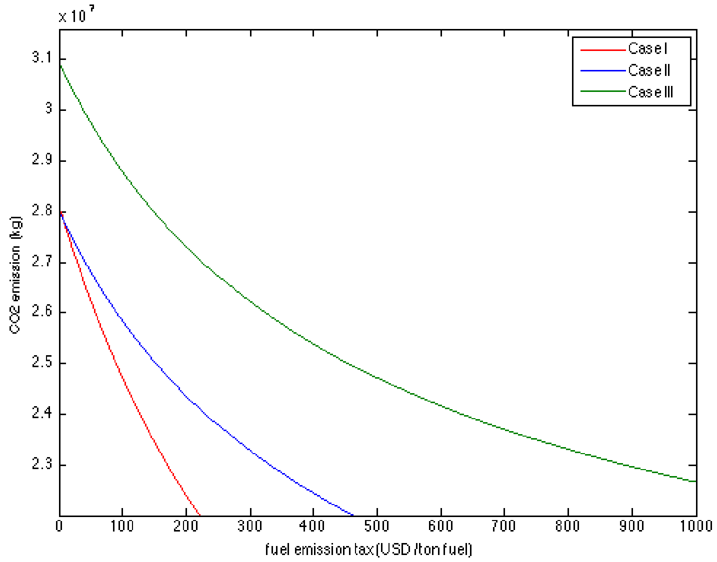

Figure 8. CO2 emission in kg with fuel emission tax χ

4.2 Effects of voyage distances on network configuration

The most significant incentive for shipping firms to relocate trans-shipment activities from Singapore to Dubai is the savings in fuel tax owing to Dubai's proximity to Europe. To analyze the effects of voyage distance on shipping network configuration, we simulate a carrier's profit with varying values of D_{35} and D_{45}. This also serves as a robust check to our calibration results, since alternative ports (instead of Singapore / Dubai) may be involved and voyage distances may be different from our assumptions. The results are depicted in Figure 9. As expected, the threshold values χ_1 and χ_2 decreases (increases) with the D_{35} (D_{45}). That is, if the new trans-shipment hub (e.g., Dubai) had a shorter distance exposed to emission charge (i.e., voyage distance to Europe in our analysis) over the current Asian hub (e.g. Singapore), it is more attractive for shipping lines to re-configure their networks from Case I to Case II or Case III. Again, profit for Case II is always higher than Case III, due to better cost efficiency of using large trans-oceanic containership to carry NE Asia cargo to the port of Dubai. The threshold values χ_1 and χ_2 are fairly sensitive to D_{35} and D_{45}. This reflects the importance for shipping lines to optimize their network configuration in response to policy changes such as an EU emission charge scheme.

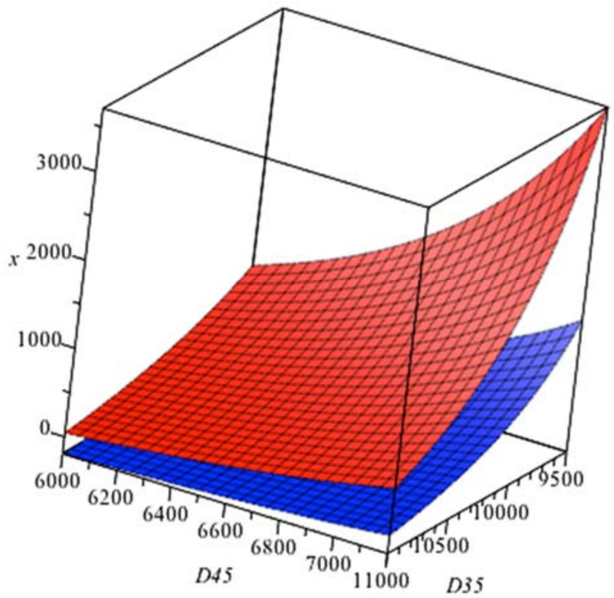

Figure 9. Values of threshold χ_1("Blue" surface) and χ_2 ("Red" surface) with different D_{35} and D_{45}

