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Sustainability-Driven Green Strategy Choices of Two Risk-Averse Competing Carriers Under Policy and Cost Uncertainty

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Abstract

Carbon emission reduction decisions are subject to risks for shipping carriers. These include policy uncertainty (an upcoming policy may be stringent or lenient) and cost uncertainty (the operation cost may increase or decrease in the future). This paper develops a two-period game model to study the carbon emission reduction strategy choices of two risk-averse shipping carriers facing both policy uncertainty and cost uncertainty, with the goal of advancing sustainable maritime transport. They can choose a high- or low-carbon emission reduction strategy in period 1. Whether they need to upgrade in period 2 depends on the strategy they choose in period 1 and the policy implemented in period 2. The results show that in a deterministic environment, a high-cost strategy translates directly into a high-price strategy. However, in period 2, when the policy is lenient, adopting a high-carbon emission reduction strategy does not always result in a higher price than adopting a low-carbon emission reduction strategy. This result is counterintuitive. In addition, the carrier adopting a high-carbon emission reduction strategy does not necessarily set a higher price than the competitor who adopts a low-carbon emission reduction strategy. The market share plays an important role in shaping the equilibrium. When the possibility of a stringent policy is extremely low or extremely high, both carriers will choose an identical strategy. However, when the possibility is medium, they will choose differentiated strategies. The carrier with a bigger market share can tolerate a higher possibility of an upcoming stringent policy than the competitor. The degree of cost volatility also has a significant impact on the equilibrium. Its influence is particularly pronounced under a moderate probability of a stringent policy. Shippers' carbon emission sensitivity also has a positive effect on encouraging carriers to choose a greener strategy. Our findings provide actionable insights for policymakers and industry stakeholders to facilitate the sustainability transition of the shipping sector through appropriate policy design.

Keywords: sustainable maritime transport; green strategy; policy uncertainty; cost uncertainty; risk aversion

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1. Introduction

Maritime transport undertakes 80% of transportation services of international trade and contributes significantly to the global economy [1]. However, it also accounts for 3%

of carbon emissions globally, and carbon emissions can increase if there is no control. In order to reduce the carbon emissions and promote sustainable development of the shipping industry, the International Maritime Organization (IMO) has taken various measures. In 2013, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) were adopted. In 2019, the Energy Efficiency Existing Ship Index (EEXI) and the Carbon Intensity Indicator (CII) were also adopted. In 2018, IMO announced an initial goal to reduce the carbon intensity of international shipping by at least 40% by 2030, pursuing efforts towards a 70% reduction by 2050, compared to 2008 [2]. In July 2023, this target was revised. It is explicitly stated that net-zero GHG emissions from shipping should be achieved around 2050. That is, the policy has become stricter. In April 2025, IMO announced a carbon emission regulation plan called "Net-Zero Framework", which combines mandatory emission limits with a carbon pricing mechanism. This plan was rejected by some parties and was delayed for one year for further discussion [3]. The adoption of this plan faces significant uncertainty. Moreover, the trend shows that policies are becoming increasingly stringent. However, a stringent policy may not be implemented eventually. Therefore, the policy uncertainty may have a significant impact on shipping carriers' green strategy choices.

A growing number of shipping carriers are moving towards a green transition to enhance their sustainability performance. There are many ways to reduce carbon emissions. One is to use alternative fuels, such as liquefied natural gas (LNG), green methanol, ammonia, biofuels, and so on. Different fuels can achieve different levels of carbon emission reduction. For example, LNG can decrease carbon emissions by about 20% compared with fossil fuels. However, green methanol can reduce carbon emissions by 85–94%, giving it a higher carbon emission reduction potential than LNG does. Ammonia can achieve zero carbon emissions. However, green methanol's price is higher than that of LNG currently. In addition, LNG has a more mature supply network than green methanol does. It is stated that there is a risk of supply shortage associated with green methanol [4]. That is, adopting a greener fuel such as green methanol may encounter a significant increase in operation costs in the future if the shortage happens. Of course, there is also a possibility that its cost may decrease due to new technology [5]. Thus, the operation cost of adopting green methanol is uncertain. Not only green fuels but also some new technologies have such characteristics, such as carbon capture systems [6]. When reducing carbon emissions is inevitable, which strategy to choose is an essential question.

This paper is motivated by the fact that the policy on carbon emissions of the shipping industry is becoming stricter, whereas there exists a possibility that a stringent policy may not be implemented eventually. As highlighted by Kanchiralla et al. [7], the postponed IMO Net-Zero Framework combines a GHG fuel-intensity standard with a pricing mechanism, but its final stringency remains highly uncertain. When the carrier initially chooses a low-carbon emission reduction strategy and then in the future, if a stringent policy is implemented, they need to upgrade their equipment and bear high operation costs. However, when adopting a high-carbon emission reduction strategy in period 1, they may need to bear higher operation costs in period 2. As a result, the carrier must trade off between the two strategies. Due to the fierce competition in the shipping industry, carriers tend to be risk-averse. Subsequently, carriers' risk-averse behavior may also have a great impact on their decisions.

Then, the following questions are proposed:

(1) What are the optimal green strategies of competing shipping carriers facing both policy uncertainty and operation cost uncertainty?

(2) What are the impacts of two kinds of risks on their decisions?

(3) What is the impact of carriers' risk aversion on their strategy choices?

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The above questions can be important for achieving sustainable maritime transport because they depict the trade-off dilemmas of the carriers when adopting between two kinds of green strategies. In order to answer the above questions, we develop a two-period game model to study the competition between two shipping carriers. In period 1, both of them choose a green strategy: a high-carbon emission reduction strategy (strategy H) or a low-carbon emission reduction strategy (strategy L). They decide their freight rates (prices) in period 1 to compete for shippers. In period 2, a policy comes into force. However, it may be stringent or lenient. Subsequently, if the policy is stringent, the carrier adopting strategy L in period 1 needs to upgrade to strategy H. If the policy is lenient, the carrier may only need to pay carbon emission fees. In period 2, the operation cost of using strategy H is uncertain. The cost may be lower or higher. We use Conditional Value-at-Risk (CVaR) to evaluate the risk of using strategy H. The interactions between policy uncertainty, operational cost uncertainty, carriers' risk attitude, and other key factors are studied to obtain managerial insights.

Question (1) is addressed in Section 4 (Equilibrium outcomes for four strategy combinations) and Section 5.2 (Proposition 5), which present the final equilibrium strategies under different parameter conditions. These are illustrated through the numerical simulations in Section 6.

