The Optimal Green Strategies for Competitive Ocean Carriers under Potential Regulation

Wei Zheng [a], Bo Li [a,✉] and Dongping Song [b]
[a]College of Management and Economics, Tianjin University, Tianjin, 300072, China
[b]School of Management, University of Liverpool, Liverpool, UK
Corresponding author: libo0410@tju.edu.cn

Citation: Zheng, W., Li, B. and Song, D.P. (2022). The Optimal Green Strategies for Competitive Ocean Carriers under Potential Regulation, *European Journal of Operational Research*, Available online 3 March 2022. (https://doi.org/10.1016/j.ejor.2022.02.052)

Abstract:
Uncertain green regulation and market competition are two major external environmental factors for ocean carriers to consider when making their decisions on business operations. The uncertainty of the green regulation arises from the probability of its occurrence. It is assumed that ocean carriers can adopt one of the two green strategies, i.e., the equipment upgrades strategy or the slow steaming strategy, to comply with the potential green regulation. This paper aims to examine the stable green strategies as well as the pricing decisions of competitive carriers in the shipping market considering the service differentiation and the upgrade risk. A two-period game model is formulated to seek the sub-game perfect Nash equilibrium under potential regulation. We obtain the final sub-game perfect Nash equilibrium, i.e., when the probability of enacting regulation is sufficiently high, there is always one carrier that will adopt the equipment upgrades strategy. However, because of the joint impact of market competition and uncertain regulation, the two carriers will never adopt the equipment upgrades strategy simultaneously. In addition, our results show that the potential regulation sometimes may help the two carriers achieve the optimal outcome. Nevertheless, the carriers may fall into a "sub-optimal outcome" in some situations.

Keywords: Maritime transport; Slow Steaming; Upgrade Risk; Uncertain Green Regulation; Service Differentiation

---

1. Introduction

Maritime transport carries the majority of global trade, accounting for 75% ~80% by volume based on the data from United Nations (Lee and Song 2017; UNCTAD 2018). Compared to other transport modes, maritime transport has a relatively 'green image'. However, given the large scale and rapid growth, it still has a huge impact on the environment. Environmental pollution from ships has been a key issue for governments and third-party institutions like International Maritime Organization (IMO). More stringent environmental regulations and policies have been introduced to control oil spills, ballast water discharge and emissions. Many important regulations about pollutions in the maritime industry are agreed in the Annexes of the International Convention for the Prevention of Pollution from Ships (MARPOL), including “IMO 2020”, which cuts the Sulphur content of ships’ fuel oil from 3.5% to 0.5% globally from 1 January 2020.

However, it should be noticed that sometimes the announced regulations may be delayed, or even never be implemented due to disagreements among member states (Lister et al. 2015). “IMO 2020” originally scheduled for January 2020, was delayed to March. The International Ballast Water Management Convention, which was actively promoted and planned to start from 2017, has been postponed to 2022. In addition, IMO has set up an initial greenhouse gas (GHG) strategy with the targets to reduce the carbon intensity of international shipping by at least 40% by 2030 and towards 70% by 2050, compared to the level of 2008 (Song 2021). However, it is unknown when the new regualtions will actually be enforced. Such uncertain regulations have a great impact on the shipping companies’ decision-making in their business operations.

Decarbonizing shipping has been on IMO’s agenda for a long time. It is expected that IMO will issue new green regualtions to reduce carbon emissions from shipping. In this study, we focus on the short-term.green regulations that are potentially to be enforced by IMO or goverments in near future. Here short-term regulations refer to the regulations that ocean carriers should respond in short-term. Generally, there are two broad categories of measures (we call them green strategies) to comply with the regulations from shipping: technical measures and operational measures. The former focuses on energy efficiency and improved equipment, e.g. engine, propulsion, scrubber, and alternative fuels. The latter focuses on reducing emissions during operations at sea or ports. Typical operational measures include routing design, speed reduction (slow steaming), ship fleet planning, etc. In addition, IMO also identified the necessity of market-based measures. Nevertheless, market-based measures are essentially different forms of green regulations, which ultimately act as an incentive or enforcement to implement technical and operational measures (Bouman et al. 2017; Balcombe et al. 2019). In summary, the technical measures require the companies to make investment in advance, e.g., conducting the process of R&D or equipment upgrades. On the other hand, the operational measures are more flexible and the companies could implement the measure after the regulation is put into practice. However, it may significantly affect the shipping companies’ service quality.

Specifically, we take the equipment upgrades strategy as the representative in the technical measures, and slow steaming strategy as the representative in the operational measures. It is assumed that ocean carriers can adopt one of the two green strategies (either the equipment upgrades strategy or the slow steaming strategy) to comply with the potential green regulation. The equipment upgrades strategy requires shipping companies to commit significant effort and time to retrofit existing equipment. In addition, since it usually relies on innovative technologies, the reliability of the retrofitting is difficult to estimate, which incurs uncertainties and risks in future operations (Wang et al. 2021). For example, the operational cost of using an LNG engine would rely on the availability of the LNG supply infrastructure and logistics in the world (Ren et al. 2017). The efficiency of new green-techs largely depends on the external environment and conditions, e.g., alternative fuels such as wind and solar power would highly rely on the weather (Wen et al. 2019). The upgrade process has to be conducted before the regulation, thus, the upgrade risk, the upgrade investment, and the uncertainty of whether the green regulation will come into force are important factors that ocean carriers have to consider. On the other hand, the slow steaming strategy requires the ships to sail at a speed that is significantly lower than the designed speed (Cariou et al. 2011). However, the adoption of slow steaming means the transit time will be increased, which reduces the carriers' service quality and may be less attractive to some shippers.

Furthermore, it should be noticed that major shipping companies often cover similar transportation routes and provide similar transportation services, which results in a low-service-differentiation market (Lee and Song 2017). Such characteristics have caused fierce competition in maritime industry. With the fierce competition and supply overcapacity, the freight rate (price) and transit time or speed (service quality) are two main fists for carriers to compete against each other. Obviously, the two green strategies will both affect the ocean carriers' competitiveness in the shipping market. The costly equipment upgrades strategy will reduce the price advantages of carriers; however, the slow steaming strategy will reduce the service quality advantages. Therefore, the service differentiation will be changed, the decision-making for ocean carriers is further complicated. Considering the above pros and cons, which green strategy is optimal for the shipping companies in response to potential regulations? What will be the final stable outcome in the competitive shipping market? How could the green regulations from IMO and Governments be more effective?

To tackle these challenges, we use game theory and behavioral economics to model the relationship between the green strategy, the pricing decisions, and the external factors in the context of two competing ocean carriers under a potential green regulation. We divide the timeframe into two periods. In the first period, there is no green regulation and the carriers have an opportunity to adopt a green strategy; in the second period, the regulation may be enforced with a certain probability. The Conditional Value-at-Risk is used to measure the carriers' attitude to the risk associated with equipment upgrades. We attempt to investigate the following research questions:

(i) How will the adoption of different green strategies influence two carriers' pricing decisions and utilities in the two-period competition model? What are the impacts of the potential regulation on their decisions and outcomes?

(ii) What are the final stable equilibriums of the green strategies for two competing carriers? What are the joint impacts of the potential regulation and the competition on the final equilibrium? Whether the final equilibrium outcomes are consistent with the ideal outcomes for two carriers?

To address the above research questions, we establish four sub-games according to the combinations of two carriers' choices of the green strategies, i.e. (*E, E*), (*E, S*), (*S, E*) and (*S, S*), where *E* represents that the carrier adopts the equipment upgrades strategy, and *S* represents that the carrier adopts slow steaming strategy. The optimal pricing decisions and profits/utilities will be derived and analyzed for each sub-game. By comparing the results of four sub-games, we obtain the final sub-game perfect equilibrium of the two-period game. Then, the final equilibrium will be analyzed and compared with the optimal economic outcomes.

We find that the potential regulation and the green strategies affect the competitive relationship in the market significantly. Specifically, there exist three types of effects that could be caused by the potential green regulation under market competition, i.e., the penalty effect, the competition-alleviation effect, and the competition-aggravation effect. The ultimate impact of the potential regulation on two carriers' decisions and payoffs depends on which effect is dominant in the system. In addition, though the slow steaming strategy is usually seen as a remedial measure under the green regulation, we find sometimes the regulation may also benefit the carrier with slow steaming. Thus, the final equilibrium outcome appears to be complicated. Nevertheless, we find when the probability of the regulation occurrence is sufficiently low, the two carriers will both adopt the slow steaming strategy; when the probability of the regulation occurrence is relatively high, there is always one carrier adopting the equipment upgrades strategy. However, because of the joint impact of the market competition and the potential regulation, two carriers will never adopt the equipment upgrades strategies simultaneously. Our results show that the potential regulation sometimes can be seen as a signal to help two carriers collude to achieve better outcomes, whereas sometimes the final equilibrium outcomes can be different from the optimal outcomes, which means, the carriers may fall into a "sub-optimal outcome situation".

To the best of our knowledge, we are among the first to investigate ocean carriers' green strategies in a competitive market facing uncertain green regulations. The two green strategies under consideration, i.e. equipment upgrades and slow steaming, are typical strategies to reduce shipping emissions in the technical measure category and the operational measure category respectively. In addition, we explicitly illustrate the impact of the green upgrade risk, the uncertain regulation and the service differentiation on carriers' decision making, which has seldom been studied in the shipping industry. Further, the final sub-game perfect equilibrium of the whole game is obtained. The characteristics of the equilibriums are analyzed to offer managerial insights.

It should be noted that slow steaming is likely to comply with the short-term regulations (e.g. the recently proposed two regulations, Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), which are expected to come into force on 1 January 2023); but slow steaming will not be able to comply with the long-term regulations (e.g. zero-carbon emission). Hence, the set-up of the problem under consideration is for short-term responses. This setting is based on the following considerations. First, the governments or some third-party organizations may be more concerned with the effectiveness of the regulation within a certain period of time. For example, IMO's EEXI and CII regulations (to be enforced on 1 January 2023) are regarded as short-term policies to reduce GHG emissions from shipping. Pang et al. (2019), Fabrizi et al. (2018) and Zhimai et al. (2021) all put forward that timeliness should be considered for environmental governance. According to European Commission, "The urgency to identify and develop adequate and timely solutions is justified by the alarming trends in global energy demand, the finite nature of conventional oil and natural gas reserves, and the need to dramatically curb greenhouse gas emissions. These actions would effectively mitigate the devastating consequences of climate change[1]." Thus, our research setting is consistent with the aims of many environmental governance bodies. Second, green technologies will continue to be improved. In the future, green technologies will become more mature and cost-efficient and the uncertainty will also be reduced. At that time, the carriers may be more willing to adopt green equipment upgrades strategy. In addition, in long-term more strict regulations such as extremely low or zero-carbon emission policies may be enforced that will force carriers to upgrade equipment or scrap the vessels. Third, some policies may not be implemented for a long time and may be changed or even be canceled. In this paper, we focus on short-term regulations and the carriers' responses to such regulations, which is highly relevant to the current industrial practices.

The rest of this paper is organized as follows: in section 2, we review the relevant literature. In section 3, the main assumptions and the problem are described. The two-period game model is established. In section 4, we analyze and compare the equilibriums for four sub-games under two carriers' given green strategies. In section 5, we obtain the final sub-game perfect equilibrium of the whole game and analyze the characteristics of the final equilibrium outcome. Extensions, including sequential green strategy making, the analysis of price sensitivity, endogenous shipping speed, are discussed in Section 6. Finally, in section 7, we draw the conclusions and indicate further research.

2. Literature Review

In this section, we review three research fields that are most related to our paper. First, literature

---

[1] Refer to https://cordis.europa.eu/programme/id/FP7-ENERGY

that handles uncertain environmental regulations is introduced in a broad context. Second, green strategies in terms of emission reduction in maritime industry are discussed. Finally, literature on competition in shipping market is reviewed.

2.1 Uncertain Environmental Regulations

With the increasing public awareness of global warming and environmental protection, more environmental regulations are coming into force at regional or international level in shipping industry, e.g., Sulphur emission regulations in Emission Control Areas (Abadie et al. 2017), ship-source pollution regulations in the Baltic Sea (Ringbom et al. 2018). It should be noticed that many of the announced regulations may be postponed or even not be implemented. The enforced date and detailed contents of the regulations are often uncertain. Marcus et al. (2011) mentioned that uncertain environmental regulation has become a major concern of companies in many industries. Lister et al. (2015) and Poulsen et al. (2016) both believed that as the IMO is accelerating its environmental regulation process, the uncertainty of regulation in the future will be increasing, which has become an important factor affecting shipping companies' decision-making.

Many researchers have studied this emerging field. Engau et al. (2011) empirically studied the impact of regulatory uncertainty. They found that most companies can't ignore the potential regulations. Ritzenhofen et al. (2016) proposed a regime-switching model to quantify the impact of regulatory uncertainty. They believe that the uncertainty of regulation will delay or even reduce the investment willingness of companies. Kraft et al. (2016) studied a two-period game model with uncertain regulation for the substance of concern. Manufacturers need to decide whether to replace the substance of concern and decide whether to collaborate with its competitor. In the shipping industry, Zhu et al. (2018) used a multi-stage stochastic integer-programming model to study the optimal navigation route and fleet planning for shipping companies in the presence of uncertain environmental regulation. Haehl et al. (2018) designed an option model to help companies mitigate the risk of uncertain regulation. Nevertheless, most of the above studies are empirical or based on the optimization methods for a single organization, without considering the effect of competition and other market characteristics.

2.2 Green Strategies in Shipping Industry

Environmental sustainability in maritime transport is regulated by IMO through the Marine Environmental Protection Committee, which issued the International Convention for the Prevention of Pollution from Ships (MARPOL) in 1974. In the last two decades, IMO has identified three categories of measures to reduce carbon emissions from shipping including: technical measures, operational measures, and market-based measures (IMO 2020).

Firstly, technical measures aim at promoting the use of more energy-efficient (or less polluting) equipment on ships. For example, IMO introduced the Energy Efficiency Design Index (EEDI) in 2011, which specifies the energy efficiency of the ship or the ship-related equipment, as a non-prescriptive performance-based mechanism. Many studies analyzed and confirmed the effectiveness of technical measures, like Yliskylä et al. (2014), Abadie et al. (2017), Busch et al. (2018), and Zheng et al. (2020). In reality, green technologies imply a high degree of uncertainty, such as R&D success uncertainty (Bhaskaran et al. 2009), development uncertainty (Song et al. 2016) and operational costs uncertainty (Bilgiç et al. 2016, Wang et al. 2021). These uncertainties may affect shipping companies' willingness to adopt green technologies. However, there is a lack of research to incorporate such uncertainties into the models to compare different green strategies in shipping context.

