Shore power vs low sulfur fuel oil: pricing strategies of carriers and port in a transport chain

Yan Jiao and Chuanxu Wang*
School of Economics and Management, Shanghai Maritime University, Shanghai, 201306, China

Abstract

With the increasingly serious pollution from the ships berthing at port and the emergence of low-carbon policies, shore power (SP) and low sulfur fuel oil (LSFO) have become effective means to reduce the emissions from ships berthing in the ports. In order to analyse two emission mitigation strategies, we establish a non-cooperative game model in a transport chain consisting of a terminal and two carriers who adopt SP or LSFO strategy and obtain the equilibrium results and pricing strategies under different conditions. We observe that, when the carbon price is lower than a threshold, both carriers will choose LSFO; otherwise, both carriers will adopt SP. However, if the two carriers cooperate to maximize their total profits, they will simultaneously choose LSFO when the carbon price is lower than another threshold or choose SP when the carbon price is higher than the threshold, which will maximize the total profits of the transport chain. If the carbon price is less than the threshold, the consumer surplus will be maximized when two carriers adopt LSFO, otherwise the consumer surplus will be maximized when two carriers use SP. If two carriers cooperate to maximize their total profits, this will maximize the entire transport chain’s profits and the consumer surplus. Finally, the validity of model is verified by taking Shenzhen Port as an example.

Keywords: carrier competition; shore power; low sulfur fuel oil; transport chain

1. INTRODUCTION

In recent years, people are paying more and more attention to environmental problems. Pollutant emission reduction has become a key factor for shipping enterprises to improve competitiveness (Witjes et al., 2017). There are many factors influencing the pollutant emissions, including shipper preference, social responsibility, government regulation, etc. Because the government has great influence on the pollutant emissions reduction of shipping enterprises, more reasonable policies must be formulated to promote the protection of environment (Zhao et al., 2019). Pollutant emissions from ships berthing at port is the main source of air pollution in the coastal and riverside ports, thus, the government need to pay more attention to maritime supervision, ship exhaust monitoring, promotion shore power (SP) and adopting low sulfur fuel oil (LSFO). At present, China’s shipping industry is strictly controlling the discharge of atmospheric pollutant from ships. Many methods have been introduced, for example, coastal emission control areas (ECAs) and riverside ECAs have been set up to control the carbon and sulfur emissions of ships.

The air pollution in the port mainly comes from the ships berthing at port. Because the powerful diesel engines in the ship must keep running to ensure that the ship’s equipment and support systems are functioning, they lead to ships to emit greenhouse gases and diesel particles. SP improves air quality by enabling ships to close diesel engines. Hall (2010) pointed out that SP can make carbon dioxide and sulfur oxide emissions reduce by about 24.5% and 91.6%, respectively. SP requires investment from both the port and the ship, because the port needs to build SP infrastructure and the ship needs to upgrade the electricity receiving facilities. By contrast, LSFO is a relatively simple way to reduce emissions; shipping companies only require to use a clean but expensive fuel with less than 0.1% sulfur content. SP and LSFO are becoming more and more popular in reducing shipping emissions, and the investment of SP and LSFO have
great environmental and social benefits. However, the revenues from adopting SP and LSFO vary at different carbon prices, which will affect the willingness of ports and carriers to use SP or LSFO. Whether the carriers use SP or LSFO depends on different carbon prices and is based on their own profit maximization. At the same time, the choice of SP or LSFO may not be optimal for the entire transport chain. Accordingly, based on the above discussions, we propose the following questions:

1. Under the non-cooperative game, which strategy of SP or LSFO should the carriers adopt to maximize the profit of the carriers and terminal?
2. For the whole transport chain, which mode is better for the two carriers, cooperate or compete?
3. Can the whole transport chain profits and consumer surplus be maximized at the same time?

To figure out these emerging research issues, we present a non-cooperative game model in a transport chain consisting of a terminal and two carriers who adopt SP or LSFO strategy and in different conditions. By performing comparison analysis on the profit of transport chain and consumer surplus, the carrier's choice of carbon emission reduction strategy is presented. Our study provides a reference for shipping companies to choose carbon emission reduction strategies and government departments to formulate carbon emission policies.

The main contributions of this paper can be concluded as follows. Firstly, this study investigated the carriers’ equilibrium strategies of adopting SP or LSFO under different carbon prices, which are rarely studied in existing literature. Secondly, the terminal’s service price and carriers’ freight rates are compared in different cases to analyze the applicability of different carbon emission reduction strategies. At last, by comparing the consumer surplus and profits of the terminal and carriers under different carbon prices, the paper concludes important results on the providers of carbon emission reduction strategies and government departments.

The rest of this article is organized as follows. In Section 2, some relevant literature is reviewed. Section 3 presents the decision models under different carbon prices and the solution of the proposed models. The equilibrium results in different models are compared in Section 4. The strategies of two carriers are analyzed in Section 5. Section 6 presents numerical analysis. Section 7 summarizes the conclusions and proposes the future research directions.

2. LITERATURE REVIEW

Our work is closely related to three streams of literature, port SP, shipping emission reduction strategies as well as pricing strategy in a transport chain.