Question (2) is analyzed in Section 5.1 (Corollaries 1–4) and Sections 6.1–6.3, which discuss the effects of policy uncertainty and cost uncertainty on pricing, demand, and strategic equilibrium, respectively.

Question (3) is analyzed in Section 6.3, which examines the impact of risk-aversion parameters on strategy selection and, in conjunction with Corollary 1, illustrates the relationship between risk attitude and pricing.

The answers to the above questions will be developed progressively in the following sections and summarized in Section 8 (Conclusions).

The rest of the study is organized as follows. In Section 2, the relevant literature is studied. In Section 3, the problem formulation and notations are presented. Section 4 presents the detailed models in four strategy profiles and equilibrium results. In Section 5, we compare the equilibrium of the four subgames and derive the final equilibrium of the game. The impacts of parameters on the equilibrium are studied in Section 6. Model extension is discussed in Section 7, and we conclude the study in Section 8.

2. Literature Review

This work is closely related to carbon emission reduction strategy in the shipping industry, environmental policy uncertainty, and the risks in adopting green strategy.

2.1. Carbon Emission Reduction Strategy in the Shipping Industry

Multiple measures are available for carbon emission reduction, and the relevant studies can be grouped into three main streams. The first stream is alternative fuel adoption. There are many fuel choices such as LNG, biofuels, green methanol, hydrogen, and ammonia. Some of them are relatively mature, such as LNG, which is more accessible. However, green methanol, hydrogen, and ammonia, which can reduce carbon emissions significantly compared with LNG and biofuels, have not been used on a large scale due to production capacity limit or technological issues. Moshiul et al. [8] studied the criteria for alternative fuel selection and found that the most important criteria for shipping firm-level stakeholders are technological aspects, technology status, expenditures, ecosystem impact, and health-safety considerations. Wang and Iris [9] studied the selection of fuel types for each ship in a fleet and determined the number and sizes of ships to add or remove under uncertainty, considering emissions, investment and operation costs, and revenues. Li et al. [10] stated that the life-cycle environmental and economic analysis can provide important guidance for adopting alternative fuels for different ships. A recent case study on the Shanghai–Los Angeles green shipping corridor by Jiang et al. [11] demonstrated that the total cost of ownership and regulatory penalty levels jointly determine the optimal timing for fuel transition, which is highly sensitive to carbon pricing. The second stream is technical ways, such as carbon capture systems [12,13], wind-assisted ship propulsion [14], solar photovoltaic systems [15], and battery-electric ships [16]. Xiao et al. [17] analyzed the application of digital technology in decarbonizing shipping from 2005 to 2024. They proposed some directions for future research about speed optimization, emissions forecasting, routing optimization, and so on. The third stream is market-oriented policies such as cap-and-trade (C&T) and carbon taxes [18,19]. For example, the European Union (EU) has implemented the EU Emissions Trading System (EU ETS) starting from 2024, and there is no free allocation for international shipping. Zhou et al. [20] compared this allocation mechanism with the traditional free allocation policy and found that some policies may hinder the adoption of efficient emission reduction technologies at certain allowance price levels.

2.2. Uncertain Environment Policy

Many carbon emission reduction policies are implemented to promote green transmission in the shipping industry. For example, the carbon-trading mechanism plays an increasingly important role in promoting decarbonization, advancing green technological innovation, and improving resource allocation efficiency [21–23]. Ye et al. [24] analyzed the performance of cap-and-trade systems, tax and subsidy mechanisms, and collaborative policy frameworks in decarbonizing shipping. Park et al. [25] explored comprehensive cost mitigation strategies adopted by shipping companies in response to multiple regulations, including carbon intensity indicators and the EU Emissions Trading System. They demonstrated that firms needed to adapt proactively within complex policy environments. Sun et al. [26] focused on the direct effects of carbon taxes and emission-trading schemes on operation costs and emission reduction incentives. Liu et al. [27] found that stringent green regulations could encourage shipping carriers to make early green investments but may also lead to more conservative investment scales. Huang et al. [23], in the context of carbon-trading systems, discussed fluctuations in the shipping market across different periods. They revealed that low-carbon policies were more effective in stimulating carriers' emission reduction efforts during market booms. Wang and Zhang [28] analyzed shore power adoption under subsidies and carbon taxes using a game-theoretic model, confirming that shipper carbon preference and carbon price levels jointly influence carriers' strategic choices. Additionally, Lehmann et al. [29] systematically investigated the impacts of international shipping organizations and four EU regulations in addressing challenges related to the green transition of international shipping.

However, regulatory uncertainty regarding carbon emission reduction policies is regarded as a key external factor affecting the green transition of the shipping industry. This uncertainty may trigger two seemingly contradictory strategic responses. On one hand, it could drive shipping companies to make substantial upfront investments to avoid future risks, potentially leading to overcapacity and increasing emissions [30]. Moreover, Fu et al. [31] argued that risky policies and the attribution of environmental liability can lead to stranded asset risks. Jeong et al. [32] found that under carbon pricing, shipping carriers are expected to face approximately USD 26.5 million in stranded asset risks. However, if vessels slow down to comply with carbon intensity regulations, this risk would decrease to USD 25.2 million. On the other hand, under high-carbon-tax scenarios, shipping companies might prefer to maintain operational flexibility by increasing chartering activities. While this may raise operation costs, it nonetheless contributes to emission reduction [33]. This finding revealed the complex relationship between corporate behavior and emission reduction outcomes under uncertainty. Caprace et al. [34] emphasized that achieving zero-emission shipping required an integrated strategy combining regulatory frameworks, alternative fuels, and energy-saving technologies. Du et al. [35] found that potential stringent regulations prompted firms to adopt strategic behaviors.

2.3. Risks in Adopting Green Strategy

Relating to adopting a new green strategy, there may be many kinds of uncertain risks. Xia et al. [36] stated that there may be decarbonization outcome uncertainty and demand uncertainty regarding the utilization of green technology. Zheng et al. [5] proposed that there may be policy uncertainty and cost fluctuation risk. Yu et al. [37] studied the stochasticity of innovation outcomes in decarbonization.

Some studies propose methods to measure risk. Ozbiltekin et al. [38] utilized graph theory and matrix methods to determine the risks causing carbon emissions and the risks that should be prioritized. Chen et al. [39] developed an advanced joint risk measurement framework focusing on the risk spillover effect and investment management in green bonds and the shipbuilding market. Li et al. [40] quantified the interdependence by evaluating the risks related to the adoption of alternative fuels from the perspective of shipping carriers. They used leak noise in combination with Bayesian network models, identifying the mutual dependencies. Fu et al. [41] constructed a three-party stochastic evolutionary game model using the theory of Ito stochastic differential equations to simulate the uncertainty in the emission reduction process and analyze the strategic interactions among the government, shippers, and carriers.