4.3 Sensitivity tests and model robustness

In this section, we conduct additional sensitivity tests with alternative parameter values of ship's fuel efficiency, capital/operating cost and the share of NE Asia cargo in the total Asia - Europe container shipment. These tests help evaluate the effects of key parameters on shipping lines' network configuration strategy. Meanwhile, they verify the robustness of our conclusions to changes in model assumptions. Figure 10 reports the threshold values of χ_1 and χ_2 corresponding to different ship fuel efficiency parameter δ_U and δ_u. When trans-oceanic containerships are more fuel efficient (lower δ_U), shipping lines are less likely to shift to Dubai for transition. This is because trans-oceanic ships will pay less emission charge when sailing from Singapore to Europe, thereby enhancing shipping lines' ability to mitigate the cost increase under status quo network configuration in Case I. χ_2 is more sensitive than χ_1 in response to changes in δ_U because in Case III intra-oceanic, instead of trans-oceanic containership, is used to carry cargo from NE Asia to Dubai. The fuel efficiency improvement of large trans-oceanic containership grants Case I more cost advantage over Case III. Better fuel efficiency of intra-oceanic containership (lower δ_u) has the opposite effect on χ_1 and χ_2. In Case II, the intra-oceanic ships has to sail a longer distance from SE Asia to Dubai, than to Singapore. Thus lower δ_u has more significant cost reduction effect in Case II, which makes the choice of Dubai as transition hub (lower value of χ_1) more likely. In addition, since intra-oceanic ships are also used to carry cargo in NE Asia in Case III, χ_2 is sensitive to the change in δ_u.

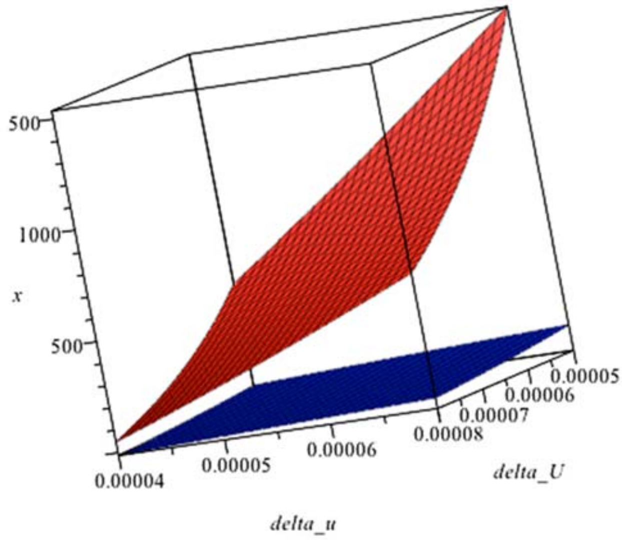

Figure 10. Values of threshold χ_1("Blue" surface) and χ_2 ("Red" surface) with different ship's fuel efficiency (δ_U, δ_u)

The containership capital/operating cost used in our model calibration is based on the estimates in Wang et al. (2015). A sensitivity test is conducted with alternative containership capital/operating costs. The simulation result is collated in Figure 11. In a wide range of ship capital/ operating cost, simulated values of χ_1 and χ_2 are fairly stable. Therefore, our simulation results are unlikely to be sensitive to the assumptions of capital/ operating cost. In addition, as also shown in the figure carriers are more likely to adopt Case II network to hub in Dubai if containership capital/ operating cost is high. This is because in Case II, without emission charge ship speed is high on the routes to Dubai, thus requiring fewer containerships for operations outside of the EU emission charge zone. The curves of χ_1 and χ_2 have the similar shapes as in Figure 9, because $\alpha_U = \alpha_u$ is assumed as explained in the model calibration section.

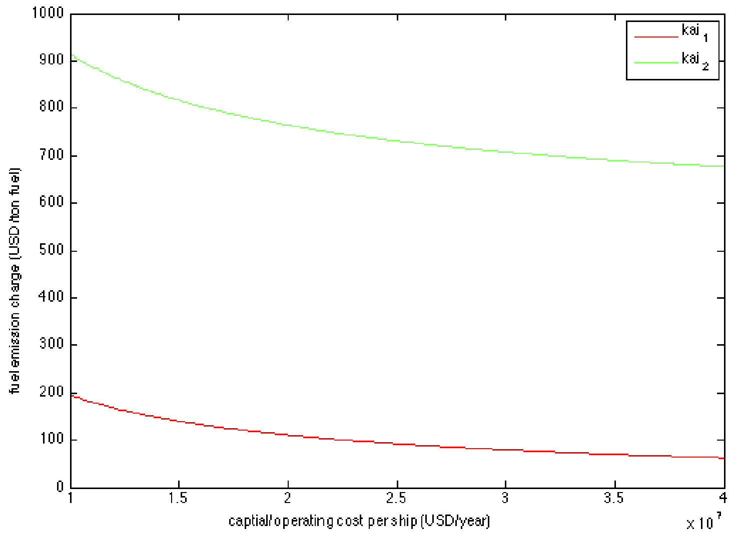

Figure 11. Values of threshold χ_1 ***and*** χ_2 ***with ship's capital/ operating cost***