2.1. Port shore power

SP strategy is one of the emission mitigation strategies by providing electricity power from shore rather than the auxiliary engines of ships, which can reduce the pollutant emissions generated by ships berthing at the port. Some of the studies on the SP have focused on the policy aspect. Peng (2016) mainly studied the policies of China’s SP and the development prospect of China’s SP. Peng et al. (2019) mainly investigated the allocation strategy of SP supply, including the additional power capacity of SP supply and the SP supply mode. However, due to the high cost of SP, the introduction of SP has become a problem to be considered by relevant departments. Some studies have mainly focused on the economic and environmental benefits of SP. Winkel et al. (2016) quantified the economic and environmental benefits of the European SP and provided a reference for relevant authorities to accelerate the implementation of SP in European harbors. Yu et al. (2019) developed a multi-objective model to determine when the SP is favorable for the environment and the shortest payback period. Tseng and Pilcher (2015) studied the financial benefits and environmental impact of introducing SP in the port of Kaohsiung (Taiwan). Dai et al. (2019a) proposed a framework for assessing the economic feasibility of SP considering environmental and techno-economic factors. Li (2019b) deeply analyzed the relationship and influence of related factors of SP and studied the investment and return of SP, and then they proposed related suggestions for promoting the implementation of SP from the perspective of economy. Dai et al. (2019b) proposed a framework for evaluating the economic feasibility of SP investment by taking environmental, technological, and economic factors into account. Some studies mainly investigated the technical problems of SP. Song and Xu (2016) analyzed the high voltage power system to simulate the real SP system, and simulation results show that the model can provide a basis for the construction of SP system. Kumar et al. (2019) introduced the development status and future trend of SP, discussed the SP technology for ships berthing at ports and considered the technical requirements of voltage, frequency, and power of ships on board and on shore. However, inadequacy SP infrastructure and disruption at some ports may cause delays, and container ships will have to speed up to remedy the delay, which will lead to excessive carbon dioxide emissions that will offset the reductions achieved by SP. Aksoy and Dumusoglu (2020) proposed organic Rankine cycle as an onshore power supply system within the framework of green port concept, which can effectively reduce the harmful gas emissions from ships berthing in ports, and used Boston Consulting Group (BCG) combination analysis method to compare the simulation results of the terminal’s annual cargo throughput and market share obtained in different scenarios.

The above papers mainly analyzed the policies, benefits and technologies of SP. This paper mainly studies whether carriers need to adopt SP and under what circumstances the carriers and the port can obtain the maximum profit and the maximum consumer surplus by adopting SP.

2.2. Shipping emission reduction strategies

The shipping industry generates a large amount of pollutant emissions, which includes carbon dioxide (CO2), sulfur dioxide (SO2),
heavy metals, particulate matter (PM), etc. Since NOx, SO2 and PM have obvious environmental impact and critical damage to human health, IMO adopted environmental regulations to control the emissions of sulfur oxides (SOx), nitrogen oxides (NOx) and PM from ships. According to the requirements of the International Maritime Organization, from January 1, 2020, the sulfur content of fuel oil used by ships worldwide should not exceed 0.5%. In ECAs, there is even more stringent control of the sulfur emissions with a limit of 0.1% sulfur content in the ship’s fuel. Some scholars have carried out the research on shipping emissions reduction. Schwartz et al. (2020) modelled annual emissions reduction potentials and cost structures for the ships engaged in short-haul transport to study the operational and technical measures by which shipping companies cannot only reduce pollutant emissions but also obtain economic benefits. Chen et al. (2019) explored the potential relationship between the fleet size and corresponding greenhouse gas emissions from ships by an allometric approach and found that both the decrease of navigation speed and the implementation of Energy Efficiency Design Index and Energy Efficiency Operation Index are effective. Chang and Huang (2019) used data from different types of vessels to studied emissions levels during three different business climates. Kontovas (2020) proposed a way to measure greenhouse gases, sulfur and nitrogen oxide on a common scale and estimate their overall impact. Sheng et al. (2019) took ship speed as a continuous decision variable and fleet size as an integer decision variable and developed a hybrid integer convex cost minimization model to optimize the sailing speed and fleet size through ECAs. Yuan et al. (2016) proposed a way to systematically quantify and explain the impact of the operational and technical measures proposed by IMO on emissions reduction. Ren and Lützen (2015) combined the fuzzy analytic hierarchy process with the VIKOR method to study the three emissions reduction technologies, which are low-sulfur fuel, scrubber and liquefied natural gas (LNG), which can help shipping companies to choose the most sustainable emissions reduction technology under uncertainty and incomplete information. Antturi et al. (2016) performed cost–benefit analysis of the sulfur emissions reduction policy in the Baltic Sea Sulphur Emission Control Area (SECA). They calculated the cost savings based on shipowners’ choices between low-sulfur fuel and a sulfur scrubber and quantified the benefits through a high-resolution impact pathway analysis. Lähteenmäki-Uutela et al. (2017) identified and discussed systematically the relevant impact categories for the SECA regulations and argued that the cost of SECA compliance will finally be borne by northern fringe industries such as paper, forestry or metals. Kalli et al. (2015) analysed the costs and the health and environmental benefits of SECA in Finland and found that even though the benefits are more significant than the costs in wide scale, there may be differences between countries due to the different geography, business structure and population density. Notteboom (2011) analysed the impact of the International Maritime Organization’s Tier II/III standards on costs and prices of roll on/roll off traffic in the ECAs in North Europe and on the competitiveness of roro shipping in the ECAs.