There are also numerous methods to cope with risk. Sun et al. [42] proposed a risk hedging strategy for the shipping industry, incorporating risk aversion into the stochastic optimization model. They pointed out that moderate risk aversion was a wise choice. Chen et al. [43] discovered that there was asymmetric risk contagion between the oil/carbon market and the shipping market, with risks spreading from the oil/carbon markets to the shipping market more rapidly and intensively. Minematsu et al. [44] proposed a strategy for ship development leveraging synergy effects to address the uncertainty associated with green fuels. Wang et al. [45] constructed a risk transfer model to explore the impact of carbon tax fluctuations on the carbon-trading mechanism of the shore-based power system and the risk transfer in pricing and profits for the members of the shipping supply chain. Zhao et al. [46] developed a two-stage stochastic programming model to study the impact of operational demands and fuel prices on the environmental constraints and uncertainties in the commercial decisions regarding the renewal of green fleets. Choi et al. [47] focused on the influence of risk attitudes and demand fluctuations on service pricing. They found that an increase in risk tolerance would raise the equilibrium price, and a moderate risk preference would contribute to profit maximization. Tao et al. [48] analyzed the impact of risk aversion and contract uncertainty on pricing and contract preferences, while Wang et al. [49] explored the long-term freight decisions of carriers and the procurement decisions of shippers from the perspective of carrier risk aversion. Zheng et al. [50] studied the competition of risk-averse shipping carriers in the context of corporate social responsibility. They found that social responsibility efforts can achieve a win–win situation under specific conditions. Additionally, Huang et al. [51] through the construction of a three-tier maritime supply chain, including carbon emission reduction investment and low-carbon service investment, discovered that carriers' high-risk aversion awareness would have a positive impact on greenness, social welfare, and system stability.

2.4. Research Gap

Though substantial research has been conducted on reducing carbon emissions in the maritime sector for sustainable development. There are still some limitations.

Firstly, existing research often overlooks the compound risks faced by enterprises when selecting different carbon emission reduction strategies. For example, whilst Haehl and Spiner [52] examined regulatory uncertainty in shipping capacity expansion, they did not consider the uncertainty associated with green technology effectiveness. Conversely, Xia et al. [36] focused on the uncertainty of technological effectiveness but neglected the uncertainty surrounding policy direction. In fact, uncertainty surrounding carbon emission reduction policies may lead to the premature stranding of low-emission assets, whilst cost uncertainty associated with high-emission reduction technologies (such as green methanol and ammonia fuels) may give rise to operational risks. These two types of risks frequently coexist and influence one another, yet few studies have examined them simultaneously.

Secondly, much of the existing literature overlooks the impact of the competitive environment on the choice of green strategies. Some studies (such as Wang and Iris [9]) focus on the technology selection of individual firms, without considering the feedback effects of competitors' strategies on their own decisions. However, the shipping market is a typical oligopolistic market. Particularly when shippers are sensitive to both price and carbon emissions, competition significantly alters firms' pricing and investment incentives. Currently, there remains a gap in the literature regarding how two competing shipping companies balance high- and low-emission reduction strategies under asymmetric market positions.

Thirdly, the risk-averse nature of decision makers is largely overlooked in existing models. The vast majority of studies on green technology selection [6,10] employ an expected profit maximization framework, assuming that firms are risk-neutral. However, carriers often exhibit significant risk-averse behavior when faced with costly green investments and an uncertain policy environment [42,47]. Ignoring this characteristic leads to systematic discrepancies between model predictions and actual decision-making behavior.

In order to bridge the above gaps, this paper considers the carbon emission reduction strategies of two competing risk averse carriers. Policy uncertainty and cost uncertainty are both considered. We find that the market position plays a vital role in shaping the equilibrium.

This paper is closely related to Zheng et al. [5]. However, this paper is quite different. Firstly, they studied a market only sensitive to speed and price. We assume that the market demand is sensitive to both carbon emissions and price. Secondly, they focused on the slow-steaming strategy and the equipment upgrade strategy. This paper focus on two kinds of strategies that have different carbon emission reduction levels. One has a high-carbon emission reduction level, and the other is a low-carbon emission reduction level. Our model can adapt to more scenarios when two green strategies with different potential in reducing carbon emissions are considered. Thirdly, we consider a common scenario where the two competing carriers have asymmetric market positions and find that it has a significant impact on the equilibrium.

3. Problem Formulation and Notations

We considered a two-period game model of duopolistic competition consisting of two risk-averse shipping carriers (A and B) facing both policy uncertainty and cost uncertainty. At the start of period 1, the carriers need to choose their carbon emission reduction strategies. Each of them can choose strategy L, which has a low-carbon emission reduction level, or strategy H, which has a high-carbon emission reduction level. At the

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beginning of period 2, a policy will come into force. It is uncertain whether it may be stringent or lenient. If it is stringent, strategy *L* will not meet the requirements of the policy and may not be able to operate anymore. The carrier adopting strategy *L* in period 1 needs to upgrade to strategy *H* immediately. We assume that the asset (such as a ship or other equipment that can reduce carbon emissions) bought in period 1 is stranded and the salvage value is zero. The carrier needs to buy a new asset that can reduce more carbon emissions (strategy *H*) to comply with the policy. It is worth noting that asset stranding in maritime economics can manifest in multiple forms: supply-side stranding occurs when carbon-intensive vessels become unable to operate profitably under stricter emission regulations. Demand-side stranding arises from decreased demand for fossil fuel transport. In our model, the zero salvage value assumption represents an extreme case of supply-side stranding, wherein the vessel loses all operational and market value upon the enactment of a stringent policy. While this simplification facilitates analytical tractability, we acknowledge that in practice, stranded vessels may retain residual value through secondary markets (e.g., sale to routes with less stringent regulations) or scrap recycling. We relaxed this assumption in Section 7 to examine the robustness of our findings under positive salvage values. If the carrier adopts strategy *H* in period 1, no matter whether the policy is stringent or not, they do not need to change their strategy. It is important to note that we used the terms green strategy *H* and green strategy *L* as alternatives to specific strategies. For example, ships powered by LNG can only reduce carbon emissions by about 20% compared with conventional fossil fuels, which can be viewed as strategy *L*. Ships powered by green methanol can reduce carbon emissions by about 80%. Ammonia can even achieve zero carbon emission. Green methanol or ammonia can be viewed as strategy *H*. However, the supply networks of green methanol or ammonia are not as well-established as LNG. It is stated that green methanol may encounter a shortage in the future if more and more carriers adopt it [4]. Green methanol, ammonia, and other novel technologies are associated with unforeseen risks due to their early stage of development, which may lead to higher operation costs in the future. For example, the equipment may need frequent maintenance and repair. Thus, we assume that in period 2, besides policy uncertainty, the operation costs of strategy *H* are also uncertain. The cost may increase due to the advanced nature of the technology, the inadequacy of the supply facilities, and the fact that it has not yet reached a scale of production. Of course, there is still a possibility that the cost may decrease due to technology improvement.