Secondly, operational measures aim at reducing emissions during transport operations. For example, IMO introduced the Ship Energy Efficiency Management Plan (SEEMP) in 2011, which establishes a mechanism for ship operators to improve energy efficiency. The SEEMP essentially acts as a benchmark practice for ship operators to better manage ships but without punitive or incentive mechanisms to encourage a high energy efficiency operational indicator. Slow steaming strategy is regarded as one of the most effective operational measures to cut emissions, reduce transport costs, and comply with green regulations (Kontovas and Psaraftis 2011). Maloni et al. (2013) and Sheng et al. (2017) examined the pros and cons of slow steaming strategy. They both believe that the slow steaming strategy can reduce the cost of carriers and shippers and can maintain the relationship between the stakeholders. Mander et al. (2017) and Cariou et al. (2019) compared the slow steaming strategy and the technology upgrade strategy. Nevertheless, they didn't consider the service differentiation and competition in the shipping market, which is a major factor affecting the carriers' choices of the green strategies. Moreover, the impact of the uncertainty about whether the green regulation will come into force is largely ignored in the existing models.

Finally, IMO recognized that technical and operational measures alone may not be sufficient to satisfactorily reduce the amount of GHG emissions from shipping, and has agreed there is a need for market-based measures as regulation of GHG emissions from ships. A number of market-based measures have been proposed by different countries including GHG Fund, Emission Trading Scheme, Energy-efficiency Credit Trading Scheme, Cost or Compensation Measures (Lagouvardou et al. 2020). Nevertheless, market-based measures are essentially different forms of green regulations (Bouman et al. 2017; Balcombe et al. 2019). So far, none of these market-based measures has been implemented in practice.

2.3 Competition in the shipping market

Due to the capital-intensive and low-service-differentiation nature, competition between ocean carriers is fierce (Lee and Song 2017). Many studies considered the competition and pricing decisions between ocean carriers in the shipping industry, such as Zhou and Lee (2009), Yilmaz et al. (2012), Lüer-Villagra et al. (2013), Chen et al. (2016), Lu et al. (2020), etc. Song et al. (2019) further examined the competition between carriers and forwarders. In addition, some researchers analyzed the contract design in the competitive shipping market, such as Mutlu et al. (2013), Lee et al. (2015) and Trapp et al. (2020). However, the above research ignored the uncertainties in the shipping market. Zheng et al. (2017) analyzed the pricing decisions of two competing carriers by considiering demand uncertainty and constrained capacity in the shipping market. Choi et al. (2020) addressed the effect of risk attitude and uncertainty in a competitive shipping market. They found sometimes the uncertainty may bring benefits to the liner companies. Service differentiation could be another major factor affecting the competition between shipping companies. A few studies have paid attention to the delivery service in the competitive shipping market. Shah et al. (2012) proposed a general competition model for carriers considering the effect of pricing and service frequency. They analyzed the short-term and long-term effects of customer loyalty brought by on-time delivery on the final economic outcomes. Lu et al. (2020) proposed a multi-stage game model between shippers, customers and carriers in a competitive environment considering the service differentiation. They obtained the optimal delivery speed for carriers and the optimal delivery plan for shippers. However, the potential environmental regulations and the carriers' green strategies were not considered in the above research.

In summary, the research on maritime environmental regulation and green strategy has mainly focused on cost optimization, or examined the effect of the regulation empirically. The uncertainties of the green regulations and the choice of the green strategies have largely been ignored. Moreover, competition and service differentiation may have a huge impact on the competing shipping firms' decisions on green strategies. However, to the best of our knowledge, no study has been published in this aspect. In this paper, we focus on the optimal green strategies and pricing decisions for ocean carriers responding to uncertain green regulations in a competitive market. The risk caused by green technology implementation is also considered. We attempt to investigate the joint effects of the market competition and potential regulation on the carriers' decision-making processes by using game theory and behavioral economics.

3. The Model

We consider a competitive maritime shipping market consisting of two risk-averse shipping carriers with different initial ship sailing speeds. One carrier is a high-speed carrier, denoted by carrier H, and the other is a low-speed carrier denoted by carrier L. The phenomenon of asymmetric carriers competing with each other is common in the shipping market. There are some researchers stating that the carriers would compete with each other through different service qualities such as speeds (transit times), reliability, environmental impact, and profits

(Thai, 2008; Zondag et al. 2012; Mansouri et al. 2020). In practice, different vessels often have different design speeds, thus, the carriers with different ships may set different sailing speeds which are appropriate for their vessels (Eide et al. 2020; Ricci et al. 2012). In addition, individual carriers may have their preferences to the sailing speeds. With these in mind, we made the assumption of asymmetric carriers in terms of operational speed. In order to focus on the effect of the potential regulation and the green strategies of two carriers, we simplify our assumption that the two carriers compete for a point-to-point spot transportation market in two periods ($T = 1, 2$). Specifically, in the first period, the two carriers provide shipping services with the existing equipment and compete on pricing decisions. In the second period, there is a potential green regulation coming into force with a certain probability. This reflects the fact that it is still uncertain whether and to what degree that IMO will issue carbon emission regulations on international shipping in the near future.

We assume there are two green strategies that are able to comply with the potential regulation, i.e., committing effort to upgrade the equipment in period 1 (termed equipment upgrades strategy), or limiting the ship sailing speed to a lower level at period 2 if the green regulation comes into force (termed slow steaming strategy). Here the equipment upgrades can be interpreted as changing the existing engine to a dual-fuel engine or retrofitting an exhaust gas scrubber which is assumed to be completed by the end of period 1. If a carrier chooses the equipment upgrades strategy at period 1, he can keep his speed at period 2 regardless of whether the regulation comes into force. Nevertheless, besides the fixed investments, the equipment upgrades strategy also brings about uncertainty in terms of future operational costs. As shipping companies are rather conservative, they may care more about the risks towards such uncertainty. On the other hand, slow steaming strategy is more flexible because it requires no investment and allows carriers to operate business as usual if the regulation doesn't occur. However, if the regulation is enforced, the carrier adopting the slow steaming strategy will lose the service competitive advantage in the market. Clearly, the carriers' decisions will influence their competitiveness and pricing decisions in both periods.

It should be noticed that that carrier H may become the low-speed carrier in period 2 when the regulation occurs if he adopts slow steaming strategy. Thus, we use the term 'initial speeds' to represent the speeds of two carriers at the beginning of period 1, which are used to classify two carriers to be carrier H and carrier L. To simplify the narrative, we use the term 'realized speeds' to represent the actual speeds of two carriers in two periods. Based on the above description, the two carriers' realized speeds in period 1 are the same as their initial speeds respectively, whereas their realized speeds in period 2 may differ from their initial speeds depending on their green strategies and the enforcement of the green regulation.

3.1 Sequence of Events

The system can be represented by a two-period game model. The full sequence of the events in the two-period game model is shown in figure 1.

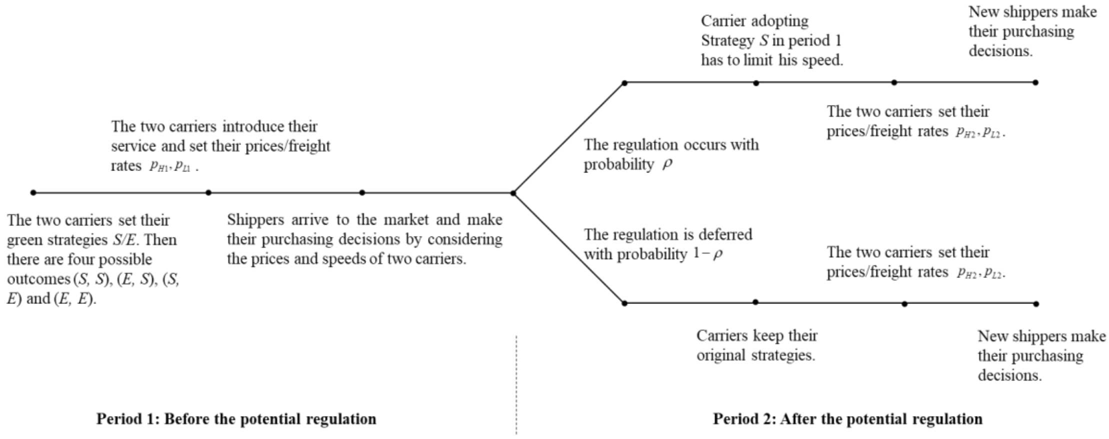


Figure 1. Sequence of Events

The details are summarized as follows:

Period 1: Before the potential regulation

At the beginning of the game, all the players in the game notice that there may be a green regulation to be enforced in period 2. The two carriers have to decide their green strategies simultaneously. The assumption of simultaneous decision-making for the green strategy (i.e. un-informed or ignoring such information) can be explained as follows. The green strategy is a relatively long-term decision. Although switching from strategy S (slow steaming) to strategy E (upgrade equipment) is relatively easy technically, it may incur various implications such as bunker fuel management (e.g. the use of bunker derivative products such as forward contracts, swaps and options), the supply chain relationships with ports and shippers, and the shipping network adjustments. Nevertheless, in Section 6.1, we will mak an extension by considering another case where the two carriers decide the green strategy sequentially.

We use $A_i = \{E, S\},\ i = H, L$ to represent the action set of firm *i*, where *E* represents that the carrier adopts the equipment upgrades strategy and *S* represents that the carrier chooses the slow steaming strategy. Then, there are four possible equilibrium outcomes: $(a_H^*, a_L^*) \in \{(S,S),(E,S),(S,E),(E,E)\}$, $a_i^* \in A_i$. For example, (E, S) indicates that carrier H chooses E strategy and carrier L choose S stratege. We assume that the firm adopting *E* strategy will spend the whole first period to perform the upgrades. During this time, he still provides transportation service with the existing equipment. We assume that the upgrades process will not influence the operational capacity of the firm in the first period.

Next, the two carriers compete by their service quality (speeds) and prices (i.e., freight rates), where the prices (p_{H1}, p_{L1}) are treated as decision variables and will be set simultaneously. Then, the customers (i.e., shippers) enter the market and choose the transportation service according to their utility functions by observing the prices and the speeds. We will provide the details of consumer utility in Section 3.2.1.

Period 2: After the potential regulation

At the beginning of period 2, the upgrades will be finished if the equipment upgrade strategy has been chosen. The green regulation occurs with a probability $\rho \in [0,1]$. If the regulation does occur, then the carrier adopting the slow steaming strategy will be forced to limit his steaming speed to reduce carbon emissions and comply with the regulation; whereas the carrier adopting the equipment upgrade strategy will keep its initial seailing speed in period 2 and comply with the regulation. If the regulation does not occur in period 2, then the two carriers will keep their speeds the same as that in period 1. Finally, the two carriers set their prices (p_{H2}, p_{L2}) for the second period. After that, the new shippers enter the market and choose the transportation service from one of the carriers according to their utility functions.

All parameters and notations used in our paper are listed in Table 1.

Table 1. Notations and Parameters

Notation	Definition
Model parameters:	
i	$i = H, L$, where $i = H$ represents the carrier with higher initial speed and $i = L$ represents the carrier with lower initial speed;
j	Transportation period, $j = 1, 2$;
v_{ij}	The vessel speed of carrier *i* in period *j*, the initial speeds of two carriers $v_{H1} = 1$, $v_{L1} = v \in (0, \bar{v}_{\max}]$, where $\bar{v}_{\max} = \min\left(\frac{2 - 2\sqrt{1-\sigma(2-B)}}{2\sigma}, \frac{-1+\sqrt{1+4B(1+\sigma)}}{2B}, 1 \right)$ ensures that the demands of carriers are non-negative.
v_0	The slow steaming speed that can comply with the green regulation.
ρ	The probability that the green regulation will come into force in period 2
V_{ij}	The utilities of shippers taking service from carrier *i* in period *j*,
u	The shippers' basic willingness to pay.
θ	The shipper's sensitivity to the speed, which is distributed uniformly over the interval [0,1]. $\hat{\theta}_j$ represents the indifference point between the utility functions for two carriers in period j.
D_{ij}	The demands of carrier *i* in period *j*.
σ	The unit cost coefficient with the existing equipment.
$\bar{\sigma}_{ij}(v_{ij})$	The unit delivery cost per trip.

ξ	The unit cost coefficient with the upgraded equipment, which is a random variable distributed in [$\sigma-\varepsilon$, $\sigma+\varepsilon$] with cumulative distribution function $\Phi(\cdot)$ and probability density function $\varphi(\cdot)$. The mean of ξ is σ and $\varepsilon<\sigma$.
η_i	The risk-averse indicator of carrier *i*.
B_i	The perceived operational cost of green upgrade for the risk-averse carrier *i* with risk preference indicator η.
π_{ij}	The profit of carrier *i* in period *j*
$CVaR_{i2}$	The utility (conditional value at risk) of carrier *i* with strategy *E* in period 2.
$U_i^{a_H a_L}(\eta_i)$	The total utility function of the carriers in sub-game (a_H, a_L) within two periods.
Decision variables:	
A, a_i	The green strategy action of carriers, $A=\{a_H, a_L\}$, $a_i = E$ means that carrier *i* upgrades the equipment in period 1; and $a_i = S$ represents that carrier *i* adopts the slow steaming strategy.
p_{ij}	The price (freight rate) per unit for carrier i in period *j*.