The above research mainly analysed the internal and external factors that affect shipping emissions reduction or evaluated the effects of emissions reduction strategies such as low-sulfur fuel, scrubber and LNG. Our research focuses on the pricing decisions under two different strategies, i.e. port SP and LSFO, which are two popular ways to reduce pollutant emissions from ships today, and analyses the different results when different numbers of shipping companies adopt these two strategies.

2.3. Pricing strategy in a transport chain

Ports play a vital role in connecting inland and maritime areas. Recently, the world economy has entered a new period of slowing growth and weak trade, and the great challenges have been faced by ports. Meanwhile, the increase of the number of small and medium-sized ports has gradually filled the gap between the large port markets, which will lead to increasingly fierce competition among ports serving overlapping hinterlands (Feng and Notteboom, 2013). Aiming at the design of multimodal transport network and pricing strategy, Zhang et al. (2018) established the game-theoretical model of port competition to determine the port location and pricing strategy with the consideration of the shipper’s route choice behavior. Wang and Meng (2019) studied the optimal pricing problem for a firm operating a joint-venture terminal with congestion effect and determine the optimal price to be charged to cargo suppliers. Qiu et al. (2015) studied the dry port operation problem by modeling the storage pricing of outbound containers. Zheng et al. (2017) studied the pricing strategies of two kinds of maritime carriers facing the uncertain demand.

The above studies mainly analysed the pricing strategies of ports and shipping companies. In this paper, by establishing a two-stage game model in which a port acts as a leader and carriers act as followers, we studied the mutual influence of their pricing strategies and the impact of carriers’ choice of different emissions reduction methods on port profits.

All of the above researches simply analysed the benefits of the SP, or just compared the benefits of SP and LSFO across the port serving one shipping company; this study attempts to compare prices, profits, customer surplus and social welfare under different carbon prices in a transport chain consisting of one port and two carriers who use SP or LSFO and present the optimal strategy choice for carriers and port.

3. MODEL DISCUSSION

The corresponding parameters are shown in Table 1.

To simplify the calculation, we set $c_4 + c_1 = c'_1, c_2 + c_1 = c'_2$. The demand function of the carriers is $q_1 = a_1 - b_1 p_1 + y p_2, q_2 = a_2 - b_2 p_2 + y p_1, a_1, a_2, b_1, b_2, y > 0$, since two carriers are served by the same terminal, we assume that their service are perfectly substitutable from a shipper’s perspective, that is $a_1 = a_2 = a, b_1 = b_2$, to simplify the calculation. We assume $b_1 = b_2 = 1$, since the customer of the one carrier is more sensitive to the change of the carrier’s freight rates than that of
another carrier, that is, $0 < y < 1$. (Dong et al., 2016, Cui and Notteboom, 2017; Qian et al., 2018; Yang et al., 2017).

Our study addresses the decisions on whether carriers choose SP or LSFO. Since most of the ports have stronger bargaining power than the carriers, to make the research universal, we use Stackelberg game in which terminal acts as leader and two carriers act as followers, carriers decide optimal freight rates $p$ first and then the terminal decides the optimal service price $s$. According to China Port (2017) and Tseng and Pilcher (2015) who concluded that SP is more environmentally friendly than LSFO, we assume that $m_E < m_L$. Additionally, the total cost of the LSFO is cheaper, this indicates $c_E + c_1 > c_2$. In addition, two carriers can independently or simultaneously choose either SP or LSFO; therefore, there are three possible cases for the two carriers’ strategies:

1. SS—both carriers adopt SP strategy.
2. LS—both carriers adopt LSFO strategy.
3. SL—carrier 1 adopts SP and carrier 2 adopts LSFO. Note that the SL and LS arrangements are the same as the carriers are indistinguishable.

### 3.1. Model 1 (both carriers adopt SP)

In this case, the profit functions of the terminal and carriers can be formulated by

$$\pi_{TSS} = (s_{SS} - c_E) (q_{1SS} + q_{2SS}) - \left[ (q_{1SS} + q_{2SS}) m_E - K \right] p_c$$

(1)

$$\pi_{1SS} = (p_{1SS} - s_{SS} - c_1) q_{1SS}$$

(2)

$$\pi_{2SS} = (p_{2SS} - s_{SS} - c_1) q_{2SS}$$

(3)

In equation (1), the first term describes the terminal’s profits from offering berthing service after installing the SP, and the second term represents revenues/costs from carbon trading. Equation (2) and equation (3) represent carrier 1’s and carrier 2’s profits respectively, which can be obtained by freight rates from shippers minus the berthing cost in the terminal, the cost of transportation and using SP. The carbon emissions from the terminal are as follows:

$$T_{SS} = (q_{1SS} + q_{2SS}) m_E$$

(4)

By using backward deduction in Stackelberg game model, carriers decide the optimal freight rates firstly:

$$p_{1SS}^* = p_{2SS}^* = \frac{m_E p_c + c_E + c_1 + 2a}{2 (2 - y)} + \frac{a}{2 (y - 1) (y - 2)}$$

(5)