The sequence of events is shown in Figure 1. In period 1, two shipping carriers choose their respective green strategies simultaneously between strategy *H* and strategy *L*. There are four potential equilibrium outcomes: (*H*, *H*), (*H*, *L*), (*L*, *H*), and (*L*, *L*). Subsequently, shipping carriers determine their respective freight rates at the same time. Finally, by observing the freight rates and green strategies of the carriers, shippers choose carriers to purchase green transportation services.

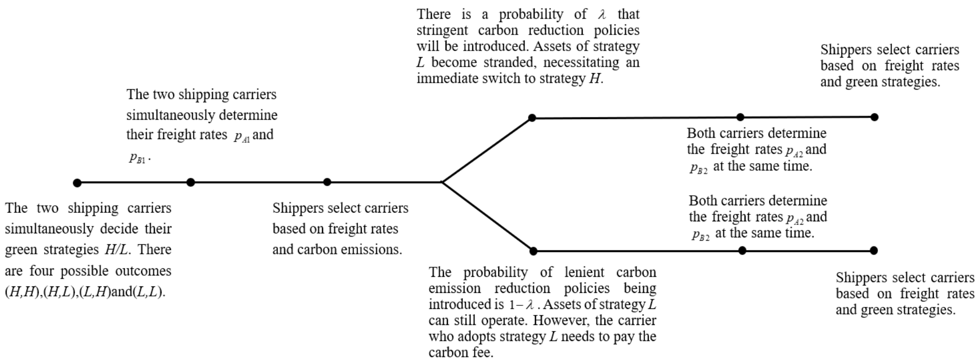

Figure 1. The sequence of events.

In period 2, the shipping industry implements a new policy, which may be stringent or lenient. To simplify the model, we assume that the stringent policy occurs with probability λ. Then, the probability of the lenient policy is $1-\lambda$. When the stringent policy occurs, the green strategy *L* no longer fulfils policy requirements. The shipping carrier adopting strategy *L* needs to upgrade to strategy *H*. When the policy is lenient, the green strategy *L* can continue to be adopted. Finally, two carriers determine their respective freight rates, and shippers choose carriers to purchase green transportation services. Table 1 presents all notations used in this study.

Table 1. Notation.

Parameters	Description
m	Total market demand of the shipping industry
α	Proportion of total market demand of carrier A
β	Cross price sensitivity of shippers $(0<\beta<1)$
γ	Carbon sensitivity of shippers $(0<\gamma<1)$
λ	Probability of the carbon emission reduction policies introduced in period 2 will be stringent
c^k	Unit operation cost for the adoption of strategy k, $k\in\{H,L\}$
ξ	Unit operation cost of strategy *H* in period 2, a random variable
ε	Range of variation in unit operation cost for strategy *H* in period 2
e^k	Unit carbon emission under strategy k, $k\in\{H,L\}$
r	Unit cost of carbon emission
F^k	Fixed investment cost under strategy k, $k\in\{H,L\}$
φ	Net residual value rate for vessels represented by strategy *L*, $\varphi\in[0,1)$
δ	Discount rate
η_A, η_B	Risk-averse indicators for carrier A and B, $\left(0<\eta_A\le 1, 0<\eta_B\le 1\right)$
Decision variable	
p_{A1}^k, p_{B1}^k	Unit freight rate for carrier A or B in period 1
p_{A2}^{k1}, p_{B2}^{k1}	Unit freight rate of carrier A or B when the policy is stringent in period 2
p_{A2}^{k2}, p_{B2}^{k2}	Unit freight rate of carrier A or B when the policy is lenient in period 2
Indexes	
k	Green strategy, $k\in\{H,L\}$
j	Period, $j\in\{1,2\}$
A,B	Carriers A，B
Other notations	
$\pi_{A1}^{k_1k_2},\pi_{B1}^{k_1k_2}$	Profits of carriers A and B in period
$\pi_{A2}^{k_1k_2 1},\pi_{B2}^{k_1k_2 1}$	Profits of carriers A and B in period 2 when the new policy is stringent
$\pi_{A1}^{k_1k_2 2},\pi_{B1}^{k_1k_2 2}$	Profits of carriers A and B in period 2 when the new policy is lenient.
$q_{A1}^{k_1k_2},q_{B1}^{k_1k_2}$	Market demands of carriers A and B in period 1
$q_{A2}^{k_1k_2 1},q_{B2}^{k_1k_2 1}$	Market demands of carriers A and B in period 2 when the new policy is stringent

$q_{A1}^{k_1 k_2 2}, q_{B1}^{k_1 k_2 2}$	Market demands of carriers A and B in period 2 when the new policy is lenient
$\text{CVaR}_\text{A}, \text{CVaR}_\text{B}$	Conditional value at risk of carrier A and B
$U_i (i = A, B)$	The objective functions of carriers A and B, taking CVaR values into account

3.1. Demand Functions

We assume that the market shares of carriers A and B in the shipping market are asymmetric and that the demand for each carrier is linearly related to its own freight rate and its competitor's freight rate. In addition, as shippers become increasingly concerned about environmental issues, carbon emissions can influence their purchasing decisions [53]. Shippers' low-carbon preference increases carriers' willingness to reduce emissions [41]. Thus, we incorporated the impact of shippers' sensitivity to carbon emissions into our demand functions. Specifically, the demands of carriers A and B are as follows:

$$q_{Aj} = \alpha m - p_{Aj} + \beta p_{Bj} - \gamma e_A^k \tag{1}$$

$$q_{Bj} = (1-\alpha) m - p_{Bj} + \beta p_{Aj} - \gamma e_B^k \tag{2}$$

Note that $j \in \{1, 2\}$ denotes period 1 or period 2 and $k \in \{H, L\}$.