3.2 Customer Demands

In our model, shippers are customers of the two carriers and the market sizes in both periods are normalized to 1. Following Kalish (1985), Chiang et al. (2003) and other prior literature, we model the demands considering customers' willingness-to-pay (WTP). Shippers' utilities are the value they derive from the basic WTP, the steaming speed and the price of the carrier' service. Thus, the consumer utility for carrier *i*, $i = H, L$, in period *j*, $j = 1,2$, is $V_{ij} = u + \theta v_{ij} - p_{ij}$, where the parameter $u \in [0,1]$ represents the basic shipper's WTP for the shipping service, which means the utility that the shipper can derive when his cargos are transported successfully. The shipper's sensitivity to the price is fixed and normalized to 1. In section 6.2, we further consider the effect of price sensitivity by relaxing the assumption of shippers' sensitivity. In addition, shippers can derive extra utility if the delivery time is shorter, i.e., we assume that shippers are heterogenous in the preference of the steaming speeds. v_{ij} represents the realized speed of carrier *i* in period *j* and θ represents the shippers' sensitivity to the steaming speed, which is uniformly distributed over [0,1] to describe the shipper's heterogeneity. Hence, θv_{ij} indicates the shippers' preference of ship speed. At the beginning of period 2, the green regulation will occur with probability $\rho \in [0,1]$. If the green regulation does not come into force or the carrier has committed the equpement upgrades at period 1, the carrier's realized speed in period 2 will be kept the same as the speed in period 1, i.e., $v_{i2} = v_{i1}$. On the other hand, if the regulation occurs and the carrier chooses the slow steaming strategy in period 1, his realized speed in period 2 will be limited to v_0 to reduce the carbon emission and comply with the green regulation. The initial speeds of two carriers in period 1 satisfy: $v_0 < v_{L1} < v_{H1}$. To simplify the model analysis, we apply a linear transformation to normalize the speed range [v_0, v_{H1}] to be [0, 1]. In other words, we can assume $v_0 = 0$ and $v_{H1} = 1$. It means shippers can't gain any extra utility from the slow steaming speed. Moreover, to ensure that the demands of carriers are positive, there is a bound of pricing decisions. Since the price is an endogenous variable, the condition is converted to the constraint of v, that is, we assume $v_{L1} = v \in (0, \overline{v}_{\max}]$, where $\overline{v}_{\max}$ is given in Table 1. This setting of carrier L's initial speed also ensures that the initial market competition is not too drastic and helps us focus on interesting scenarios. It should be noted that the initial speeds of two carriers v_{i1} are treat as a pre-specified exogenous parameter at strategic planning level. The assumption is consistent with the reality that vessel operators may have a preference to specific sailing speed. For example, different vessels often have different design speeds; thus, the carriers with different ships may set different sailing speeds which are appropriate for their vessel, which is an exogenous factor (Eide et al. 2020; Ricci et al. 2012). In the last decade, although many vessels have deviated from their designed speeds by adopting slow steaming practices, there are three common categories of slow steaming: normal slow steaming around 21 knots, extra slow steaming around 18 knots, and super slow steaming around at 15 knots. Shipping companies often have a preference to one category of the slow steaming practice at strategic and tactical planning level. In addition, it is also reasonable to regard the ship speed as an exogenous parameter when the main concern of the problem is about other decisions, e.g. shipping service pricing, shipping network design, ship schedule design. For example, Wang et al. (2014) considered the exogenous shipping speed (shipping time) in their model and they also believed that the freight rate and shipping time are two major factors affecting the demands. Zhang et al. (2019) and Lu et al. (2020) stated that the shipping speed would affect the service quality of carriers and they also set them (service quality or shipping speed) as exogenous factors. In section 6.3, we have made an extension to extend the model to consider the shipping speed as an endogenous decision variable.

In addition, we assume that u is large enough so that all the shippers will purchase the delivery service in the market during a period. It is reasonable because the transportation service is requested timely and the shippers will always choose one transportation service or they may have to bear a considerable loss (e.g., goods spoilage loss). Let $\hat{\theta}_j$ represent the indifference point between the shipper's utility functions corresponding to two carriers in period j, i.e., $\hat{\theta}_j = (p_{Hj} - p_{Lj})/(v_{Hj} - v_{Lj})$. Thus, for the shippers with high θ ($\theta > \hat{\theta}_j$), their utility from carrier H is higher than that from carrier L and they prefer to choose the shipping service from carrier

H ($V_{Hj} > V_{Lj}$). Similarity, the shippers with low θ ($\theta < \hat{\theta}_j$) prefer to choose carrier L. As a result, the demands of two carriers in period j are given by $D_{Hj} = 1 - \hat{\theta}_j$ and $D_{Lj} = \hat{\theta}_j$ respectively.

3.3 Firm Profits

Carrier i can earn a revenue of p_{ij} from each shipper in period j. In the shipping industry, the vessel operating cost is predominantly determined by the fuel consumption cost. We assume that the unit delivery cost of carriers is proportional to the fuel consumption. Empirical studies have shown that the daily fuel consumption of a vessel is roughly a cubic relationship with the steaming speed (e.g. Wang and Meng 2012). Hence, the unit delivery cost per trip can be represented by $\bar{\sigma}_{ij}(v) = \sigma v_{ij}^3 t = \sigma v_{ij}^3 \cdot d / v_{ij} = \sigma d v_{ij}^2$, where t is the delivery time, d is the delivery distance, v_{ij} is the realized steaming speed and σ is the delivery cost coefficient. Without loss of generality, we normalize the delivery distance d to 1. Thus, the unit delivery cost could be represented as $\bar{\sigma}(v) = \sigma v_{ij}^2$. In addition, to represent the uncertainty of equipment upgrades, if the carrier adopts the equipment upgrades strategy in period 1, then the delivery cost will be represented by $\bar{\sigma}(v) = \xi v_{i2}^2$ after the upgrades process. ξ is a random variable distributed in the interval [$\sigma - \varepsilon$, $\sigma + \varepsilon$] with cumulative distribution function $\Phi(\cdot)$ and probability density function $\varphi(\cdot)$, $\sigma - \varepsilon > 0$. The mean of ξ is σ. The assumptions about the random unit cost coefficient for upgraded equipment can be explained as follows. First, green initiatives and equipment upgrade usually rely on innovative technologies, which imply a certain degree of uncertainty with respect to the technologies and the operational cost. For example, the reliability of the retrofitting is difficult to guarantee, which incurs uncertainties and risks in future operations (Wang et al. 2021). The operational cost of using alternative fuels such as LNG and methanol will rely on the availability of the supply infrastructure and logistics in the world, which is hard to estimate in advance (Ren et al. 2017). The efficiency of new green-techs may depend on the external environment and conditions, e.g., alternative fuels such as wind and solar power would highly rely on the weather (Wen et al. 2019). Several studies have explicitly considered the operational uncertainty of green technologies, e.g. Bilgiç et al., (2016) and Wang et al., (2021). Therefore, we assumed that the operational cost after the green upgrades is uncertain. Second, the main purpose of the equipment upgrade strategy in our model is to reduce GHG emissions to satisfy the potential regulatory requirements. It is possible that the unit operational cost may increase. For example, to meet the emission requirements, shipping companies may adopt equipment upgrade strategies such as using more expensive refined fuels (rather than heavy fuel oils), introducing dual-fuel engine to run on both gaseous and liquid fuels, and installing an onboard carbon capture and storage unit to reduce emissions. Such strategies are likely to incur more operational costs. Several studies indicated that this is one of the main reasons that many firms in the maritime industry are reluctant to upgrade their equipment (Burel et al. 2013; Song 2021). To reflect this phenomenon, we assumed that the operational costs after green upgrades may increase to $\sigma+\varepsilon$. However, the operational cost after the green upgrade may be reduced sometimes (the new system may be more energy-efficient). Therefore, we also consider that possibility, which is represented by the lower bound of the operational cost ($\sigma-\varepsilon$) in our model. In our model, we try to focus on the uncertainty of green tech, as well as the impact of competition and service differentiation on the carriers' choice of green strategies. Thus, we set that the average operational cost after the green upgrade is equal to σ to reduce the complexity of the computations.

The profits of two carriers in period j is defined as:

$$\pi_{ij} = D_{ij}\left(p_{ij} - \bar{\sigma}\left(v_{ij}\right)\right) \tag{1}$$

To capture the value lapsing between periods, we discount the profits in the second period by δ. To ensure that the potential regulation in period 2 won't be ignored, we set $\delta \in [0.5,1]$. What's more, the carrier adopting the equipment upgrades strategy has to invest a fixed cost F at the beginning of the game, which represents the cost of fitting the new green equipment or other transforming costs.

Thus, the total profits over two periods for the carriers are:

$$\pi_i = \pi_{i1} + \delta\left[\rho\pi_{i2}^{r} + (1-\rho)\pi_{i2}^{n}\right] - F\mathbb{k}_{a_{i1}=E} \tag{2}$$

where $\mathbb{k}_{a_{i1}=E} = 0,1$ is an indicator function, $\mathbb{k}_{a_{i1}=E} = 1$ when $a_{i1} = E$, the superscript r and n represent the case with regulation and without regulation. For the convenience of comparison and analysis, as well as to ensure that all the utilities of shippers and the profits of carriers are positive, the marginal costs and the fixed costs in our model are normalized to $[0,1]$, which is reasonable, e.g., 100 USD is equal to 0.1 thousand USD.

3.4 Risks Generated from Green Upgrade

In period 1, the utilities of two carriers are equal to their profits. However, the equipment upgrades often involve the implementation of new green technologies, which not only requires an initial investment but also implies uncertainty in future operations. That is, when a carrier adopts the equipment upgrades strategy, he has to bear the risks generated from the uncertain green technology outcomes in period 2. To measure the effect of risks, we use the Conditional Value-at-Risk (CVaR) as the carrier's utility function in period 2 if the equipment upgrades strategy is adopted. CVaR is defined as the average profit below the η-quantile level, ignoring the contribution of the profit exceeding the specified quantile, i.e.,

$\mathrm{CVaR}^{\eta}(\pi)=E\left[\pi \mid \pi \le \kappa^{\eta}(\pi)\right]$. Following Rockafellar et al. (2000) and Li and Song (2021), the CVaR utility can be represented by:

$$\mathrm{CVaR}^{\eta}(\pi)=\max_{\kappa}\left\{\kappa+\frac{1}{\eta}E\left[\min\left(\pi-\kappa,0\right)\right]\right\} \tag{3}$$

It should be pointed out that when $\eta = 1$, CVaR is equal to the expected profit, which means the decision-maker does not care about the risk when making decisions. When $0<\eta<1$, the decision-maker cares about the risk and will be more risk-averse as η decreases. Plug the carrier's profits into Equation (3), we obtain the utility of the carrier in period 2 under the equipment upgrades strategy as follows:

$$\begin{aligned} CVaR_{i2}(\eta_i) &= \max_{\kappa}\left\{\kappa+\frac{1}{\eta_i}E\left[\min\left(D_{i2}\left(p_{i2}-\xi v_{i2}^{2}\right)-\kappa,0\right)\right]\right\} \\ &= D_{i2}p_{i2}-D_{i2}\left\{\Phi^{-1}(1-\eta_i)-\frac{1}{\eta_i}\int_{\Phi^{-1}(1-\eta_i)}^{+\infty}\left[\Phi^{-1}(1-\eta_i)-\xi\right]d\Phi(\xi)\right\} \end{aligned} \tag{4}$$

If the carrier adopts the slow steaming strategy, then in period 2, his utility is the same as his profits, i.e., $CVaR(\pi_{i2})=\pi_{i2}$.

Thus, the total payoff/utility function of the carriers is given by:

$U_i(\eta)=\pi_i=\pi_{i1}+\delta\left[\rho\pi_{i2}^{r}+(1-\rho)\pi_{i2}^{n}\right]$, if the carrier adopts *S* strategy;

$U_i(\eta)=\pi_{i1}+\delta\left[\rho CVaR_{i2}^{r}+(1-\rho)CVaR_{i2}^{n}\right]-F$, if the carrier adopts *E* strategy with risk preference η.

In summary, there are three types of decisions to be made by two carriers. At the beginning of period 1, the two carriers have to decide the green strategy (*E* or *S* strategy) simultaneously. Given the green strategy, the two carriers decide their prices in period 1. At the beginning of period 2, depending on whether or not the green regulation comes into force, the two carriers change their steaming speeds and decide their prices in period 2. Thus, the problem is a sub-game perfect Nash game. Based on the green strategies of two carriers at the beginning of period 1, we have four types of sub-games as *(S, S)*, *(E, S)*, *(S, E)*, *(E, E)*, which are related to the four potential equilibrium outcomes.

In our two-period game model, an important issue is to investigate the stable green strategies of two carriers, which corresponds to the final equilibrium of the game model. Here the final equilibrium is a stable state that both carriers will not deviate from their strategies and decisions unilaterally. Thus, the results in the final equilibrium may be different from the optimal results among all sub-games. The final equilibrium analysis proceeds in two steps as follows. First, in Section 4, we will use the backward induction method to derive the equilibriums of each sub-game in terms of two carriers' optimal pricing decisions in two periods. Then, in Section 5, we analyze the outcomes of four sub-games and derive the final sub-game perfect Nash equilibrium, which leads to the stable green strategies for two carriers.

4. Equilibriums of Four Sub-games

In this section, we first derive the optimal pricing decisions and the resulting profits for each sub-game. Then, we analyze the effects of the potential regulation in each sub-game and examine the common characteristics. The rationale to analyze individual sub-games in detail is twofold. Firstly, it is an essential step to establish the final equilibrium. Secondly, individual sub-games can represent the cases that the carriers select their green strategies without considering the other carrier's response. As a result, the system becomes a two-period price competition model under given green strategies, which is also worth investigating.

4.1 Sub-game Equilibrium Outcomes

In sub-game (*S, S*), the two carriers both adopt strategy *S,* i.e., the slow steaming strategy. If the green regulation does not come into force in period 2, then each carrier's steaming speeds, unit delivery costs in two periods will be the same, i.e., $v_{H1}^{SS}=v_{H2}^{SS,n}=1$, $v_{L1}^{ss}=v_{L2}^{ss,n}=v$, $\bar{\sigma}_{ij}^{SS}(v)=\sigma v_{ij}^{2}$. On the other hand, if the green regulation occurs in period 2, then the two carriers have to limit their steaming speed to be the threshold level to comply with the green regulation, i.e., $v_{H2}^{SS,r}=v_{L2}^{SS,r}=v_0$. The utility functions, demand functions, profit functions and object functions for two carriers are given in Table A1 in Appendix, and we can obtain the equilibrium of sub-game (*S, S*) in Table 2.