And then the terminal’s service price is obtained as follows:

$$s_{SS}^* = \frac{m_E p_c + c_E - c_1}{2} - \frac{a}{2 y - 2}$$

(6)

The optimal profits of terminal and carriers, and the carbon emissions from the terminal, are as follows:

$$\pi_{TSS}^* = \frac{\left[ (m_E p_c + c_E + c_1) (y - 1) + a \right]^2}{2 (y - 2) (y - 1)} + K p_c$$

(7)

$$\pi_{1SS}^* = \pi_{2SS}^* = \frac{\left[ (m_E p_c + c_E + c_1) (y - 1) + a \right]^2}{2 (y - 2)}$$

(8)

$$T_{SS}^* = \frac{m_E \left[ (m_E p_c + c_E + c_1) (y - 1) + a \right]}{2 - y}$$

(9)

### 3.2. Model 2 (both carriers adopt LSFO)

When two carriers both adopt LSFO, similar to model 1, the profit functions can be derived as

$$\pi_{TLL} = s_{LL} \left( q_{1LL} + q_{2LL} \right) - \left[ \left( q_{1LL} + q_{2LL} \right) m_L - K \right] p_c$$

(10)

$$\pi_{1LL} = (p_{1LL} - s_{LL} - c_1') q_{1LL}$$

(11)

$$\pi_{2LL} = (p_{2LL} - s_{LL} - c_1') q_{2LL}$$

(12)

In equation (10), the first term describes the terminal’s profits from offering berthing service after the carriers adopt LSFO, and the second term represents revenues/costs from carbon trading. Equation (11) and equation (12) represent the carrier 1’s and carrier 2’s profits, respectively, which can be obtained by subtracting the berthing cost in the terminal, the transportation cost and LSFO cost from the freight rates. And the carbon emissions from terminal is

$$T_{LL} = \left( q_{1LL} + q_{2LL} \right) m_L$$

(13)

Similarly, by using backward deduction process to solve the Stackelberg game model, carriers firstly determine the optimal freight rates as follows:

$$p_{1LL}^* = p_{2LL}^* = \frac{m_L p_c + c_1' + 2a}{2 (2 - y)} + \frac{a}{2 (y - 1) (y - 2)}$$

(14)

And then the terminal decides the optimal service price:

$$s_{LL}^* = \frac{m_L p_c - c_1'}{2} - \frac{a}{2 y - 2}$$

(15)

The profits of the terminal and carriers and total carbon emissions are respectively:

$$\pi_{TLL}^* = \frac{\left[ (m_L p_c + c_1') (y - 1) + a \right]^2}{2 (y - 2) (y - 1)} + K p_c$$

(16)
The functions of the terminal and two carriers are defined as

\[ \pi_{1LL} = \pi_{2LL} = \left( \frac{(m_L p_c + c'_L) (y - 1) + a}{2 (y - 2)} \right)^2 \]

\[ T_{LL}^* = \frac{m_L [ (m_L p_c + c'_L) (y - 1) + a ]}{2 - y} \]

3.3. Model 3 (carrier 1 adopts SP and carrier 2 adopts LSFO)

In this model, we assume carrier 1 chooses SP and carrier 2 chooses LSFO. Similar to the previous two models, the profit functions of the terminal and two carriers are defined as

\[ \pi_{TSL} = (s_{SL} - c_E) q_{1SL} + s_{SL} q_{2SL} - (q_{1SL} m_E + q_{2SL} m_L - K) \]

\[ \pi_{1SL} = (p_{1SL} - s_{SL} - c'_L) \]

\[ \pi_{2SL} = (p_{2SL} - s_{SL} - c'_L) \]

\[ T_{SL} = q_{1SL} m_E + q_{2SL} m_L \]

In equation (16), the first and second terms describe the terminal's profits from offering berthing service after carriers use SP and LSFO, respectively, and the third term represents revenues/costs from carbon trading. Equation (17) represents the profit of carrier 1 who adopt SP, which can be obtained by subtracting the berthing cost in the terminal, the transportation cost and the cost of using SP from the freight rates. Equation (18) represents the profit of carrier 2 who adopt LSFO, which can be obtained by freight rates from shippers minus the berthing cost in the terminal, the cost of transportation and using LSFO.

Similar to model 1 and model 2, we can obtain the equilibrium freight rates of the carriers firstly:

\[ p_{1SL}^* = \frac{m_E + m_L}{4 (2 - y)} p_c + c_E + 3c'_L - c'_L + 4a \]

\[ + \frac{a}{2 (y - 2) (y - 1)} \]

\[ p_{2SL}^* = \frac{m_E + m_L}{4 (2 - y)} p_c + c_E + 3c'_L - c'_L + 4a \]

\[ + \frac{a}{2 (y - 2) (y - 1)} \]

Then the optimal service price of the terminal is as follows:

\[ s_{SL}^* = \frac{(m_E + m_L) p_c + c_E - c'_L - c'_L}{4} - \frac{a}{2y - 2} \]