In subsequent subgames, where the strategy adopted by the carrier is determined by the subgame scenario, we shall denote the carbon emissions of strategy *L* simply as e (the carbon emission of strategy *H* is 0) and shall omit the superscript for the strategy to keep the formula concise.

3.2. Profit Functions

Carrier i can receive a per-unit freight rate p_{ij} from shippers. The relevant costs for carriers consist of three main components: the operation costs c^k, the fees paid for carbon emissions re^k, and fixed investment costs F^k.

In period 1 (the new regulatory policies have not been issued), both carriers fulfill the regulatory requirements, and neither needs to pay a fee of carbon emissions. Therefore, carriers only have operation costs and fixed investment costs. It can be concluded that the profit function of carrier i in period 1 is

$$\pi_{i1}^k = (p_{i1} - c^k) q_{i1} \tag{3}$$

where q_{i1} and p_{i1} denote the demand and freight rates of carriers in period 1.

Note that Equation (3) does not take into account the fixed investment costs (F^k) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1 in the context of strategy selection (Equations (9) and (10)).

In period 2 (the new regulatory policies have been issued), if the newly implemented policy is stringent, the carriers adopting strategy *H* in period 1 do not have to change, but carriers adopting strategy *L* need to switch to strategy *H*. Thus, both of them will encounter an uncertain cost of strategy *H*. Because of the high cost of retrofitting and upgrading, we assume that the salvage value of the vessels used in strategy *L* is zero, and carriers need to repurchase the vessels used in strategy *H*. Therefore, carriers adopting strategy *H* only have operation costs, and carriers adopting strategy *L* have operation costs and fixed investment costs in period 2. The profits of the two carriers in period 2 when the policy is stringent are shown in Equation (4).

$$\pi_{i2}^{H1} = (p_{i2} - \xi) q_{i2} \tag{4}$$

Note that Equation (4) does not take into account the fixed investment costs (F^k) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1, in the context of strategy selection (Equation (10)).

If the newly implemented policy is lenient, the carriers adopting strategy *H* or *L* in period 1 do not need to change. However, carbon emissions of the green strategy *L* do not meet the requirements, and carriers adopting strategy *L* will have to pay a fee of carbon emissions. We assume that the unit fee of carbon emission is r . As a result, the carriers adopting strategy *L* will have to pay re . Green strategy *H* is assumed to have zero carbon emissions due to its strong emissions reduction and fulfilment of policy requirements. In addition, there may be uncertainty about operation costs of strategy *H* in period 2. For example, the cost of green methanol may increase due to supply shortages, inadequate infrastructure, and an increase in the number of green methanol vessels. Moreover, technological breakthroughs could also lead to the large-scale availability of green methanol, which could significantly reduce operation costs. We assume that the operation costs of strategy *H* is a random variable ξ . For computational convenience, ξ is assumed to obey a uniform distribution over the interval $[c^H-\varepsilon, c^H+\varepsilon]$ with the probability density function of $1/(2\varepsilon)$. Therefore, if the carrier adopts strategy *H* in period 1, then the profit function of carrier i in period 2 is

$$\pi_{i2}^{H2}=\left(p_{i2}-\xi\right)q_{i2} \tag{5}$$

If the carrier i adopts strategy *L* in period 1, the profit function of carrier i in period 2 is

$$\pi_{i2}^{L2}=\left(p_{i2}-c^L-re\right)q_{i2} \tag{6}$$

3.3. Objective Functions Under Risk-Averse Attitudes

In maritime shipping markets, carriers often exhibit risk-averse behavior when facing high uncertainty, such as volatile fuel costs, unclear future regulations, or unproven green technologies [45,50]. Therefore, we adopt Conditional Value-at-Risk (CVaR) as the risk measure for carriers adopting strategy *H*, facing uncertain operation costs in period 2.

Several risk measures are commonly used in operations research: mean-variance, Value-at-Risk (VaR), and Conditional Value-at-Risk (CVaR). Mean-variance assumes normally distributed returns and treats upside and downside risks symmetrically, which is inappropriate for asymmetric or fat-tailed distributions. VaR is intuitive but lacks subadditivity (thus not a coherent risk measure) and does not capture the magnitude of losses beyond the quantile. In contrast, CVaR, introduced by Rockafellar and Uryasev [54], provides a more accurate reflection of the expected return under the assumption that the carrier is extremely risk-averse. It is convex, computationally tractable, and better reflects a risk-averse decision-maker's concern about extreme losses. Since the operation cost of strategy *H* in our model follows a uniform distribution (bounded but potentially asymmetric in terms of profit impact), CVaR is a suitable choice to evaluate the downside risk of adopting high-abatement technologies. Moreover, CVaR has been successfully applied in maritime operations under various uncertainties, including vessel schedule recovery, Arctic route planning, dual-fuel ship operations, and cap-and-trade supply chains [55–58].

Following Rockafellar and Uryasev [54] and Zheng et al. [5], the CVaR value can be rewritten as follows:

$$\mathrm{CVaR}^{\eta}\left(\pi\right)=\max_{v}\left\{v+\frac{1}{\eta}\mathrm{E}\left[\min\left\{\pi-v,0\right\}\right]\right\} \tag{7}$$

where v is the Value-at-Risk (VaR) at the same confidence level. In practice, CVaR represents the average profit below the η-quantile, ignoring the contribution of profits above that quantile. In simple terms, CVaR answers the question: "If we look only at the worst $\eta \times 100\%$ of possible outcomes, what is the average profit?" For example, if $\eta = 0.05$, CVaR is the average profit in the worst 5% of scenarios. Unlike VaR, which only tells the profit threshold at the 5th percentile (e.g., "profit will not fall below $X in 95% of cases"), CVaR further reveals how bad things can become beyond that threshold. Hence, a risk-averse carrier using CVaR focuses on avoiding extreme downside losses rather than merely maximizing expected profit.

When $\eta = 1$, the carrier is risk neutral. In this case, the carrier ignores the risk. The CVaR value is equal to the expected profit. When $0 < \eta < 1$, the carrier is risk averse, and when η decreases, the carrier becomes increasingly risk averse.

Adopting strategy *L* involves no operation cost risk, the carrier is therefore assumed to be risk neutral, i.e., $\eta = 1$, then $\mathrm{CVaR}\left(\pi_i^L\right) = \pi_i^L$. The CVaR value is used as the objective function of the carrier under two different green strategies.