Table 2. Equilibrium for sub-game (*S, S*)

			Carrier H	Carrier L
Period 1		Optimal Price	$p_{H1}^{SS}=\frac{1}{3}\left(2+2\sigma-2v+\sigma v^{2}\right)$	$p_{L1}^{SS}=\frac{1}{3}\left(1+\sigma+v\left(-1+2\sigma v\right)\right)$
		Optimal Utility	$\pi_{H1}^{SS}=\frac{1}{9}\left(1-v\right)\left(2-(\sigma+\sigma v)\right)^{2}$	$\pi_{L1}^{SS}=\frac{1}{9}\left(1-v\right)\left(1+(\sigma+\sigma v)\right)^{2}$
Period 2	With regulation	Optimal Price	$p_{H2}^{SS,r}=\sigma v_0^{2}\rightarrow 0$	$p_{L2}^{SS,r}=\sigma v_0^{2}\rightarrow 0$
		Optimal Utility	$\pi_{H2}^{SS,r}=0$	$\pi_{L2}^{SS,r}=0$
	Without regulation	Optimal Price	$p_{H2}^{SS,n}=\frac{1}{3}\left(2+2\sigma-2v+\sigma v^{2}\right)$	$p_{L2}^{SS,n}=\frac{1}{3}\left(1+\sigma+v\left(-1+2\sigma v\right)\right)$
		Optimal Utility	$\pi_{H2}^{SS,n}=\frac{1}{9}\left(1-v\right)\left(2-(\sigma+\sigma v)\right)^{2}$	$\pi_{L2}^{SS,n}=\frac{1}{9}\left(1-v\right)\left(1+(\sigma+\sigma v)\right)^{2}$
Total utilities			$U_i^{SS}=\pi_{i1}^{SS}+\delta\left[\rho\pi_{i2}^{SS,r}+\left(1-\rho\right)\pi_{i2}^{SS,n}\right]$	

It should be noted that when the green regulation occurs in the sub-game (*S, S*), both carriers have to limit their speed to the threshold level v_0, which means they are competing with each other through the same service quality at period 2, i.e., perfect competition. As a result, they have to lower their prices to their marginal cost and obtain no profits.

In the following, we set $B_i = \Phi^{-1}(1-\eta_i) - \frac{1}{\eta_i}\int_{\Phi^{-1}(1-\eta_i)}^{+\infty}\left[\Phi^{-1}(1-\eta_i)-\xi\right]d\Phi(\xi), i = H, L$, which can be interpreted as the perceived operational cost for a risk-averse carrier. For convenience, we restrict $B_i < \sigma + \varepsilon$, i.e., the perceived cost is smaller than the upper limit of the uncertain cost. It should be noticed that we have $\partial B_i / \partial \eta_i < 0$; thus, we can treat B_i as the new risk-averse indicator; when B_i increases, the carrier cares more about risks. Similarly, we can obtain the equilibriums of sub-game *(E, S)*, *(S, E)* and *(E, E)*, which are shown in Appendix A1.

Then, we compare the prices and payoffs of two carriers for each individual sub-game. The comparison among different sub-games will be provided in Section 5.

Proposition 1. Within each individual sub-game, comparing the prices and utilities of two carriers at two periods respectively, we can obtain:

(i) The carrier with higher realized steaming speed will set a higher service price.

(ii) If the green regulation occurs in period 2 under the sub-game (*S, S*), then two carriers both obtain no profits in period 2. In all other situations, we can difine a function of σ in each sub-game, $\tau_j^{a_H^*,a_L^*}(\sigma)$. If ξ follows a uniform distribution, then $\tau_j^{a_H^*,a_L^*}(\sigma)$ has a positive relationship with σ. When $\tau_j^{a_H^*,a_L^*}(\sigma) < 1/2$, the carrier with higher realized speed gets higher utilities, otherwise, the other carrier gets higher utilities.

The function $\tau_j^{a_H^*,a_L^*}(\sigma)$ and the related proofs are given in the Appendix.

Proposition 1(i) shows the relationship between the pricing decisions of two carriers. In general, the carrier providing delivery service with higher realized speed will set a higher price because most customers like to pay more for better services. The relationship between two carriers' utilities is more interesting. There is a special case, as Proposition 1(ii) shows, in sub-game (*S, S*), when the green regulation occurs, the two carriers' realized steaming speeds will be both restricted to v_0. Carriers have to survive in a perfect competition market, in which they provide the same services and compete against each other only by pricing decisions. As a result, the two carriers will reduce prices to their marginal costs and obtain no extra profits, which is in line with the traditional Bertrand competition (Bertrand, 1883). In reality, the carriers' service speeds may not be exactly the same. Besides, the other aspects of the service qualities of the carriers may be different. Thus, their profits may not be as low as zero. Nevertheless, the green regulation and the choice of the slow steaming strategy will lead two carriers' service quality to be more similar (Ferrari et al., 2015; Raza et al., 2019). Hence, the competition in the market becomes fiercer in period 2 under (S, S), which will reduce the carriers' profits significantly.

In addition, Proposition 1(ii) further highlights the effect of the cost coefficient σ, firstly, in most situations, when $\tau_j^{a_H^*, a_L^*}(\sigma) < 1/2$ (i.e., the delivery cost coefficient σ is low), the carrier with higher realized steaming speed will get higher utilities. That is because when σ is relatively low, the cost advantage of the slower carrier is not obvious. As a result, the positive impact of higher delivery speed on customer attraction outweighs the negative effect of the cost disadvantage incurred by higher speed. On the contrary, when σ is sufficiently large, the carrier with lower realized speed will obtain higher utility.

4.2 Effects of Potential Regulation

In this section, we further examine the effect of the potential regulation on pricing decisions and utilities of two carriers. This can shed light on the combined impact of competition and regulation, which will be used to explain the final equilibrium in Section 5. To simplify the analysis, in the following, we assume two carriers have the same risk-averse indicators, i.e., $\eta_H = \eta_L = \eta$. The parameter η can also be interpreted as the risk preference of the players in the market.

Proposition 2. Comparing the situations with regulation and without regulation, we have the following results in terms of the pricing decisions and the utilities of two carriers:

(i) In sub-game (*S, S*), the regulation will reduce the prices of two carriers to their marginal costs and drive down the profits to be zero. In sub-game (*E, E*), the occurrence of the regulation has no influence on the results.

(ii) In sub-game (*E, S*), the price of carrier H in the case with regulation is always higher than that in the case without regulation; when v is relatively high, the price of carrier L in the case without regulation is higher than that in the case with regulation, vice versa. As for the utilities, when the regulation occurs, both carriers can always obtain higher utilities.

(iii) In sub-game (*S, E*), when v is relatively high, the prices and the utilities of two carriers in the case with regulation are higher than that in the case without regulation, vice versa.

Proposition 2 reveals several joint effects of the regulation and the competition on the pricing decisions and the carriers' utilities. First, there is a negative impact on the carrier who does not upgrade the equipment if the regulation happens. We call it the *penalty effect*. The penalty effect of the regulation forces the carrier with strategy *S* to reduce the delivery speed to the threshold level and become less attractive to customers. On the contrary, the penalty effect helps the carrier with strategy *E* increase its competitive advantage. Second, the regulation will change the competition intensity in the market. We call it the *competition effect*. The competition effect can be further divided into three sub-categories. (i)when $v > 0.5$, one carrier adopts *S* strategy, and the other adopts *E* strategy, then if the regulation occurs, the difference of delivery speeds between two carriers in period 2 will be enlarged because of the speed limitation for the carrier with strategy *S*. The service differentiation between two carriers will be larger, which means the competition intensity in the market will decrease. We call it the *competition-alleviation effect*. Similarly, in the situations when $v < 0.5$, carrier L adopts strategy *S*, and carrier H adopts *E* strategy, the competition-alleviation effect of the regulation will also be generated because of enlarged speeds of two carrierst. (ii) in the situations when $v < 0.5$, carrier H adopts strategy *S*, and carrier L adopts strategy *E*, the competition intensity of the market will increase when the regulation happens because the service differentiation (i.e. speed difference) between two carriers is reduced. We call this effect the *competition-aggravation effect*. (iii) if both carriers adopt strategy *S*, and the regulation happens, the competition in the market is equivalent to the traditional Bertrand competition without service differentiation.

More specifically, in sub-game (*E, S*), carrier H updates his equipment and his service will not be affected by the regulation, but his competitor's steaming speed will be restricted. Therefore, when the regulation occurs, carrier H will provide relatively higher service quality and set a higher price than that in the non-regulation case. Interestingly, when v is relatively low, we find that carrier L will also set a higher price in the regulation case. This can be explained as follows. The occurrence of the green regulation amplifies the service differentiation, which reduces the competition intensity between two carriers, i.e., the competition-alleviation effect, this effect is dominant and can offset the negative effect of the speed restriction (i.e., the penalty effect). Besides, his delevery cost just decreases marginally when v is relatively low. As a result, it's better for carrier L to set a higher price to focus on the loyal customers rather than to fight for a price war. It should be noticed that, though carrier L will set a lower price in the case with regulation when v is higher, due to the competition-alleviation effect, he will still earn higher utilities because he can attract more demands by the low-price strategy since his marginal costs are reduced significantly.

In sub-game (*S, E*), the occurrence of the regulation will restrict carrier H's speed. The steaming speed of carrier H will significantly affect the competition effect of the regulation. When v is extremely high (close to $\overline{v}_{\max}$), the regulation will reduce the competition intensity dramatically. As v decreases, the effect will become weak gradually, then turn to increase the competition intensity (when v is below 0.5). When v is extremely lowe, the competition-aggravation effect will turn to the maximum. Thus, when v is extremely high and the regulation occurs, the competition in the market is allieviated, the prices and the utilities of two carriers are higher than the case without regulation. As the steaming speed of carrier L decreases, the difference between the two cases is shrinking until the prices and the utilities of two carriers in the case without regulation exceed that in the case with regulation. It should be noticed that the marginal delivery cost and the risk-averse attitude will affect the prices and utilities, too (but the impacts on them are lower than the competition effect), so the turning point of *v* deviates from 0.5.

Thus, we prove that, in sub-game (*E, S*) and some cases in sub-game (*S, E*), when the regulation occurs, the carriers with *S* strategy can also have a chance to obtain more utilities. This indicates that if one carrier takes the equipment upgrades strategy, the other carrier has an incentive to take strategy *S* because he can still be better off. This behavior can be regarded as a credible promise (McNamara et al, 2002), i.e., one carrier will reduce its steaming speed in the second period with regulation, through which the two carriers can be out of a fiercely competitive market and both obtain more profits than the case without regulation. The above phenomena together with the three effects caused by the regulation complicate the final equilibrium of the whole game. In the next section, we will analyze it thoroughly.

5. The Equilibrium Upgrade Strategies

In this section, we aim to find the final equilibrium of the whole game, i.e., the stable green strategies of two carriers at the beginning of period 1. The stable equilibrium refers to the state that no carrier has an incentive to change his green strategy unilaterally. In Section 5.1, we compare the four sub-games to obtain the final stable equilibrium. In Section 5.2, we analyze the characteristics of the equilibrium and examine the managerial insights behind the results using numerical experiments.

5.1 The Final Equilibrium Outcomes

In this section, we first derive the final equilibrium outcomes, i.e., the stable green strategies in the market. When the two carriers reach a stable sub-game perfect Nash equilibrium, no player can increase his own expected payoff by changing his strategy while the other player remains the same (Osborne et al. 2004). Then, we examine the effect of risk attitude on the outcomes.

Based on the utilities of the carriers in two periods, we construct the payoff matrix of the game in Table 3.

Table 3. Payoff matrix of two carriers

	Carrier L	
Carrier H	Slow steaming ($a_L = S$)	Equipment upgrades ($a_L = E$)
Slow steaming ($a_H = S$)	$\left(U_H^{SS}, U_L^{SS}\right)$	$\left(U_H^{SE}, U_L^{SE}\right)$
Equipment upgrades ($a_H = E$)	$\left(U_H^{ES}, U_L^{ES}\right)$	$\left(U_H^{EE}, U_L^{EE}\right)$

From Table 3, we can obtain Lemma 1 as follows.

Lemma 1. Compare the utilities in different sub-games, we have the following results:

(i) Suppose carrier L chooses strategy *S*. Then carrier H will choose strategy *E* if $\rho > \bar{\rho}_{H(NL)}$;

otherwise, he will adopt strategy *S*;

(ii) Suppose carrier L adopts the green upgrade strategy. Then,

a) if $\pi_{H2}^{SE,n} > \pi_{H2}^{SE,r}$, then when $\rho > \bar{\rho}_{H(GL)}$, carrier H will choose strategy *E*; otherwise, he will adopt strategy *S*;

b) if $\pi_{H2}^{SE,n} < \pi_{H2}^{SE,r}$, then when $\rho < \bar{\rho}_{H(GL)}$, carrier H will choose strategy *E*, otherwise, he will adopt strategy *S*.

(iii) Suppose carrier H chooses Strategy *S*. Then carrier L will choose to upgrade his equipment if $\rho > \bar{\rho}_{L(NH)}$; he will adopt strategy *S*, otherwise.

(iv) Suppose carrier H adopts strategy *E*. Then carrier L will choose strategy *E* if $\rho < \bar{\rho}_{L(GH)}$; he will adopt strategy *S*, otherwise.

where $\bar{\rho}_{H(NL)} = \dfrac{-9F + 4\delta\sigma - \delta\sigma^2 + \delta B^2 + (9F - 4\delta\sigma)v + 2\delta\sigma^2 v^2 - 2\delta B\,(2 - 2v + \sigma v^2)}{\delta\left(-(-2+\sigma)^2 + (4 - 4\sigma + B^2)v + 2\sigma(\sigma - B)v^2\right)}$;

$$\bar{\rho}_{H(GL)} = \frac{9F + \delta(\sigma-4)\sigma - 9Fv + \delta\left(4(\sigma - B)v - (B-4)B + 2(B-\sigma)Bv^2\right)}{\delta\left((\sigma-2)^2 + v\left(4\sigma - 9 + v\left(5 + B\,(2 - 2\sigma + v(B\,(2v-1) - 2))\right)\right)\right)}$$

$$\bar{\rho}_{L(NH)} = \frac{9F + v\left(-9F + \delta(\sigma - B)v\left(v(2 + (\sigma + B)v) - 2(1+\sigma)\right)\right)}{\delta v\left(4 + v\left(B^2(1-2v)v - 2(2 + \sigma + \sigma^2) + 2B\,(\sigma + v - 1) + \sigma v(2 + \sigma v)\right)\right)}$$

$$\bar{\rho}_{L(GH)} = \frac{9F + v\left(\delta(\sigma - B)v\left(v(2 + (\sigma + B_L)v) - 2 - 2B\right) - 9F\right)}{\delta v\left(-1 + B^2 - 2\sigma Bv + v\left(1 - 2\sigma + \sigma v(2 + \sigma v)\right)\right)}$$

The proof of Lemma 1 is shown in Appendix.

Lemma 1 shows when one carrier has adopted a specific green strategy and made it known to the other carrier, the other carrier's preference of the green strategy will depend on the probability of the green regulation and the relationships between the carrier's utilities at period 2. However, since the carriers' green strategies and the utilities actually are the results of the competition game, Lemma 1 is cannot be used directly to characterize the final equilibrium outcomes. Interestingly, we find that by using the initial steaming speed *v* and the probability of the regulation occurrence, we can identify the final equilibrium outcomes.