And the profits of carriers and terminal and carbon emissions of terminal are as follows:

\[ \pi_{1SL}^* = \frac{1}{4} \left[ \frac{(m_E + m_L) p_c + 3c'_L + c_E - c'_L}{2y - 4} (y - 1) + 2a \right] + \frac{2y (c'_L - c'_L)}{y^2 - 4} \]

\[ \pi_{2SL}^* = \frac{1}{4} \left[ \frac{(m_E + m_L) p_c + 3c'_L + c_E - c'_L}{2y - 4} (y - 1) + 2a \right] + \frac{2y (c'_L - c'_L)}{y^2 - 4} \]

\[ \pi_{TSL}^* = \frac{1}{4} \left[ (m_E + m_L) p_c + 3c'_L + c_E - c'_L (y - 1) + 2a \right] + \frac{2y (c'_L - c'_L)}{y^2 - 4} \]

4. PRICES, PROFITS AND CUSTOMER SURPLUS ANALYSIS

4.1. Prices of terminal and carriers

Whether SP or LSFO is adopted by two carriers, the optimal service prices of the terminal increase in \( p_c, m_L, m_E \) and \( c_E \), but decrease in \( c'_L \) and \( c'_L \). The optimal freight rates of the carriers in three models increase in \( p_c, m_L, m_E \) and \( c_E \) and the optimal freight...
rates of the carriers in model 1 and model 2 increase in $c'_L$ and $c'_E$. In model 3, the optimal freight rates of the carrier who use SP increase in $c'_L$ but decrease in $c'_E$; meanwhile, the freight rates of the carrier adopting LSFO increase in $c'_E$ but decrease in $c'_L$. Then Proposition 1 compares the terminal's optimal prices under three different cases.

**Proposition 1.** In three different cases (SS, LL, SL), the equilibrium prices of terminal satisfy: if $p_c \leq \frac{c'_L-c_E-c'_E}{m_L-m_E}$, then $s^*_LL < s^*_SL < s^*_SS$; otherwise, $s^*_SS < s^*_SL < s^*_LL$.

We can conclude from Proposition 1 that under a low carbon price, the more carriers adopt SP, the higher service prices charged by the terminal, but while carbon price is high, the opposite is true. Since the terminal is acted as the leader, it can influence the carriers' choice of SP or LSFO by changing the service prices to obtain more profits, with the increase of carbon price, the optimal service prices faced by carrier who using LSFO is also increasing, while the carrier adopting SP can pay a lower service price.

**Proposition 2.** When two carriers simultaneously adopt SP or LSFO, the equilibrium freight rates of carriers satisfy: when $p_c < \frac{c'_E-c_E-c'_L}{m_L-m_E}, p^*_SS > p^*_LL$, when $p_c > \frac{c'_E-c_E-c'_L}{m_L-m_E}$, $p^*_SS < p^*_LL$. When carrier adopts SP and the other chooses LSFO, if $c'_L < c'_E$, then $p^*_2LL < p^*_1LL$, otherwise, $p^*_2LL > p^*_1LL$.

**Proposition 3.** When two carriers adopt the same technologies, the terminal’s profit satisfies: if $0 < p_c < \frac{c'_E-c_E-c'_L}{m_L-m_E}$, then $\pi^*_TSS < \pi^*_TLL$, if $\frac{c'_E-c_E-c'_L}{m_L-m_E} < p_c < \frac{a-c'_L(1-y)}{m_L(1-y)}$, then $\pi^*_TSS > \pi^*_TLL$.

**Proposition 4.** When two carriers adopt the same strategy, the carrier's profits satisfy: if $0 < p_c < \frac{c'_E-c_E-c'_L}{m_L-m_E}$, then $\pi^*_1SS < \pi^*_1LL$, if $\frac{c'_E-c_E-c'_L}{m_L-m_E} < p_c < \frac{a-c'_L(1-y)}{m_L(1-y)}$, then $\pi^*_1SS > \pi^*_1LL$.

**Proposition 5.** When two carriers served by the same terminal adopt different strategies, their profits satisfy: if $c'_L < c'_E$, then $\pi^*_1SL < \pi^*_2SL$, otherwise $\pi^*_1SL > \pi^*_2SL$.

**Proposition 6.** When two carriers adopt the same strategy (SS, LL), the consumer surplus satisfies: if $0 < p_c < \frac{c'_E-c_E-c'_L}{m_L-m_E}$, then $c^*_SS < c^*_LL$, if $\frac{c'_E-c_E-c'_L}{m_L-m_E} < p_c < \frac{a-c'_L(1-y)}{m_L(1-y)}$, then $c^*_SS > c^*_LL$.

4.3. **Customer surplus**

Finally, this section compares customer surplus under different strategy choices of two carriers, the results help regulators to promote the adoption of SP or LSFO from the perspective of optimizing the consumer surplus.

**Proposition 6.** When two carriers adopt the same strategy (SS, LL), the consumer surplus satisfies: if $0 < p_c < \frac{c'_E-c_E-c'_L}{m_L-m_E}$, then $c^*_SS < c^*_LL$, if $\frac{c'_E-c_E-c'_L}{m_L-m_E} < p_c < \frac{a-c'_L(1-y)}{m_L(1-y)}$, then $c^*_SS > c^*_LL$. And when cross price elastic coefficient of demand $y = 0.5$, the consumer surplus is equal to the sum of the profits of the two carriers.