By associating Equations (3) and (7), it can be obtained that if carrier i chooses strategy *H* in period 2, his objective function is

$$\mathrm{CVaR}^{\eta}\left(\pi_i^H\right) = \max_{v}\left\{v + \frac{1}{\eta_i}\mathrm{E}\left[\min\left\{\pi_i^H - v, 0\right\}\right]\right\} \tag{8}$$

If carrier i chooses strategy *L* in period 2, then its objective function is equivalent to Equation (6).

In our study, we denote the objective function of the two carriers after considering the CVaR value of risk by $U_i (i = A, B)$, and the carriers need to choose the optimal freight rate to maximize it.

If carrier i adopts strategy *H* in period 1, then the sum of its two-period utilities is

$$U_i^H = \pi_{i1}^H + \delta\left[\lambda CVaR_{i2}^{H1} + (1-\lambda) CVaR_{i2}^{H2}\right] - F^H \tag{9}$$

If carrier i adopts strategy *L* in period 1, then the sum of its two-period utilities is

$$U_i^L = \pi_{i1}^L + \delta\left[\lambda CVaR_{i2}^{L1} + (1-\lambda)\pi_{i2}^{L2}\right] - F^L - \delta\lambda F^H \tag{10}$$

As shown in Figure 1, the chronological order of the game is as follows:

Firstly, at the beginning of period 1, both carriers simultaneously choose their green strategies: *H* or *L*. Then, the two carriers set their freight rates for period 1.

Secondly, at the beginning of period 2, depending on whether a stringent policy is implemented or not, the two carriers set their respective freight rates.

Therefore, the problem is a subgame perfect Nash game. There are four types of subgames: (*H*, *H*), (*H*, *L*), (*L*, *H*), and (*L*, *L*).

In the two-period game model, the primary goal is to obtain the stable strategy of the two carriers, which is the final game equilibrium. In the final game equilibrium, neither carrier is motivated to deviate unilaterally.

The procedure for deriving the final equilibrium is as follows:

Firstly, backward induction is used to obtain the optimal prices of the two carriers in both periods. Then, the equilibrium of the four subgames is analyzed. Finally, the equilibrium result of the game is obtained.

In Section 4, we analyze the optimal freight rates under each subgame. Subsequently, we analyze the equilibrium of the game in Section 5 to find a steady state where no carrier will unilaterally deviate from that state.

4. Equilibrium of Four Sub-Games

4.1. Scenario (H, H)

In this case, both carriers adopt strategy *H* in period 1, such as green methanol-fueled ships, with fixed investment costs of F^H. Strategy *H* has no carbon emissions and therefore has no negative utility to shippers.

(1) In period 1.

The demand functions of carriers A and B are as follows.

$$q_{A1}^{HH} = \alpha m - p_{A1} + \beta p_{B1} \tag{11}$$

$$q_{B1}^{HH} = (1-\alpha)m - p_{B1} + \beta p_{A1} \tag{12}$$

The profit functions of carriers A and B are as follows.

$$\pi_{A1}^{HH} = (p_{A1} - c^H)q_{A1}^{HH} \tag{13}$$

$$\pi_{B1}^{HH} = (p_{B1} - c^H)q_{B1}^{HH} \tag{14}$$

Note that Equations (13) and (14) do not take into account the fixed investment costs (F^H) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1 in the context of strategy selection (Equation (20)).

(2) In period 2.

In period 2, since both carriers choose strategy *H* in period 1, there is no need to switch strategies regardless of whether the policy is stringent or not, and in period 2, strategy *H* still meets the emission requirements. However, the operation costs of strategy *H* in period 2 are stochastic.

The demand functions of carriers A and B are, respectively,

$$q_{A2}^{HH} = \alpha m - p_{A2} + \beta p_{B2} \tag{15}$$

$$q_{B2}^{HH} = (1-\alpha)m - p_{B2} + \beta p_{A2} \tag{16}$$

The profit functions of carriers A and B are, respectively,

$$\pi_{A2}^{HH} = (p_{A2} - \xi)q_{A2}^{HH} \tag{17}$$

$$\pi_{B2}^{HH} = (p_{B2} - \xi)q_{B2}^{HH} \tag{18}$$

In the shipping industry, where carriers tend to be more cautious due to fierce competition, we have considered the risk-averse behavior of carriers. As a result of adopting strategy *H*, their operation costs in period 2 are random variables. To measure this risk, CVaR is used in period 2.

$$\text{CVaR}_{i2}^{HH} = \max_{v}\left\{ v + \frac{1}{\eta}\text{E}\left[\min((p_{i2} - \xi)q_{i2}^{HH} - v, 0)\right]\right\} \tag{19}$$

In period 1, since the operation costs of strategy *H* are known, the CVaR is equal to its profit, assuming there is no uncertainty.

In this study, we denote the objective function of the two carriers after considering the CVaR value of risk by $U_i(i = A, B)$, and the carriers need to decide the optimal freight rate to maximize the value of the objective function.

$$U_i^{HH}(\eta) = \pi_{i1}^{HH} + \delta\text{CVaR}_{i2}^{HH} - F^H \tag{20}$$

Proposition 1. *The equilibrium price decisions of the two carriers in the scenario (H, H) are shown in Table 2.*

Table 2. The equilibrium solutions of scenario (*H*, *H*).

Period	Policy Severity	The Price of Carrier A	The Price of Carrier B
1	-	$p_{A1}^{HH*}=\frac{M_A+c^H(2+\beta)}{4-\beta^2}$	$p_{B1}^{HH*}=\frac{M_B-c^H(2+\beta)}{4-\beta^2}$
2	-	$p_{A2}^{HH*}=\frac{M_A+c^H(2+\beta)+\varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$	$p_{B2}^{HH*}=\frac{M_B+c^H(2+\beta)+\varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$

where $M_A=m\left(2\alpha+\beta-\alpha\beta\right)$ $M_B=m\left(2-2\alpha+\alpha\beta\right)$.

4.2. Scenario (L, H)

In this case, in period 1, carrier A adopts strategy *L* (e.g., LNG fuel), while carrier B chooses strategy *H* (e.g., green methanol, a zero-carbon fuel) and acquires a ship, paying a one-time fixed investment cost of F^L and F^H, respectively. Since LNG fuel has carbon emissions and shippers are sensitive to carbon emissions, strategy *L* will have a negative impact on demand.

(1) In period 1.