From Lemma 1, comparing the thresholds $\bar{\rho}_{H(NL)}$, $\bar{\rho}_{H(GL)}$, $\bar{\rho}_{L(NH)}$ and $\bar{\rho}_{L(GH)}$, we can obtain the final equilibrium of the sub-game perfect Nash equilibrium. The results are summarized in Table 4 (its proof is given in Appendix).

Table 4. The Final Equilibrium Outcomes

(a) $F < \bar{F}$

	$\rho \in [0, \bar{\rho}_A]$	$[\bar{\rho}_A, \bar{\rho}_B]$	$[\bar{\rho}_B, \bar{\rho}_C]$	$[\bar{\rho}_C, 1]$

$v \in (0, \hat{v}_{\rho 1})$	(S,S)	(E,S)	(E,S)	(E,S)
$v \in (\hat{v}_{\rho 1}, \min(\hat{v}_{\rho 2}, \hat{v}_1))$	(S,S)	(E,S)	(E,S) or (S,E)	(E,S)
$v \in \begin{pmatrix} \min(\hat{v}_{\rho 2}, \hat{v}_1), \\ \min(\hat{v}_{\rho 3}, \hat{v}_1) \end{pmatrix}$	(S,S)	(S,E)	(E,S) or (S,E)	(E,S)
$v \in (\min(\hat{v}_{\rho 3}, \hat{v}_1), \hat{v}_1)$	(S,S)	(E,S)	(E,S) or (S,E)	(E,S)
$v \in (\hat{v}_1, \max(\hat{v}_{\rho 2}, \hat{v}_1))$	(S,S)	*Null*	(E,S)	(E,S) or (S,E)
$v \in \begin{pmatrix} \max(\hat{v}_{\rho 2}, \hat{v}_1), \\ \min(\max(\hat{v}_{\rho 3}, \hat{v}_1), v_{\max}) \end{pmatrix}$	(S,S)	(S,E)	*Null*	(E,S) or (S,E)
$v \in \begin{pmatrix} \min(\max(\hat{v}_{\rho 3}, \hat{v}_1), v_{\max}), \\ v_{\max} \end{pmatrix}$	(S,S)	*Null*	(E,S)	(E,S) or (S,E)

(b) $F > \bar{F}$

	$\rho \in [0, \bar{\rho}_A]$	$[\bar{\rho}_A, \bar{\rho}_B]$	$[\bar{\rho}_B, \bar{\rho}_C]$	$[\bar{\rho}_C, 1]$
$v \in (0, \hat{v}_{\rho 1})$	(S,S)	(E,S)	(E,S)	(E,S)
$v \in (\hat{v}_{\rho 1}, \hat{v}_1)$	(S,S)	(E,S)	(E,S) or (S,E)	(E,S)
$v \in (\hat{v}_1, v_{\max})$	(S,S)	*Null*	(E,S)	(E,S) or (S,E)

where $\bar{\rho}_A = \min(\bar{\rho}_{H(NL)}, \bar{\rho}_{L(NH)})$, $\bar{\rho}_B = \min(\max(\bar{\rho}_{H(NL)}, \bar{\rho}_{L(NH)}), \max(\bar{\rho}_{H(GL)}, \bar{\rho}_{H(NL)}))$, $\bar{\rho}_C = \max(\max(\bar{\rho}_{L(NH)}, \bar{\rho}_{H(GL)}), \bar{\rho}_{H(NL)})$, $\bar{F}$ is the solution of F to the equation $\hat{v}_{\rho 2}(F) = \bar{v}_{\max}$ and $\hat{v}_1$, $\hat{v}_{\rho 1}$, $\hat{v}_{\rho 2}$, $\hat{v}_{\rho 3}$ are defined in the Appendix.

Then we can summarize the results in proposition 3.

Proposition 3. The final equilibrium outcomes can be characterized by a few threshold values of ρ and v as shown in Table 4. Accodring to Table 4, some qualitative results are summarized as follows:

(i) When the probability of the regulation occurrence is sufficiently low, i.e., $\rho < \bar{\rho}_A$, the two carriers will both adopt strategy *S*;

(ii) When the probability of the regulation occurrence is sufficiently high ($\rho > \bar{\rho}_A$) and the difference of initial speeds between two carriers is high (e.g., $v < \hat{v}_{\rho 1}$), carrier H will adopt strategy *E* and carrier L will adopt strategy *S*;

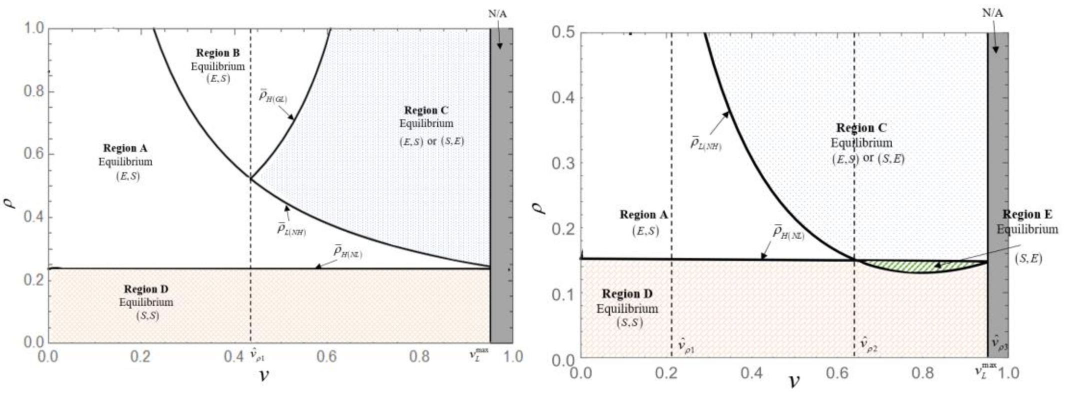
(iii) When the probability of the regulation occurrence is sufficiently high ($\rho > \bar{\rho}_A$) and the difference of initial speeds between two carriers is low, i.e., $v > \max(\hat{v}_{\rho 2}, \hat{v}_1)$, the equilibrium (*S, E*) may occur;

(iv) When the probability of the regulation occurrence exceeds a certain level ($\rho > \bar{\rho}_A$), there is always one carrier adopting strategy *E* and the other adopting strategy *S*. Which carrier will adopt the strategy *E* depends on the difference of the initial speeds between two carriers and the degree of the risk-averse behavior;

(v) The green strategy (*E, E*) will never be a final equilibrium.

All the proofs are shown in Appendix.

According to Proposition 3 and Table 4, we can illustrate the final equilibrium in Figure 2.



(a) $F > \bar{F}$ (b) $F < \bar{F}$

Figure 2. The final equilibrium outcomes

It is fairly intuitive that if the probability of the green regulation occurrence is sufficiently low, then the two carriers will both adopt strategy *S* to avoid the investment cost in equipment upgrades. However, Proposition 3 states that if the probability of the regulation occurrence exceeds a certain level, then there is always one carrier who will upgrade his equipment whereas the other carrier will adopt strategy *S*. In addition, it is found that both carriers adopt the *E* strategy will never be the final equilibrium.

Some interesting results in Figure 2 can be observed and explained as follows. The condition $\rho < \bar{\rho}_{L(NH)}$, as shown in Figure 2, implies that either the probability of the regulation occurrence is low, or carrier L's initial delivery speed is low. It means that either the regulation is unlikely to occur, or the regulation will happen but with a small penalty effect on carrier L. Thus, the better choice for him is to take strategy *S* regardless of whether carrier H upgrades his equipment. Given the strategy of carrier L, as long as the probability is not too low ($\rho > \bar{\rho}_{H(NL)}$), carrier H will upgrade his equipment because the impact of the regulation on him is too significant to ignore (due to the penalty effect and the competition-aggravation effect of the regulation). This interprets the final equilibrium outcome (*E, S*) in Region A in Figure 2.

In Region B in Figure 2a, the competition-aggravation/alleviation effect is relatively small and the probability of the regulation occurrence is quite high. This implies that the penalty effect on carrier H is serious and dominant; thus, he will always upgrade his equipment to comply with the regulation. Given the strategy of carrier H, it's better for carrier L to adopt strategy *S* because the penalty effect on him is relatively small (his initial speed is not very high and he can enjoy the cost advantage by the slow steaming strategy). Hence, the final equilibrium in Region B is (*E, S*), too. In Region C, the probability of the regulation occurrence is pretty high and the competition is drastic (carrier L's speed v is quite close to carrier H's speed). Therefore, the competition-alleviation effect of the regulation is dominant. The better outcome would be one carrier upgrades the equipment and the other adopts strategy *S*. Thus, the final equilibrium in Region C would be (*E, S*) or (*S, E*).

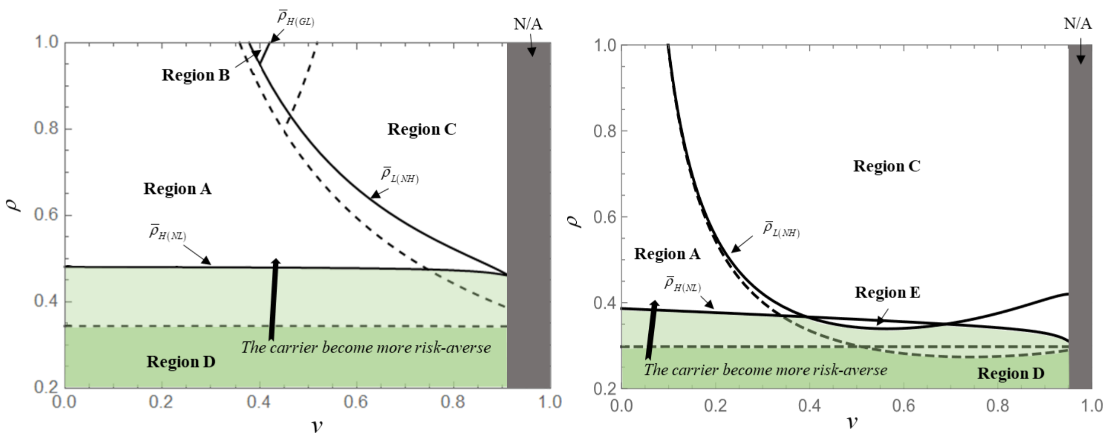
In Figure 2b, there is a small region, termed Region E, which occurs when the fixed cost of equipment upgrades F is relatively low ($F < \bar{F}$). The final stable equilibrium in Region E is that carrier L upgrades the equipment but carrier H adopts the slow steaming strategy. Note that in Region E, the competition is fierce, and the probability of the regulation occurrence is moderate. Carrier H is the dominant player in period 1 and can bear the loss caused by either the occurrence or non-occurrence of the regulation in period 2. However, for carrier L, he can't afford the case (*S, S*) to happen (he would get zero profit) because his profit in period 1 is not high enough to offset the loss. Hence, his preferred choice is to upgrade the equipment regardless of carrier H's action. Given the action of carrier L, the better choice for carrier H is to adopt strategy *S* to reduce the competition in the market, thus, the equilibrium (*S, E*) is formulated.

It is worth noting that the equilibrium (*E, E*) will never be the final stable equilibrium even if the probability of the regulation occurrence approaches to 1. The implication is that using the flexible regulation (the regulation which allows the carrier to adopt both the equipment upgrades strategy and the slow steaming strategy to comply with), carriers in the shipping market will never upgrade their equipment unanimously. This outcome may deviate from the regulation maker's original intention, i.e., to encourage all the carriers to replace/upgrade green equipment across the board. The reason for this outcome can be explained as follows. Suppose that the probability of the regulation occurrence is extremely high. Firstly, when the carrier L's initial speed is high, the competition in the original market is fierce; thus, the regulation can reduce the competition intensity, which leads to (*S, E*) or (*E, S*). Secondly, when carrier L's initial speed is low, the regulation will have a weak impact on him; thus, he will not adopt the equipment upgrades strategy. Thirdly, when carrier L's initial speed v is moderate, the explanation is similar to the results shown in Region B. The results explain the following industrial phenomenon. In practice, different from other modes of transportation, carriers in the maritime industry are able to cut the emission by slow steaming without lots of costs and time. In addition, the customers choosing maritime transportation usually are not sensitive to the timeliness so much. These are unique characteristics in the maritime industry (Cariou et al. 2011). Thus, it's hard for the third-party institution (IMO, governments, etc) to induce all the carriers to upgrade their equipment through a simple flexible emission regulation. For example, IMO introduced the energy efficiency design index (EEDI) regulation in 2011, which formally entered into force from 1 January 2013. The purpose is to promote the use of more energy-efficient and less polluting equipment and engines in new ships (Song 2021). However, it has been found that EEDI regulation couldn't in the first place stimulate all the carriers to adopt new ship engine technologies or clean fuels, but rather encouraged the carriers to provide shipping service with a reduced speed (Steve et al. 2015). In fact, the majority of ocean carriers have adopted the slow steaming strategy to reduce their emission to comply with the regulations (Kontovas et al. 2011; Mander 2017). In June 2021, IMO announced the introduction of two new regulations, Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII), which will come into force on 1 January 2023 to reduce GHG emissions from shipping as short-term measures. According to the chief executive of Ocean Network Express (ONE, the world's sixth-largest container shipping line), they have chartered in six scrubber-fitted 24,000 TEU vessels and are expecting to adopt slow steaming for most existing vessels to comply with the upcoming stricter emission rules (Shen 2021). The implication is that both equipment upgrade and slow steaming strategies are likely to be used to comply with the EEXI and CII regulations. Our study offers a new perspective to explain the above phenomenon. Thus, besides the emission regulation, it's better for the governments or IMO to make other assistant efforts like providing upgrade subsidies to the carriers, cultivating customers' green innovation awareness. In addition, announcing a compulsive upgrading regulation, which excludes the slow steaming strategy to comply with, is also a feasible measure.

In summary, Proposition 3 shows the joint effect of the service quality-based competition and the potential flexible regulation on the green strategies of two carriers. Competition induces the carriers to upgrade their equipment and provides a high-quality service to attract more demands, but at the same time competition also prevents carriers from upgrading equipment because it may decrease the service differentiation. Flexible regulation helps the carriers alleviate the competition in the market. Next, we further examine the effect of the risk-averse attitude on the final equilibrium outcomes which is illustrated in Proposition 4 and Figure 3.

Proposition 4. As the carriers care more about the equipment upgrade risk, the equilibrium (S, S) is more likely to happen. In addition, the fixed cost F will amplify the effect of carriers' risk preference.