**Proposition 6 compares the customer surplus when both carriers use SP or adopt LSFO. It is shown that when carbon price is low, more customer surplus can be obtained if two carriers use LSFO, and when carbon price is high, more customer surplus can be obtained if two carriers adopt SP. Propositions 3, 4, 5 and 6 indicate that the government should encourage carriers to use LSFO when carbon price is low and use SP when carbon price is high.**

5. **CARRIERS’ STRATEGY CHOICE**

Based on the optimal profits of the two carriers in three models, there will be four cases when two carriers make their own decisions, the game matrix for two carriers is depicted in Table 2, the
first term of each strategy portfolio represents the profits of the carrier 1.

**Proposition 7.** When \( \frac{c_E + 3c_s - 3c_L}{m_L - m_E} + \frac{4y(c_L - c_s)}{(y+2)(y-1)(m_L - m_E)} < p_c < a - c_E (1-y) \frac{m_E}{m_L (1-y)} \), whatever strategy carrier 1 adopts, carrier 2 will always choose SP. Because the two carriers are homogeneous, in the same way, whatever strategy carrier 2 adopts, carrier 1 will always choose SP. When \( 0 < p_c < \frac{c_E + 3c_s - 3c_L}{m_L - m_E} + \frac{4y(c_L - c_s)}{(y+2)(y-1)(m_L - m_E)} \), no matter carrier 1 uses SP or LSFO, carrier 2 will choose LSFO, and vice versa.

From **Proposition 7**, we can find that under non-cooperation situation, carriers’ choice of SP or LSFO do not affect each other, two carriers will choose SP at high carbon price and choose LSFO at low carbon price to maximize their profits, one carrier chooses SP and the other chooses LSFO will not exist in this situation, but this choice may not be the best choice for the total transport chain and customer surplus, the specific analysis is performed in the next section.

6. **NUMERICAL ANALYSIS**

In this section, we use some real data to verify the previous propositions. Referring to Yang et al. (2019), the corresponding data are given as follows: \( a = 200, y = 0.5, c_E = 2.8, c_L = 1.6, c_t = 3.6, c_s = 0.6, m_E = 4.2, m_L = 4.9, K = 100. \) Because the implicit assumption in our models is that the demand is greater than zero, the following analysis is all the cases where the carbon price is less than 80.

6.1. **Impact of carbon price on service prices and profits of terminal.**

From **Figure 1a**, we can conclude that the terminal’s profits are increasing with the increase of the number of carrier using LSFO when the carbon price is low; therefore, the terminal will charge a lower service prices for carrier using LSFO to encourage more carriers to use LSFO, as shown in **Figure 1b**. While with the increase of carbon price, the terminal with more carriers using SP can get higher returns, so the service prices for carrier using SP will gradually be lower than those for carrier using LSFO. Therefore, in order to promote the development of SP, the government can subsidize carriers using SP when the carbon price is low, or raise the carbon price, because carriers will choose SP spontaneously when the carbon price is high.

6.2. **Impact of carbon price on pricing strategies and profits of carriers**

6.2.1. **Impact of carbon price on pricing strategies and profits of individual carriers**

Firstly, we consider two different cases i.e. both carriers use SP and both carriers use LSFO, which correspond to model 1 and

Table 1. Parameters and notions

| Parameter | Description |
|-----------|-------------|
| \( a \)   | Market size faced by carriers |
| \( y \)   | Cross-price-elastic coefficient |
| \( c_t \) | Unit ocean transportation cost of the carriers |
| \( c_s \) | Unit cost of the carriers adopting SP |
| \( c_L \) | Unit cost of the carriers adopting LSFO |
| \( c_E \) | Unit cost of the terminal adopting SP |
| \( m_E \) | Unit carbon emissions of the terminal adopting SP |
| \( m_L \) | Unit carbon emissions of the terminal adopting LSFO |
| \( p_c \) | Unit carbon price in the carbon market |
| \( K \)   | Carbon cap assigned to the terminal |
| \( T \)   | Total carbon emissions |
| \( s \)   | Service price of the terminal adopting SP or LSFO |
| \( p \)   | Freight rate of the carrier adopting SP or LSFO |

Table 2. Game matrix for two carriers

| Carrier 1 | Carrier 2 |
|-----------|-----------|
| SP        | \( \pi_{1SP}, \pi_{2SP} \) |
| LSFO      | \( \pi_{1LS}, \pi_{2LS} \) |

6.2.2. **Impact of carbon price on pricing strategies and profits of individual carriers**

Firstly, we consider two different cases i.e. both carriers use SP and both carriers use LSFO, which correspond to model 1 and
model 2, respectively. When the carbon price is low, the cost of installing SP at a terminal is higher than the cost of carbon emissions, so carriers will be encouraged to use LSFO, as a result, the terminal service prices paid by the carriers who use LSFO will be lower and higher profits can be obtained, as shown in Figure 2a. Because the carriers using LSFO pay lower terminal service prices, they charge lower freight rates to shippers, as shown in Figure 2b. When carbon price is high, the cost of carbon emissions is higher than the cost of installing SP, the terminal hopes more carriers use SP and the carriers’ service prices who use SP charged by terminal will be lower than the carriers who use LSFO, so the profits of carriers using SP can be higher, as shown in Figure 2a. Accordingly the carriers’ freight rates using SP will be lower, as shown in Figure 2b.