The demand functions of carriers A and B are as follows.

$$q_{A1}^{LH}=\alpha m-p_{A1}+\beta p_{B1}-\gamma e \tag{21}$$

$$q_{B1}^{LH}=(1-\alpha)m-p_{B1}+\beta p_{A1} \tag{22}$$

The profit functions of carriers A and B are, respectively,

$$\pi_{A1}^{LH}=(p_{A1}-c^L)q_{A1}^{LH} \tag{23}$$

$$\pi_{B1}^{LH}=(p_{B1}-c^H)q_{B1}^{LH} \tag{24}$$

Note that Equations (23) and (24) do not take into account the fixed investment costs (F^k) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1 in the context of strategy selection (Equations (36) and (37)).

(2) In period 2.

In period 2, since carrier B chooses strategy *H* in period 1, it is not affected by the policy, whether it is stringent or not. In addition, strategy *H* has no carbon emissions, and therefore, there are no costs associated with carbon emissions. However, the operation costs of strategy *H* in period 2 are stochastic.

For carrier A, it needs to take the risk of policy uncertainty into account.

① Stringent policy occurs in period 2.

In the event of stringent policy occurring, carrier A needs to transform, adopting strategy *H* and incurring additional one-time fixed investment costs F^H. Since both carriers adopt strategy *H* after the transformation, then market demand is mainly influenced by price, and market demand functions are

$$q_{A2}^{LH1}=\alpha m-p_{A2}+\beta p_{B2} \tag{25}$$

$$q_{B2}^{LH1}=(1-\alpha)m-p_{B2}+\beta p_{A2} \tag{26}$$

The profit functions are

$$\pi_{A2}^{LH1}=(p_{A2}-\xi)q_{A2}^{LH1} \tag{27}$$

$$\pi_{B2}^{LH1}=(p_{B2}-\xi)q_{B2}^{LH1} \tag{28}$$

Note that Equation (27) does not take into account the fixed investment costs (F^H) of purchasing the vessel used in strategy *H*. These are only factored in when calculating

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the total discounted utility at the start of period 1 in the context of strategy selection (Equation (36)).

The corresponding CVaR values are

$$\mathrm{CVaR}_{A2}^{LH1} = \max_{v}\left\{v + \frac{1}{\eta_A}\mathrm{E}\left[\min((p_{A2}-\xi)q_{A2}^{HH} - v, 0)\right]\right\} \tag{29}$$

$$\mathrm{CVaR}_{B2}^{LH2} = \max_{v}\left\{v + \frac{1}{\eta_B}\mathrm{E}\left[\min((p_{B2}-\xi)q_{B2}^{HH} - v, 0)\right]\right\} \tag{30}$$

② Stringent policy does not occur in period 2.

If a stringent policy do not occur; carrier A continues to adopt strategy *L*, e.g., using LNG ships; and carrier B does not need to change its strategy, then the market demand is mainly affected by price and carbon emissions, and the market demand functions are expressed, respectively, as

$$q_{A2}^{LH2} = \alpha m - p_{A2} + \beta p_{B2} - \gamma e \tag{31}$$

$$q_{B2}^{LH2} = (1-\alpha)m - p_{B2} + \beta p_{A2} \tag{32}$$

The profit functions are expressed as

$$\pi_{A2}^{LH2} = (p_A - c^L - re)q_{A2}^{LH2} \tag{33}$$

$$\pi_{B2}^{LH2} = (p_B - \xi)q_{B2}^{LH2} \tag{34}$$

In this case, only carrier B has to deal with the uncertainty of operation costs. Therefore, carrier B needs to be measured using CVaR, while carrier A has its expected profit as its CVaR value.

The CVaR value of carrier B can be obtained:

$$\mathrm{CVaR}_{B2}^{LH2} = \left[p_{B2} - c^H - \varepsilon(1-\eta_B)\right]q_{B2}^{HL2} \tag{35}$$

Assuming that the discount factor is δ, then the sum of the utilities of the two periods is

$$U_A^{LH} = \pi_{A1}^{LH} + \delta\left\{\lambda \mathrm{CVaR}_{A2}^{LH1} + (1-\lambda)\mathrm{E}\left[\pi_{A2}^{LH2}\right]\right\} - F^L - \delta\lambda F^H \tag{36}$$

$$U_B^{LH} = \pi_{B1}^{LH} + \delta\left[\lambda \mathrm{CVaR}_{B2}^{LH1} + (1-\lambda)\mathrm{CVaR}_{B2}^{LH2}\right] - F^H \tag{37}$$

Proposition 2. *The equilibrium price decisions of the two carriers in the scenario (L, H) are shown in Table 3.*

Table 3. The equilibrium solutions of scenario (*L*, *H*).

Period	Policy Severity	The Price of Carrier A	The Price of Carrier B
1	-	$p_{A1}^{LH*} = \dfrac{M_A + \beta c^H + 2(c^L - e\gamma)}{4-\beta^2}$	$p_{B1}^{LH*} = \dfrac{M_B + 2c^H + \beta(c^L - e\gamma)}{4-\beta^2}$
2	Stringent	$p_{A2}^{LH1*} = \dfrac{M_A + c^H(2+\beta) + \varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$	$p_{B2}^{LH1*} = \dfrac{M_B + c^H(2+\beta) + \varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$
	Lenient	$p_{A2}^{LH2*} = \dfrac{M_A + 2[c^L + e(r-\gamma)] + \beta(c^H + \varepsilon - \varepsilon\eta_B)}{4-\beta^2}$	$p_{B2}^{LH2*} = \dfrac{M_B + \beta[c^L + e(r-\gamma)] + 2(c^H + \varepsilon - \varepsilon\eta_B)}{4-\beta^2}$

where $M_A = m(2\alpha + \beta - \alpha\beta)$; $M_B = m(2 - 2\alpha + \alpha\beta)$.

4.3. Scenario (H, L)

In this case, carrier A chooses strategy *H*, and carrier B chooses strategy *L* in period 1, with one-time fixed investment costs of F^H and F^L, respectively. Since scenario (*H*, *L*) is similar to scenario (*L*, *H*), we omit detailed descriptions and only present the functions accordingly.

(1) In period 1.

The demand functions of carriers A and B are, respectively,

$$q_{A1}^{HL} = \alpha m - p_{A1} + \beta p_{B1} \tag{38}$$

$$q_{B1}^{HL} = (1-\alpha)m - p_{B1} + \beta p_{A1} - \gamma e \tag{39}$$

The profit functions of carriers A and B are

$$\pi_{A1}^{HL} = (p_A - c^H)q_{A1}^{HL} \tag{40}$$

$$\pi_{B1}^{HL} = (p_B - c^L)q_{B1}^{HL} \tag{41}$$

Note that Equations (40)and (41) do not take into account the fixed investment costs of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1, in the context of strategy selection (Equations (53) and (54)).

(2) In period 2.