The proofs are shown in Appendix. We use figure 3 to explain Proposition 4, the solid lines in Figure 3 represent the thresholds in Table 4 for the case with risk-averse carriers. The dashed lines indicate the thresholds in Table 4 for the case with risk-neutral carriers.



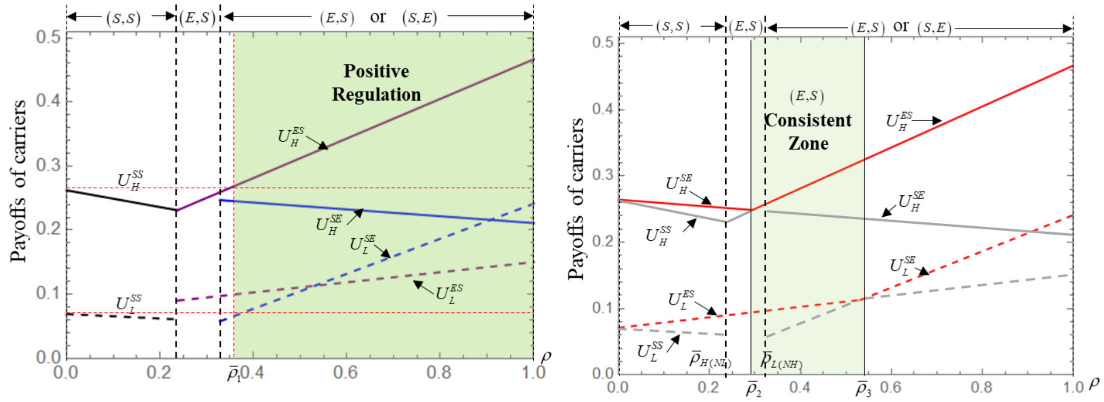
(a) $F > \bar{F}$ (b) $F < \bar{F}$

Figure 3. The effects of risk attitude on the equilibriums

When the carriers change their risk attitude from risk-neutral to risk-averse (i.e., the dashed lines are transformed into the solid lines), Region D is expanding, which implies that the final equilibrium (*S, S*) is more likely to happen. This is because when the carriers become more risk-averse, they prefer strategy *S* to avoid the uncertainty of the operational cost caused by the equipment upgrades. However, it can be seen that the effect of the risk attitude on the final equilibrium becomes more obvious when the fixed cost *F* increases. This phenomenon is interesting because when *F* increases (which means that the fixed investment is dominant for consideration by carriers), the degree of uncertainty caused by the upgrades (which is associate with the marginal delivery cost) is relatively low. One would therefore think that the impact of the risk attitude would decrease as *F* increases. This counter-intuitive phenomenon may be explained as follows. When *F* increases, the carrier would still prefer to upgrade his equipment if the obtained payoffs in period 2 could offset the investment cost. However, the profits in period 2 may be affected by the decreased cost advantage. Thus, he will pay more attention to the marginal cost in period 2, which is cosely associated with the uncertainty of the operational cost. In this way, the effect of risk attitude will be amplified and this may lead to an increased gap between the dashed line and the solid lines.

5.2 Characteristics of the final equilibrium using numerical Experiments

To further explore the characteristics of the final equilibrium, we use numerical methods to examine the utilities of two carriers. We suppose that ξ follows a uniform distribution over $[\sigma-\varepsilon,\ \sigma+\varepsilon]$. The system parameters are set as follows: $\sigma=0.05$, $\varepsilon=0.02$, $\eta=\eta=0.8$, $\delta=1$, $F=0.1$, $v=0.7$. Figure 4a shows the utilities of two carriers in different final equilibriums. Figure 4b illustrates the difference between the equilibrium outcomes and the optimal outcomes.



(a) Final equilibrium outcomes

(b) Compared with optimal outcomes

Figure 4. Payoffs of carriers in final equilibriums

From Figure 4a, firstly, it can be observed that in most situations, the utilities of the carrier with strategy *S* is decreasing as the probability of the regulation occurrence ρ increases (i.e., U_i^{SS}, U_H^{SE} in Figure 4a). However, when the probability is high, the utility of carrier L may increase with the probability though he adopts the slow steaming strategy (U_L^{ES} is increasing in ρ). In that time the regulation may help the two carriers reduce the competition in the market, i.e., the competition-alleviation effect is larger than the penalty effect; carrier L can enjoy a free ride from the equipment upgrades of carrier H. Secondly, the occurrence of the regulation may benefit both carriers. For example, under the strategy (*E, S*), the carriers' utilities when $\rho \in [\bar{\rho}_1, 1]$ are greater than those under the case in which the regulation does not occur (i.e., $\rho = 0$). We call the shaded area in Figure 4a as *positive regulation zone*, which is due to the competition-alleviation effect of the regulation.

In Figure 4b, we compare the final equilibrium outcomes with the optimal outcomes of the two carriers. Here the optimal outcomes are defined as the best payoffs among four sub-games for each carrier separately. To distinguish the two results, we use the red lines to represent the optimal outcomes. As shown in Figure 4b, when $\rho \in [0, \bar{\rho}_{H(NL)})$, the equilibrium is (*S, S*); when $\rho \in [\bar{\rho}_{H(NL)}, \bar{\rho}_{L(NH)})$, the equilibrium is (*E, S*); and when $\rho \in [\bar{\rho}_{L(NH)}, 1)$, the equilibrium is (*E, S*) or (*S, E*). On the other hand, compare the payoffs among four sub-games, we can find that for carrier H, when $\rho \in [0, \bar{\rho}_2)$, the payoff in sub-game (*S, E*) is optimal and when $\rho \in [\bar{\rho}_2, 1)$, the payoff in sub-game (*E, S*) is optimal (the red solid lines in Figure 4b). For carrier L, the payoff in sub-game (*E, S*) or sub-game (*S, E*) is optimal depending on the relationship of ρ with $\bar{\rho}_3$ (the red dashed lines in Figure 4b). That is, in most situations, the final equilibrium outcomes are not optimal for individual carriers. The competition forces two carriers to compromise and choose a suboptimal outcome as the final stable equilibrium. Nevertheless, when $\rho \in [\bar{\rho}_2, \bar{\rho}_3)$, we find that the final equilibrium outcomes are the same as the optimal outcomes. We call this area the *consistent zone*. In the consistent zone, the regulation may be interpreted as a credible signal and help carriers to increase the service differentiation.

6. Extensions

In this section, we extend our models and analysis in several aspects to examine some more general cases. Specifically, we try to examine the following issues: (1) sequential decision-making on the green strategy, (2) the effect of price sensitivity, (3) endogenous shipping speed.

6.1 Sequential green strategy making

We now consider the two carriers making their green strategy sequentially in period 1. In this case, we assume that carrier H sets its green strategy firstly. Then, after receiving the information regarding the action of carrier H, carrier L sets its green strategy accordingly. After that, the two carriers make their pricing decisions in period 1. In period 2, the settings are similar to our basic model. We can use the backward induction approach to solve this sequential decision-making model as follows: we first consider the pricing decisions of two carriers; then we concern carrier L's reaction when it receives carrier H's selection of the green strategy; finally, we determine carrier H's optimal green strategy. We can use a decision tree of the green strategies to better explain the sequence of green strategy selections for two carriers in Figure 5.

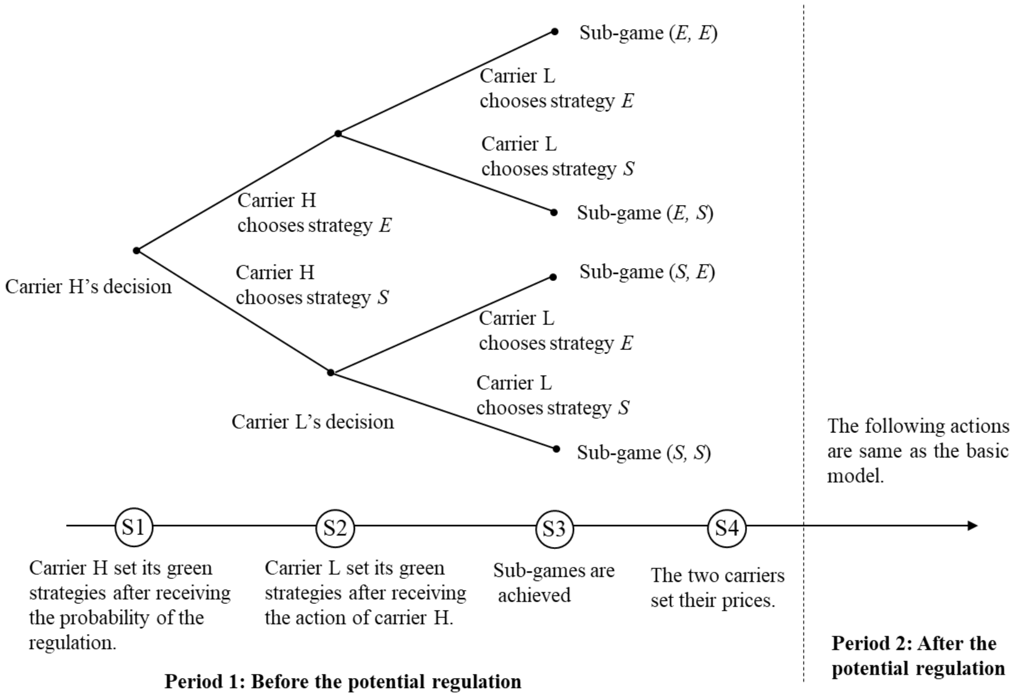
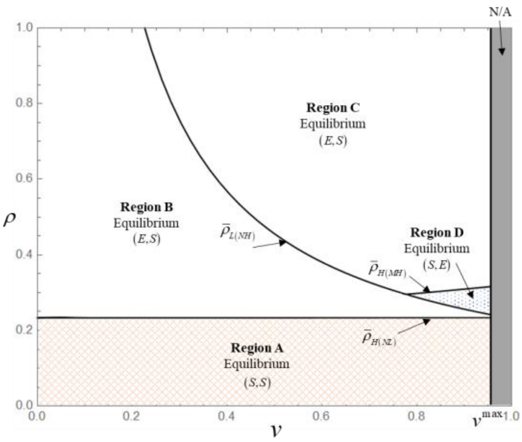
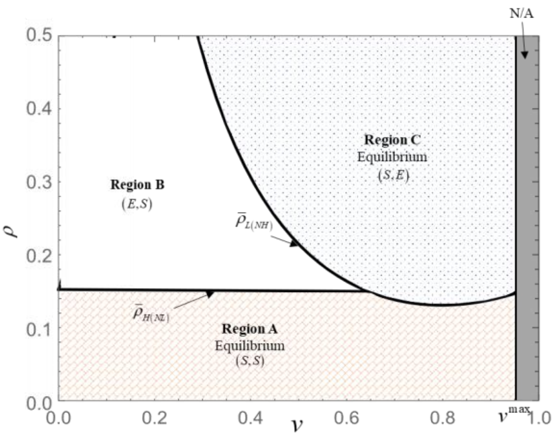


Figure 5. The decision tree of the two carriers' sequential decisions on green strategy

Since carrier L has to set its green strategy after receiving the action of carrier H, its reaction is the same as those in Lemma 1 (iii) and (iv) according to the thresholds $\bar{\rho}_{L(NH)}$ (comparing carrier L's profits in Sub-games (*S, E*) and (*S, S*)) and $\bar{\rho}_{L(GH)}$ (comparing carrier L's profits in Sub-games (*E, E*) and (*E, S*)). However, the decision of carrier H is quite different from the basic model. Apart from the need to calculate the threshold values of $\bar{\rho}_{H(NL)}$ (comparing carrier H's profits in Sub-games (*E, S*) and (*S, S*)) and $\bar{\rho}_{H(GL)}$ (comparing carrier H's profits in Sub-games (*E, E*) and (*S, E*)) given in Lemma 1, we should also compare its profits between cases (*S, S*) and (*E, E*), which defines a new threshold $\bar{\rho}_{H(ML)}$; in addition, we should compare its profits between cases (*E, S*) and (*S, E*), which leads to another threshold $\bar{\rho}_{H(MH)}$. However, due to the complicated expressions of these threshold values, it is difficult to obtain analytical results. Therefore, we use some numerical experiments to illustrate the final equilibrium as shown in figure 6 (the values of the system parameters are the same as those in Section 5).



(a) $F > \bar{F}$



(b) $F < \bar{F}$

Figure 6. The equilibrium when the two carriers decide green strategy sequentially

Similar to the results in the basic model, when the regulation probability is relatively low, the two companies will not upgrade their equipment; when the regulation probability is high, one of the two carriers will adopt the green upgrade strategy while the other will adopt the slow steaming strategy. However, different from the results in our basic model, there is always only one equilibrium in a given region in Figure 6, whereas in the basic model, the two equilibriums (*E, S*) and (*S, E*) exist simultaneously in region C in Figure 2. This can be explained as follows. For carrier L, it has more information (knowing the actions of carrier H), so it will choose a unique profitable decision given carrier H's choice. For carrier H, it also has a first-mover advantage, that is, it can predict the reaction of carrier L, and then choose a suitable strategy to induce carrier L's choice. Thus, the final equilibrium is unique. The explanations of the decision and profits of the two carriers are similar to those in section 4.