Secondly, we consider the case in which one carrier uses SP and the other carrier uses LSFO, which corresponds to model 3. We can see from previous data that the cost of carrier who use LSFO is 1.6 and the cost of the carrier who use SP is 0.6, so the carrier using SP have a cost advantage and can get higher profits, as shown in Figure 3a. At the same time, carrier using LSFO must raise his own freight rates to compensate for higher costs and to ensure his own benefits, as shown in Figure 3b. It can be seen that when the cost of using LSFO is higher than adopting SP, the carriers will be willing to use SP. However, since most of the cost of installing SP is born by the port, the government should increase the subsidy for the construction of port SP.

6.2.2. Impact of carbon price on total profits of two carriers and transport chain

Firstly, we can see that, it is most profitable for the two carriers that two carriers use LSFO when the carbon price is low and that two carriers use SP when the carbon price is high. It is not the optimal choice when one carrier adopts SP and the other carrier uses LSFO, which is consistent with Proposition 7. We can see it clearly from Figure 4, both carriers use LSFO when carbon price is less than 2.6 and both carriers use SP when it is greater than 2.6, which can maximize their total profits. This means that it is more profitable for the two carriers to cooperate than to compete. Figure 5 demonstrates that the change trend of the transport chain’s profit is the same as that of the two carriers’ total profits; this also implies that the cooperation between the
two carriers will maximize not only their total profits but also the profits of the entire transport chain.

6.3. Impact of carbon price on customer surplus
It can be clearly seen from Figures 4, 5 and 6 that the consumer surplus, the profits of the two carriers and the profits of the whole transport chain keep highly consistent change trend with the change of carbon price, that is to say, when carbon price is less than 2.6, both carriers adopt LSFO, otherwise they use SP to maximize the consumer surplus. From Sections 6.2 and 6.3, we can conclude that if carriers cooperate to maximize their total profits, this will maximize the entire transport chain’s profits and the consumer surplus too.

7. CONCLUSIONS AND FUTURE RESEARCH
SP and LSFO are the effective ways to reduce air pollutant emissions from ships, and also the future popular strategies for ship emissions reduction. This paper studies the differences in pricing, profits and consumer surplus caused by the choice of SP or LSFO at different carbon prices. By solving the three different models, we get the equilibrium solutions under different conditions. Our study is different from the existing research, we specifically study the impact of carbon price and the choice of SP or LSFO on the prices, profits, consumer surplus and social welfare in a transport chain.

When two carriers compete, carbon price is an important determinant of carrier’s decision-making, both carriers choose LSFO when carbon price is low, and adopt SP when carbon price is high. This decision is also beneficial for the terminal. When carbon emissions are high, the terminal needs to pay for the excess carbon emissions. If the carbon price is higher, the terminal would like more carriers to use SP to reduce carbon emissions, and the remaining carbon allowances can be also sold in carbon trading market, and if the carbon price is low, the terminal prefers more carriers use LSFO to reduce the cost of building SP infrastructure, because the cost of paying for excess carbon emissions is significantly lower than the cost of building SP infrastructure. It can be also found that the total profits of two carriers, the total profits of the transport chain and the consumer surplus all have the same changes with the increase of carbon price, they will be maximized at the same carbon price. If two carriers cooperate instead of making their own decisions separately to achieve the optimal profits, the total profits of the transport chain and the consumer surplus will also be maximized. For example, in Shenzhen port, two carriers will adopt LSFO when the carbon price is less than 2.6; otherwise, two carriers will choose SP, which not only maximizes the total profits of two carriers but also maximizes the transport chain’s profits and the consumer surplus.

There will be future research directions in this study. In this paper, we build a model of a two-stage transport chain consisting of a terminal and two symmetrical carriers, a more realistic transport chain may be composed of asymmetric carriers. We also have not considered other factors that affect carriers’ strategy choice such as the port congestion cost and shippers’ green preference. Another problem is that with the alliance of shipping companies,
ports may have less bargaining power, different power structures in a transport chain should be discussed. In addition, other carbon reduction policies, such as carbon taxes and government subsidies, can also be considered. Furthermore, other demand functions besides linear demand should also be considered in a future research.

ACKNOWLEDGMENT

We would like to be grateful to the editors and anonymous referees for their valuable comments. This work was supported by National Natural Science Foundation of China [grant number 71974123] and Innovation Program of Shanghai Municipal Education Commission [grant number 2017-01-07-00-10-E00016].