The composition of cargo origin in Asia also plays a role in shaping carriers' network configuration. As shown in Figure 12, the shipping line is more likely to maintain status quo network in Case I if more cargoes are originated from NE Asia. This is mainly because in Case II and Case III, cargoes from NE Asia are also loaded and unloaded in Dubai, thus bringing additional costs. However, such a parameter is unlikely change our analytical results qualitatively.

5. Conclusion

In recent years, there has been growing concerns over CO2 emissions from the maritime sector. Although a global emission system seems out of reach in the near future, the European Union has been promoting market based schemes. Such a change may bring significant changes to shipping lines and the ports/countries along the trade routes to Europe. Most studies have discussed the possible implications to ship operations such as slow steaming and ship energy standards. However, few have examined shipping network reconfiguration, and the associated implications to shipping lines, ports and regional economies.

This paper models shipping lines' operational costs and CO2 emissions under alternative geographic network configurations when an emission charge, or equivalently fuel tax, is imposed on operations from Asia to Europe. Three possible shipping networks are modeled and calibrated with real industry data. Extensive sensitivity tests are subsequently carried out on key assumptions to validate the robustness of simulation results and to examine the effects of various influencing factors. Our modeling results suggest that shipping firms' network configuration is influenced by emission charge, fuel price, port loading and unloading cost, and demand pattern of cargo transport across different markets. Total emission will be reduced by an EU emission charge scheme. However, if the charge is above a threshold, carriers will reconfigure shipping networks to minimize their costs including emission charge payments. This will offset part of the emission reduction achieved by the emission scheme. As a result, a higher charge does not always lead to a higher emission reduction. In addition, the performance of major ports along the Asia-Europe routes will be influenced in different ways, leading to conflicting views from regional countries since some will benefit economically and others lose due to such a policy. These findings reveal possible market distortions associated with regional emission systems, and highlight the complex effects of international environmental policies when market dynamics are considered.

Despite the extensive numerical simulations and sensitivity tests carried out in our study, simplifying assumptions were made in our analysis thus that the demand and traffic volumes remain unchanged no matter how much emission charges are imposed. The effects of shipping line competition and/or alliance are not modeled in details neither. In addition, since a large proportion of port costs are sunk, ports alone the trade route may use innovative pricing schemes to retain customers. Therefore, the threshold emission charge for network re-configuration is hard to determine in practice. Our study highlights the important issues that need to be considered in policy design. However, it is only one step toward more complex and realistic modeling analysis. We hope this research could trigger more advanced studies on this important issue, so that optimal emission regulations can be introduced to the maritime sector.

Reference

Berechman, J., Tseng, P.H., 2012. Estimating the environmental costs of port related emissions: the case of Kaohsiung. Transportation Research Part D: Transport and Environment 17, 35-38.

Bode, S., 2006. Muti-period Emissions Trading in the Electricity Sector-Winners and Losers. Energy Policy 34, 680-691.

Buhaug, Ø., Corbett, J., Eyring, V., Endresen, Ø., Faber, J., Hanayama, S., Lee, S., Lee, D., Lindstad, H., Markowska, A., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Wanquing, Wu, Winebrake, J. and Yoshida, K. (2009), Second IMO GHG study: Update of the 2000 IMO GHG study, MEPC 59th Session April 2009.

Corbett, J. J., et al. (2009). "The effectiveness and costs of speed reductions on emissions from international shipping." Transportation Research Part D: Transport and Environment **14**(8): 593-598.

Notteboom, T. E. and B. Vernimmen (2009). "The effect of high fuel costs on liner service configuration in container shipping." Journal of Transport Geography **17**(5): 325-337.

Yao, Z., et al. (2012). "A study on bunker fuel management for the shipping liner services." Computers & Operations Research **39**(5): 1160-1172.

Yin, J., et al. (2014). "Slow steaming of liner trade: its economic and environmental impacts." Maritime Policy & Management **41**(2): 149-158.