6.2 The effect of price sensitivity

In our basic model, we assume that the shipper's price sensitivity is fixed and normalized to 1, i.e., the customer's utility is $V_{ij} = u + \theta v_{ij} - p_{ij}$ for carrier *i* in period *j*. In this section, we extend the model to investigate the effect of price sensitivity on the final equilibrium. Similar to Han et al (2001), Casado et al. (2013), we set the customer's utility as $V_{ij} = u + \theta v_{ij} - \gamma p_{ij}$. The parameter γ represents the price sensitivity of the customer. When γ is large, the shipper is more sensitive to the shipping prices. When γ is low, the shipper is less concerned with the prices. Thus, the demands of two carriers in period *j* are changed to $D_{Hj} = 1 - \frac{\beta\left(p_{Hj} - p_{Lj}\right)}{v_{Hj} - v_{Lj}}$ and $D_{Lj} = \frac{\beta\left(p_{Hj} - p_{Lj}\right)}{v_{Hj} - v_{Lj}}$. In addition, the four thresholds to characterize the regulation probability are changed to:

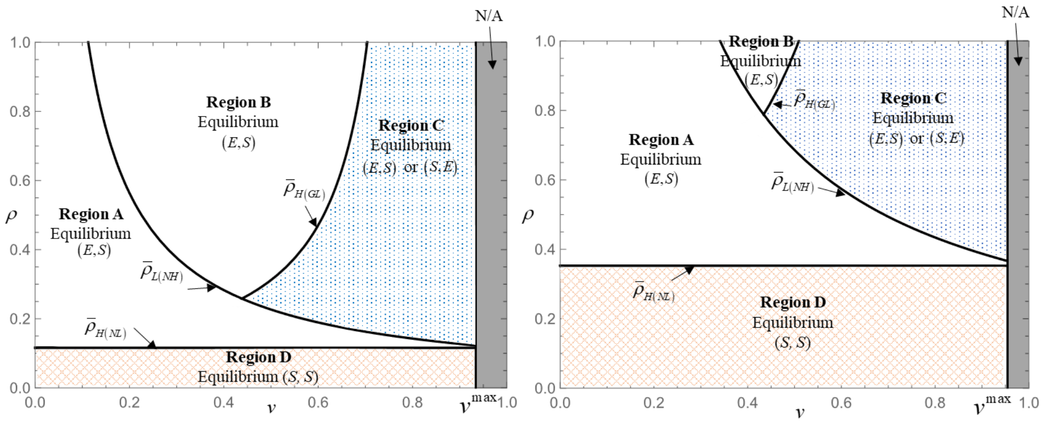
$$\bar{\rho}_{H(NL)} = \frac{\gamma\left(-9F\left(-1+v\right) - \delta\left(B-\sigma\right)\left(-4+B\gamma+4v+\gamma\sigma-2\gamma v^2\sigma\right)\right)}{\delta\left(2\gamma^2v^2\left(B-\sigma\right)\sigma - v\left(4+B^2\gamma^2-4\gamma\sigma\right)+\left(-2+\gamma\sigma\right)^2\right)}$$

$$\bar{\rho}_{H(GL)} = \frac{\gamma\left(-9F\left(-1+v\right)+\delta\left(B-\sigma\right)\left(4-4v+B\gamma\left(-1+2v^2\right)-\gamma\sigma\right)\right)}{\delta\left(-B\gamma\left(2+B\gamma\right)v^3+2B^2\gamma^2v^4+\left(-2+\gamma\sigma\right)^2+v\left(-9+4\gamma\sigma\right)+v^2\left(5-2B\gamma\left(-1+\gamma\sigma\right)\right)\right)}$$

$$\bar{\rho}_{L(NH)} = \frac{\gamma\left(9F\left(-1+v\right)+v^2\delta\left(B-\sigma\right)\left(2v+\gamma v^2\left(B+\sigma\right)-2\left(1+\gamma\sigma\right)\right)\right)}{v\delta\left(-4-\gamma v^2\left(2B+B^2\gamma+2\sigma\right)+\gamma^2v^3\left(2B^2-\sigma^2\right)+2v\left(2+\gamma\sigma+\gamma^2\sigma^2+B\left(\gamma-\gamma^2\sigma\right)\right)\right)}$$

$$\bar{\rho}_{L(GH)} = -\frac{\gamma\left(9F\left(-1+v\right)+v^2\delta\left(B-\sigma\right)\left(-2+2v+B\gamma\left(-2+v^2\right)+\gamma v^2\sigma\right)\right)}{v\delta\left(-1+B^2\gamma^2+v-2\gamma v\sigma-2B\gamma^2v\sigma+2\gamma v^2\sigma+\gamma^2v^3\sigma^2\right)}$$

Due to the complicated expressions of these threshold values, it is difficult to obtain analytical results. According to the numerical experiments (the values of the parameters are the same as those in Section 5), we can illustrate the final equilibrium results of two carriers with different price sensitivities in Figure 7.



(a) $\gamma = 0.5$ (b) $\gamma = 1.5$

Figure 7. The final equilibrium with different price sensitivities

It can be observed that the main results are similar to our basic model in Figure 2. For example, when the probability of the regulation occurrence is sufficiently low, the two carriers will both adopt strategy *S*, when the probability of the regulation occurrence is sufficiently high, there are always one carrier adopt strategy *E*. However, there are still some differences between the two cases. When shippers care less about the freight rate (γ is smaller), the attraction of the slow steaming strategy is decreasing (region D is smaller). This can be explained by the fact that when shippers become less concerned with prices, the price advantage generated by the slow steaming (with lower operational costs) is decreasing. However, in a competitive market, even though the price sensitivity is low, the two carriers still can't set an unlimited high price, especially for carrier L with a lower-quality service. Even carrier L has to set a lower price to maintain its demands (it can be found directly through the demand function, D_{Lj}). Together with the concerns about the service differentiation, there is still at least one carrier adopt strategy *S*.

6.3 Endogenous shipping speed

In our basic model, we assume that the shipping speeds of the carriers are exogenous. In this section, we relax this assumption to some extent by allowing carrier L to decide its initial shipping speed from two options, a low speed, v_L , or a high speed which is the same as carrier H's initial speed, v_H , $v_H > v_L$. In the following, we simplify the notation by letting $v_L = v$ and $v_H = 1$, which are consistent with the basic model. The sequence of the events can be summarized as follows: In period 1, the two carriers both choose their green strategies, i.e., either equipment upgrade or slow steaming. Next, carrier L chooses its initial speed v_L or v_H . Then the two carriers decide their freight rates and the demands in period 1 are realized. In period 2, all the actions have the same sequence as that in the basic model. Through the backward induction method, we can obtain the following results.

Lemma 2. (i) In sub-game (*S, S*), (*E, E*) and (*E, S*), carrier L will always choose the low initial speed v_L.

(ii) In sub-game (*S, E*), when $\rho > \bar{\rho}_v = \dfrac{9A\delta + (1+\sigma)^2 + v\sigma^2 - v - v^2\sigma(2+\sigma) - v^3\sigma^2}{\left(A + 4(1-v) - 4B(1-v^2) + B^2(1-v^3)\right)\delta}$, carrier L will choose the high initial speed v_H; otherwise, it will choose the low initial speed v_L, where $A = \dfrac{\left(1 - v - Bv^2 + \sigma\right)^2}{1-v}$.

Lemma 2 can be interpreted as follows. If carrier L chooses the high initial speed, in period 1, its speed is the same as the carrier H's. The two carriers provide the same shipping service and will obtain zero profits because of the fierce competition. Similarly, in period 2 without regulation, the two carriers both will obtain no profits, too. Thus, carrier L will choose the high initial speed only if its profit with v_H in period 2 under regulation is sufficiently higher than that choosing the low initial speed. More specifically, in sub-game (*S, S*) and (*E, S*) in which carrier L adopts the slow steaming strategy, carrier L's speed will be restricted by the potential regulation in period 2 no matter which initial shipping speed it selects. Thus, the strategy of choosing the high speed v_H in these two sub-games is strictly dominated by the strategy of choosing the low speed. Therefore, carrier L will never choose the high initial speed in sub-game (*S, S*) and (*E, S*). In sub-game (*E, E*), both carriers adopt the equipment upgrade strategy; if carrier L selects the high initial speed, then two carriers will provide the same service quality in both periods. As a result, both carriers will obtain zero profit, which prevents carrier L choosing the high initial speed. The above arguments explain Lemma 2(i). As for Lemma 2(ii) in sub-game (*S, E*), choosing the high initial shipping speed could be a profitable choice for carrier L. That is, in sub-game (*S, E*), if the regulation occurs, carrier H's speed will be restricted, carrier L could be benefited by the service competitive advantage. When the extra profits exceed the loss in period 1 and period 2 without regulation ($\rho > \bar{\rho}_v$), Carrier L may choose the high initial speed in sub-game (*S, E*).

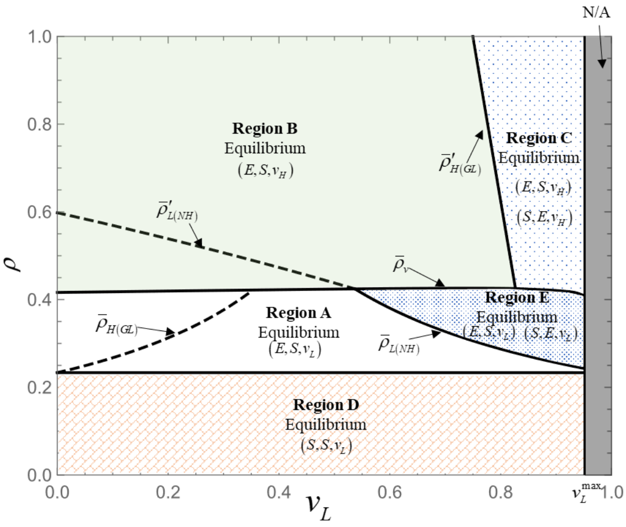


Figure 8. The equilibrium when carrier L could decide the initial speed

Based on Lemma 2, we can analyze the final equilibrium green strategies for two carrier. When $\rho < \bar{\rho}_v$, carrier L will always choose the low initial speed in all sub-games; thus, the results are the same as that in our basic model (Lemma 1). When $\rho > \bar{\rho}_v$, carrier L will choose $v_H = 1$ and the profits of two carriers in sub-game (*S, E*) will be different from that in the basic model; thus, the threshold values $\bar{\rho}_{L(NH)}$ and $\bar{\rho}_{H(GL)}$ should be changed to $\bar{\rho}'_{L(NH)}$ and $\bar{\rho}'_{H(GL)}$ given by:

$$\bar{\rho}'_{L(NH)} = \frac{(1-v)(1+\delta)(1+\sigma+v\sigma)^2 + 9F}{\delta\left(5-4B+B^2+2\sigma+\sigma^2-v^3\sigma^2-v^2\sigma(2+\sigma)+v\left(-1+\sigma^2\right)\right)}$$

$$\bar{\rho}'_{H(GL)} = \frac{(1-v)\left((-2+B+Bv)^2\delta+(-2+\sigma+v\sigma)^2\right)-9F}{(1+B)^2\delta}$$

The final equilibriums are numerically illustrated in Figure 8, which shows the equilibrium results of two carriers for the cases when carrier L could decide its initial speed. We can find that the main results are similar to that in our basic model. When the probability of the regulation occurrence is low enough, both carriers will adopt the slow steaming strategy *S* (i.e. Region D in Figure 8). When the probability of the regulation occurrence is sufficiently high and the low initial speed of carrier L, i.e., v_L is large enough, the equilibrium would be (*E, S*) or (*S, E*) (i.e. Regions B and C in Figure 8). In other situations, the equilibrium would be (*E, S*). The explanations of the decisions and profits of the two carriers are similar to those in Section 4.

7. Conclusion

Given the fact that international shipping is a large and growing source of greenhouse gas emissions. It is likely that IMO will enforce green regulations in near future to pursue the target of halving the greenhouse gas emissions from shipping by 2050 compared to the level in 2008. However, there is a high degree of uncertainty regarding when and what type of green regulations will come into force. In a highly low service differentiation industry, ocean carriers are facing the challenges of uncertain green regulation and market competition. To comply with the potential regulations in short term, carriers may adopt two different green strategies, i.e., the equipment upgrades strategy or the slow steaming strategy. This paper seeks the final stable green strategies for two risk-averse carriers in the competing shipping market and examines the joint impacts of potential regulation and market competition on carriers' pricing decisions and utilities. A two-period game model is formulated to explore the sub-game perfect Nash equilibrium.

We find that the carrier with higher realized speed will set a higher price. However, if two carriers both adopt the slow steaming strategies, and the green regulation occurs, the two carriers will have to face a perfect competition market. As a result, both of them will obtain zero profits. In addition, there exist three types of effects caused by the potential green regulation under market competition, i.e., the penalty effect, the competition-alleviation effect, and the competition-aggravation effect. In some situations the green regulation may benefit the carriers by the combined impact of three effects; thus, the final equilibrium appears to be complicated. When the probability of the regulation occurrence is sufficiently low, the two carriers will both adopt the slow steaming strategy; when the probability of the regulation occurrence is relatively high, there is always one carrier adopting the equipment upgrades strategy. However, because of the competition and the potential regulation, the two carriers will never adopt the equipment upgrades strategies simultaneously. Finally, we find that the final equilibrium outcomes can be different from the optimal outcomes, which means, sometimes, the carriers will fall into a "sub-optimal outcome". Nevertheless, it is also possible that the potential regulation can be seen as a signal to help the two carriers collude to achieve the optimal outcome.

Based on the above results, we recommend the following measures for policy-makers to make effective regulations so that the majority of ocean carriers would adopt the equipment upgrading strategy.

(1) *Less flexible regulations*: By introducing less flexible regulations, the slow steaming strategy alone may become insufficient or infeasible to meet the requirement. For example, extremely stringent GHG emission regulations or even zero-carbon regulations will essentially exclude the use of bunker fuels and therefore make the slow steaming strategy infeasible.

(2) *Subsidies for new technologies*: If governments or IMO can provide sufficient subsidies for green technologies, this will help ocean carriers to reduce their investment costs and average operational costs to achieve equilibrium (*E, E*), i.e., encourage all the carriers adopt equipment

upgrade strategy.

(3) *Encourage the development of infrastructure and logistics of new fuels*: The availability of the infrastructure and logistics to supply new fuels is one of the main factors to determine the operational cost after equipment upgrade (suppose the equipment upgrade will use new fuels). Similar to the argument in the previous measures, encouraging the infrastructure development for new fuels by subsidies or other means can reduce the operational costs of green upgrades, which may lead to the (*E, E*) result.

(4) *Regulation based on the service differentiation*: Since service differentiation is an important factor to prevent the case (*E, E*) from being an equilibrium in our basic model, setting a regulation associated with the service differentiation may be an effective measure to encourage carriers to adopt equipment upgrade. For example, different types of ships or different shipping services are given different emission requirements.

From another way of thinking, we can consider the result in a positive way. That is, our result can also explain the phenomenon that although slow steaming strategy could satisfy the regulation with lower costs, there are also some shipping companies carrying out technology upgrade, especially the major firms in the market. Indeed, the phenomenon is not rare in reality, for example, the large shipping companies like Maersk always make effort on the emission reduction and publish their emission report on their website regularly.