REFERENCES

Aksoy S, Durmusoglu Y. Improving competitiveness level of Turkish intermodal ports in the frame of green port concept: a case study. Mar Policy Manag 2020;47:203–20.
Antturi J, Hanninen O, Jalkanen J-P et al. Costs and benefits of low-sulphur fuel standard for Baltic Sea shipping. J Environ Manag 2016;184:431–40.
Chen J, Fei Y, Wan Z. The relationship between the development of global maritime fleets and GHG emission from shipping. J Environ Manag 2019;242:31–9.
Chang CC, Huang PC. Carbon allowance allocation in the shipping industry under EEDI and non-EEDI. Sci Total Environ 2019;678:341–50.
China Port. 2017. Management Suggestions on the Development of China’s Shore Power. http://www.escn.com.cn/news/show-430111.html. (12 June 2017, date last accessed).
Cui H, Notteboom T. Modelling emission control taxes in port areas and port privatization levels in port competition and co-operation sub-games. Transp Res D Transp Environ 2017;56:110–28.
Dai L, Hu H, Wang Z et al. An environmental and techno-economic analysis of shore side electricity. Transp Res D Transp Environ 2019a;75:223–35.
Dai L, Hu H, Wang Z. Is shore side electricity greener? An environmental analysis and policy implications. Energy Policy 2019b;111144.
Dong G, Huang R, Ng P. Tacit collusion between two terminals of a port. Transp Res E Log Transp Rev 2016;93:199–211.
Feng L, Notteboom T. Peripheral challenge by small and medium sized ports (SMPs) in multi-port gateway regions: the case study of northeast of China. Polish Mar Res 2013;20:55–66.
Hall W. Assessment of CO2 and priority pollutant reduction by installation of shore power. Resour Conserv Recycl 2010;54:462–7.
Kalli J, Repka S, Alhosalo J. Estimating costs and benefits of sulphur content limits in ship fuel. Int J Sust Transp 2015;9:468–77.
Kontovas CA. Integration of air quality and climate change policies in shipping: the case of sulphur emissions regulation. Mar Policy 2020;113:103815.
Kumar J, Kumpulainen L, Kauhaniemi K. Technical design aspects of harbour area grid for shore to ship power: State of the art and future solutions. Int J Electr Power Energ Syst 2019;104:840–52.
Lühteenmäki-Uutela A, Repka S, Haukojärvi T, Pohjola T. How to recognize and measure the economic impacts of environmental regulation: the sulphur emission control area case. J Clean Prod 2017;154:553–65.
Li H. 2019. Analysis for Shore Power Economy in Preventing Air Pollution of Vessels are Docked at the Berth. EES Web of Conferences, EDP Sciences.
Notteboom T. The impact of low sulphur fuel requirements in shipping on the competitiveness of ro-ro shipping in Northern Europe. WMU J Mar Affairs 2011;10:63–95.
Peng Y, Li X, Wang W et al. A method for determining the allocation strategy of on-shore power supply from a green container terminal perspective. Ocean Coast Manag 2019;167:158–75.
Peng, C.S., 2016. Application of shore power for ocean going vessels at berth in China. In 2016 International Conference on Sustainable Energy. Environment and Information Engineering (SEEIE), Thailand, 8–15.
Qiu X, Lam J.S.L, Huang G.Q. A bilevel storage pricing model for outbound containers in a dry port system. Transp Res E Log Transp Rev 2015;73:65–83.
Qian X, Liu W, Yang J. Game theory analysis of technology adoption timing and pricing decision in supply chain system under asymmetric Nash equilibrium. J Intell Fuzzy Syst 2018;35:3101–11.
Ren J, Lützen M. Fuzzy multi-criteria decision-making method for technology selection for emissions reduction from shipping under uncertainties. Transp Res D Transp Environ 2015;40:43–60.
Schwartz H, Gustafsson M, Spoehr J. Emission abatement in shipping—is it possible to reduce carbon dioxide emissions profitably? J Clean Prod 2020;120069.
Sheng D, Meng Q, Li Z. Optimal vessel speed and fleet size for industrial shipping services under the emission control area regulation. Transp Res E Emerg Technol 2019;105:37–53.
Song, T. and X. Xu 2016. Modeling and Simulation Analysis of Shore-to-ship Power System. DEStech Transactions on Engineering and Technology Research(iceea): 978-1-60595-407-3.
Tseng P, Pilcher N. A study of the potential of shore power for the port of Kaohsiung, Taiwan: to introduce or not to introduce? Res Transp Bus Manag 2015;17:83–91.
Wang X, Meng Q. Optimal price decisions for joint ventures between port operators and shipping lines under the congestion effect. Eur J Oper Res 2019;273:695–707.
Witjes S, Vermeulen W, Cramer J. Exploring corporate sustainability integration into business activities: experiences from 18 small and medium sized enterprises in The Netherlands. J Clean Prod 2017;153:528–38.
Winkel R, Weddige U, Johnsen D et al. Shore side electricity in Europe: potential and environmental benefits. Energy Policy 2016;88:584–93.
Yang L, Cai Y, Zhong Z et al. A carbon emission evaluation for an integrated logistics system—a case study of the port of Shenzhen. Sustainability 2017;9:462–85.
Yang L, Cai Y, Wei Y et al. Choice of technology for emission control in port areas: a supply chain perspective. J Clean Prod 2019;240:118105.
Yu J, Vo’S, Tang G. Strategy development for retrofitting ships for implementing shore side electricity. Transp. Res. Part D 2019;74:201–213.
Yuan J, Ng S, Sou W. Uncertainty quantification of CO2 emission reduction for maritime shipping. Energy Policy 2016;88:113–30.
Zhao ZY, Gao L, Zuo J. How national policies facilitate low carbon city development: A China study. J Clean Prod 2019;234:743–54.
Zhang Q, Wang W, Peng Y et al. A game-theoretical model of port competition on intermodal network and pricing strategy. Transp Res E Log Transp Rev 2018;114:19–39.
Zheng W, Li B, Song D. Effects of risk-aversion on competing shipping lines’ pricing strategies with uncertain demands. Transp Res B Method 2017;104:337–56.