To the best of our knowledge, our work is the first attempt to combine service differentiation and potential regulation into the green strategy choice problem in the shipping industry. This study enriches the literature on shipping companies' pricing decisions in competing markets and complements the literature on shipping decarbonization under green regulations. The model and results can help shipping companies to make better business decisions, and help the IMO/governments to set up effective green regulations. Nevertheless, there are some limitations in this study. First, we only consider two carriers competing against each other. A complete shipping market consists of multiple carriers. For example, in the container shipping sector, there are hundreds of individual shipping lines. Nevertheless, most of them are very small. The major shipping lines have formed three dominant alliances (i.e. 2M Alliance, THE Alliance, and Ocean Alliance), which control 96% of all East-West trades' container capacity. By treating one alliance as a player, using two or three players to model the market competition is still meaningful. Further research could relax the assumptions mentioned above. Second, in our model, the focus is on the uncertainty of green tech, and the impact of competition and service differentiation on the carriers' choice of green strategies. We have set that the average operational cost after the green upgrade is equal to the original operational cost to reduce the complexity of the computations. Further research is required to fully characterize the final equilibriums under various combinations of the system parameters. Third, our research focuses on ocean carriers' short-term responses to the potential regulations by using two periods of time (before and after the realization of the potential regulation). We did not consider the long-term effect of the green policy. Because the slow steaming is a short-term strategy and the equipment upgrade strategy might have long-term effects, our model may not sufficiently represent the benefits of the equipment upgrade strategy. Nevertheless, we might factor the long-term beneficial effects of the equipment upgrade strategy into our model by setting the operational cost after green upgrades and the fixed cost of the green upgrade to be sufficiently low levels. We have conducted extra numerical experiments, which shows that (E, E) can become a final equilibrium in the situations where the average operational cost after the equipment upgrade is significantly smaller than the initial operational costs and the fixed cost of the equipment upgrade is extremely low. However, appropriately quantifying the long-term effects of the equipment upgrade strategy is challenging. Further research is required in this direction.

Acknowledgments

We would like to thank the anonymous reviewers for their constructive comments that have helped to improve the quality of our work significantly. This work was supported by the International (Regional) Cooperation and Exchange Program of the National Natural Science Foundation of China [Grant No. 71881330167].

References

Abadie, L. M., Goicoechea, N., &Galarraga, I. 2017. Adapting the shipping sector to stricter emissions regulations: Fuel switching or installing a scrubber?. *Transportation Research Part D: Transport and Environment*, 57, 237-250.

Balcombe, P., Brierley, J., Lewis, C., Skatvedt, L., Speirs, J., Hawkes, A., and Staffell, I. 2019. How to decarbonise international shipping: options for fuels, technologies and policies. *Energy Conversion and Management*. 182, 72–88.

Bertrand, J. 1883. Book review of theorie mathematique de la richesse sociale and of recherches sur les principles mathematiques de la theorie des richesses. *Journal de Savants*. 67, 499–508.

Bhaskaran, S. R., & Krishnan, V. 2009. Effort, revenue, and cost sharing mechanisms for collaborative new product development. *Management Science*, 55(7), 1152-1169.

Bilgiç, T., &Güllü, R. 2016. Innovation race under revenue and technology uncertainty of heterogeneous firms where the winner does not take all. *IIE Transactions*, 48(6), 527-540.

Bouman, E. A., Lindstad, E., Rialland, A. I. and Stromman, A. 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping-A review, *Transportation Research Part D: Transport and Environment*. 52, 408-421.

Burel, F., Taccani, R., & Zuliani, N. 2013. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. *Energy*, 57, 412-420.

Busch, J., Barthlott, W., Brede, M., Terlau, W., & Mail, M. 2019. Bionics and green technology in maritime shipping: an assessment of the effect of Salvinia air-layer hull coatings for drag and fuel reduction. *Philosophical Transactions of the Royal Society A*, 377(2138), 20180263.

Cariou, P. 2011. Is slow steaming a sustainable means of reducing CO2 emissions from container shipping?. *Transportation Research Part D: Transport and Environment*, 16(3), 260-264.

Cariou, P., Parola, F., &Notteboom, T. 2019. Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. *International Journal of Production Economics*, 208, 17-28.

Casado, E., & Ferrer, J. C. 2013. Consumer price sensitivity in the retail industry: latitude of acceptance with heterogeneous demand. *European Journal of Operational Research*, 228(2), 418-426.

Chen, R., Dong, J. X., & Lee, C. Y. 2016. Pricing and competition in a shipping market with waste shipments and empty container repositioning. *Transportation Research Part B: Methodological*, 85,

32-55.
Choi, T. M., Chung, S. H., &Zhuo, X. 2020. Pricing with risk sensitive competing container shipping lines: Will risk seeking do more good than harm?. *Transportation Research Part B: Methodological*, 133, 210-229.
Eide, L., Årdal, G. C. H., Evsikova, N., Hvattum, L. M., & Urrutia, S. 2020. Load-dependent speed optimization in maritime inventory routing. *Computers & Operations Research*, 123, 105051.
Engau, C., & Hoffmann, V. H. 2011. Corporate response strategies to regulatory uncertainty: evidence from uncertainty about post-Kyoto regulation. *Policy Sciences*, 44(1), 53-80.
Fabrizi, A., Guarini, G., & Meliciani, V. 2018. Green patents, regulatory policies and research network policies. *Research Policy*, 47(6), 1018-1031.
Ferrari, C., Parola, F., & Tei, A. (2015). Determinants of slow steaming and implications on service patterns. *Maritime Policy & Management*, 42(7), 636-652.
Haehl, C., &Spinler, S. 2018. Capacity expansion under regulatory uncertainty: A real options-based study in international container shipping. *Transportation research part E: logistics and transportation review*, 113, 75-93.
Han, S., Gupta, S., & Lehmann, D. R. 2001. Consumer price sensitivity and price thresholds. *Journal of retailing*, 77(4), 435-456.
IMO. 2017. Status of Conventions, International Maritime Organization (IMO)
IMO. 2020. *The Fourth IMO GHG Study 2020*, International Maritime Organization (IMO): London.
Jain, T., Hazra, J., & Cheng, T. E. 2020. Illegal Content Monitoring on Social Platforms. *Production and Operations Management*, 29(8), 1837-1857.
Kontovas, C. A., &Psaraftis, H. N. 2011. The link between economy and environment in the post-crisis era: lessons learned from slow steaming. *International Journal of Decision Sciences, Risk and Management*, 3(3-4), 311-326.
Kraft, T., & Raz, G. 2017. Collaborate or compete: Examining manufacturers' replacement strategies for a substance of concern. *Production and Operations Management*, 26(9), 1646-1662.
Lagouvardou, S., Psaraftis, H.N. and Zis, T. 2020. A Literature Survey on Market-Based Measures for the Decarbonization of Shipping. *Sustainability*, 12, 3953.
Lee, C. Y., Tang, C. S., Yin, R., & An, J. 2015. Fractional price matching policies arising from the ocean freight service industry. *Production and Operations Management*, 24(7), 1118-1134.
Lee, C.Y. and Song, D.P. 2017. Ocean container transport in global supply chains: overview and research opportunities. *Transportation Research Part B: Methodological*, 95, 442-474.
Li, B. and Song, D.P. (2021*). Dual-Channel Supply Chain Decisions with Risk-Averse Behavior*, World Scientific, London.
Lister, J., Poulsen, R. T., & Ponte, S. 2015. Orchestrating transnational environmental governance in maritime shipping. *Global Environmental Change*, 34, 185-195.
Lu, T., Chen, Y. J., Fransoo, J. C., & Lee, C. Y. 2020. Shipping to heterogeneous customers with competing carriers. *Manufacturing & Service Operations Management*, 22(4), 850-867.
Lu, T., Lee, C. Y., & Lee, L. H. 2020. Coordinating Pricing and Empty Container Repositioning in Two-Depot Shipping Systems. *Transportation Science*, 54(6), 1697-1713.
Lüer-Villagra, A., & Marianov, V. (2013). A competitive hub location and pricing problem. *European journal of operational research*, 231(3), 734-744.
Maloni, M., Paul, J. A., &Gligor, D. M. 2013. Slow steaming impacts on ocean carriers and shippers. *Maritime Economics & Logistics*, 15(2), 151-171.
Mander, S. 2017. Slow steaming and a new dawn for wind propulsion: A multi-level analysis of two low carbon shipping transitions. *Marine Policy*, 75, 210-216.
Mansouri, S. A., Lee, H., & Aluko, O. 2015. Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions. *Transportation Research Part E: Logistics and Transportation Review*, 78, 3-18.
Marcus, A., Aragon-Correa, J. A., &Pinkse, J. 2011. Firms, regulatory uncertainty, and the natural environment. *California Management Review*, 54(1), 5-16.
McNamara, J. M., & Houston, A. I. 2002. Credible threats and promises. Philosophical Transactions of the Royal Society of London. *Series B: Biological Sciences*, 357(1427), 1607-1616.
Mutlu, F., &Çetinkaya, S. 2013. Pricing decisions in a carrier–retailer channel under price-sensitive demand and contract-carriage with common-carriage option. *Transportation Research Part E: Logistics and Transportation Review*, 51, 28-40.
Osborne, M. J. 2004. An introduction to game theory (Vol. 3, No. 3). New York: Oxford university press.
Pang, R., Zheng, D., Shi, M., & Zhang, X. 2019. Pollute first, control later? Exploring the economic threshold of effective environmental regulation in China's context. *Journal of environmental management*, 248, 109275.

Poulsen, R. T., Ponte, S., & Lister, J. 2016. Buyer-driven greening? Cargo-owners and environmental upgrading in maritime shipping. *Geoforum*, 68, 57-68.
Raza, Z., Woxenius, J., & Finnsgård, C. 2019. Slow steaming as part of SECA compliance strategies among RoRo and RoPax shipping companies. *Sustainability*, 11(5), 1435.
Ren, J., &Lützen, M. 2017. Selection of sustainable alternative energy source for shipping: Multi-criteria decision making under incomplete information. *Renewable and Sustainable Energy Reviews*, 74, 1003-1019.
Rezaee, A., Dehghanian, F., Fahimnia, B., & Beamon, B. 2017. Green supply chain network design with stochastic demand and carbon price. *Annals of Operations Research*, 250(2), 463-485.
Ricci, S., Marinacci, C., & Rizzetto, L. 2012. The modelling support to maritime terminals sea operation: The case study of port of Messina. *Journal of Maritime Research*, 9(3), 39-44.
Ringbom, H. 2018. Regulation of ship-source pollution in the Baltic Sea. *Marine Policy*, 98, 246-254.
Ritzenhofen, I., &Spinler, S. 2016. Optimal design of feed-in-tariffs to stimulate renewable energy investments under regulatory uncertainty—A real options analysis. *Energy Economics*, 53, 76-89.
Shah, N., &Brueckner, J. K. 2012. Price and frequency competition in freight transportation. *Transportation Research Part A: Policy and Practice*, 46(6), 938-953.
Shen, C. 2021. ONE chief shrugs off boxship orderbook concerns, *Lloyds List*, 02 Nov 2021.
Sheng, D., Li, Z. C., Fu, X., & Gillen, D. 2017. Modeling the effects of unilateral and uniform emission regulations under shipping company and port competition. *Transportation Research Part E: Logistics and Transportation Review*, 101, 99-114.
Song, D.P. 2021. Container Logistics and Maritime Transport. London: Routledge.
Song, Y., & Zhao, M. 2016. Dynamic R&D Competition under Uncertainty and Strategic Disclosure. *Available at SSRN* 2853132.
Song, Z., Tang, W., & Zhao, R. 2019. Encroachment and canvassing strategy in a sea-cargo service chain with empty container repositioning. *European Journal of Operational Research*, 276(1), 175-186.
Stevens, L., Sys, C., Vanelslander, T., & Van Hassel, E. 2015. Is new emission legislation stimulating the implementation of sustainable and energy-efficient maritime technologies?. *Research in transportation business & management*, 17, 14-25.
Thai, V. V. 2008. Service quality in maritime transport: conceptual model and empirical evidence. *Asia Pacific Journal of Marketing and Logistics*, 37(3), 179-194.
Trapp, A. C., Harris, I., Rodrigues, V. S., & Sarkis, J. 2020. Maritime container shipping: Does coopetition improve cost and environmental efficiencies?. *Transportation Research Part D: Transport and Environment*, 87, 102507.
UNCTAD. 2018. *Review of Maritime Transport*, United Nations Publication, Geneva.
Wang, H., Meng, Q., & Zhang, X. 2014. Game-theoretical models for competition analysis in a new emerging liner container shipping market. *Transportation Research Part B: Methodological*, 70, 201-227.
Wang, S., Meng, Q., 2012. Sailing speed optimization for container ships in a liner shipping network. *Transportation research part E: logistics and transportation review*, 48, 701–714.
Wang, X., Cho, S. H., & Scheller-Wolf, A. (2021). Green technology development and adoption: Competition, regulation, and uncertainty—a global game approach. *Management Science*, 67(1), 201-219.
Wen, S., Zhang, C., Lan, H., Xu, Y., Tang, Y., & Huang, Y. (2019). A hybrid ensemble model for interval prediction of solar power output in ship onboard power systems. *IEEE Transactions on Sustainable Energy*, 12(1), 14-24.
Yilmaz, O., & Savasaneril, S. (2012). Collaboration among small shippers in a transportation market. *European journal of operational research*, 218(2), 408-415.
Yliskylä-Peuralahti, J., &Gritsenko, D. 2014. Binding rules or voluntary actions? A conceptual framework for CSR in shipping. *WMU Journal of Maritime Affairs*, 13(2), 251-268.
Zhang, M., Fu, Y., Zhao, Z., Pratap, S., & Huang, G. Q. 2019. Game theoretic analysis of horizontal carrier coordination with revenue sharing in E-commerce logistics. *International Journal of Production Research*, 57(5), 1524-1551.
Zheng, W., Huang, H. F., Song, D. P., & Li, B. 2020. Optimal CSR and Pricing Decisions With Risk-Averse Providers in a Competitive Shipping System. *IEEE Transactions on Systems, Man, and Cybernetics: Systems*, 50(12), 4959-4973.
Zheng, W., Li, B., & Song, D. P. 2017. Effects of risk-aversion on competing shipping lines' pricing strategies with uncertain demands. *Transportation Research Part B: Methodological*, 104, 337-356.
Zhimai, Y. 2021. Environmental protection interview, government environmental protection subsidies and enterprise green innovation. *Foreign Economics & Management*, 43(07), 22-37.
Zhou, W. H., & Lee, C. Y. 2009. Pricing and competition in a transportation market with empty equipment

repositioning. *Transportation Research Part B: Methodological*, 43(6), 677-691.
Zhu, M., Chen, M., & Kristal, M. 2018. Modelling the impacts of uncertain carbon tax policy on maritime fleet mix strategy and carbon mitigation. *Transport*, 33(3), 707-717.
Zondag, B., Bucci, P., Gützkow, P., & de Jong, G. 2010. Port competition modeling including maritime, port, and hinterland characteristics. *Maritime Policy & Management*, 37(3), 179-194.