① Stringent policy occurs in period 2.

The demand functions are

$$q_{A2}^{HL1} = \alpha m - p_{A2} + \beta p_{B2} \tag{42}$$

$$q_{B2}^{HL1} = (1-\alpha)m - p_{B2} + \beta p_{A2} \tag{43}$$

The profit functions are

$$\pi_{A2}^{HL1} = (p_{A2} - \xi)q_{A2}^{HL1} \tag{44}$$

$$\pi_{B2}^{HL1} = (p_{B2} - \xi)q_{B2}^{HL1} \tag{45}$$

Note that Equation (45) does not take into account the fixed investment costs of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1 in the context of strategy selection (Equation (54)).

The corresponding CVaR values are

$$\mathrm{CVaR}_{A2}^{HL1} = \max_{v}\left\{v + \frac{1}{\eta_A}\mathrm{E}\left[\min((p_{A2} - \xi)q_{A2}^{HL1} - v, 0)\right]\right\} \tag{46}$$

$$\mathrm{CVaR}_{B2}^{HL1} = \max_{v}\left\{v + \frac{1}{\eta_B}\mathrm{E}\left[\min((p_{B2} - \xi)q_{B2}^{HL1} - v, 0)\right]\right\} \tag{47}$$

② Stringent policy does not occur in period 2.

The market demands are

$$q_{A2}^{HL2} = \alpha m - p_{A2} + \beta p_{B2} \tag{48}$$

$$q_{B2}^{HL2} = (1-\alpha)m - p_{B2} + \beta p_{A2} - \gamma e \tag{49}$$

The profit functions are, respectively,

$$\pi_{A2}^{HL2} = (p_{A2} - \xi)q_{A2}^{HL2} \tag{50}$$

$$\pi_{B2}^{HL2} = (p_{B2} - c^L - re)q_{B2}^{HL2} \tag{51}$$

The CVaR value of carrier A can be obtained as

$$\mathrm{CVaR}_{A2}^{HL2} = \left[p_{A2} - c^H - \varepsilon(1-\eta_A)\right]q_{A2}^{HL2} \tag{52}$$

Assuming that the discount factor is δ, the sum of the utilities of the two periods is

$$U_A^{HL} = \pi_{A1}^{HL} + \delta\left[\lambda \mathrm{CVaR}_{A2}^{HL1} + (1-\lambda)\mathrm{CVaR}_{A2}^{HL2}\right] - F^H \tag{53}$$

$$U_B^{HL}=\pi_{B1}^{HL}+\delta\left[\lambda \mathrm{CVaR}_{B2}^{HL1}+(1-\lambda)\pi_{B2}^{HL2}\right]-F^L-\delta\lambda F^H \tag{54}$$

Proposition 3. *The equilibrium price decisions of the two carriers in the scenario (H, L) are shown in Table 4.*

Table 4. The equilibrium solutions of scenario (*H*, *L*).

Period	Policy Severity	The Price of Carrier A	The Price of Carrier B
1	-	$p_{A1}^{HL*}=\dfrac{M_A+2c^H+\beta(c^L-e\gamma)}{4-\beta^2}$	$p_{B1}^{HL*}=\dfrac{M_B+\beta c^H+2(c^L-e\gamma)}{4-\beta^2}$
2	Stringent	$p_{A2}^{HL1*}=\dfrac{M_A+c^H(2+\beta)+\varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$	$p_{B2}^{HL1*}=\dfrac{M_B+c^H(2+\beta)+\varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$
	Lenient	$p_{A2}^{HL2*}=\dfrac{M_A+\beta[c^L+e(r-\gamma)]+2(c^H+\varepsilon-\varepsilon\eta_A)}{4-\beta^2}$	$p_{B2}^{HL2*}=\dfrac{M_B+2[c^L+e(r-\gamma)]+\beta(c^H+\varepsilon-\varepsilon\eta_A)}{4-\beta^2}$

where $M_A=m(2\alpha+\beta-\alpha\beta)$; $M_B=m(2-2\alpha+\alpha\beta)$.

4.4. Scenario (L, L)

In this case, both carriers adopt strategy *L* in period 1, and both incur fixed investment costs F^L.

(1) In period 1.

The demand functions of carriers A and B are

$$q_{A1}^{LL}=\alpha m-p_{A1}+\beta p_{B1}-\gamma e \tag{55}$$

$$q_{B1}^{LL}=(1-\alpha)m-p_{B1}+\beta p_{A1}-\gamma e \tag{56}$$

The profit functions of carriers A and B are, respectively,

$$\pi_{A1}^{LL}=(p_{A1}-c^L)q_{A1}^{LL} \tag{57}$$

$$\pi_{B1}^{LL}=(p_{B1}-c^L)q_{B1}^{LL} \tag{58}$$

Note that Equations (57) and (58) do not take into account the fixed investment costs (F^L) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1, in the context of strategy selection (Equations (69) and (70)).

(2) In period 2.

① Stringent policy occurs in period 2.

In the event of stringent policy, both carriers need to make the transition to strategy *H* and incur a one-time fixed investment cost F^H. Since both carriers adopt strategy *H*, market demand is mainly affected by price, and the market demands are, respectively,

$$q_{A2}^{LL1}=\alpha m-p_{A2}+\beta p_{B2} \tag{59}$$

$$q_{B2}^{LL1}=(1-\alpha)m-p_{B2}+\beta p_{A2} \tag{60}$$

The profit functions are, respectively,

$$\pi_{A2}^{LL1}=(p_{A2}-\xi)q_{A2}^{LL1} \tag{61}$$

$$\pi_{B2}^{LL1}=(p_{B2}-\xi)q_{B2}^{LL1} \tag{62}$$

Note that Equations (61) and (62) do not take into account the fixed investment costs (F^H) of purchasing the vessel. These are only factored in when calculating the total discounted utility at the start of period 1 in the context of strategy selection (Equations (69) and (70)).

The CVaR values for the two companies are

$$\mathrm{CVaR}_{A2}^{LL1} = \max_{v}\left\{v + \frac{1}{\eta_A}\mathrm{E}\left[\min((p_{A2}-\xi)q_{A2}^{LL} - F^H - v, 0)\right]\right\} \tag{63}$$

$$\mathrm{CVaR}_{B2}^{LL1} = \max_{v}\left\{v + \frac{1}{\eta_B}\mathrm{E}\left[\min((p_{B2}-\xi)q_{B2}^{LL} - F^H - v, 0)\right]\right\} \tag{64}$$

② Stringent policy does not occur in period 2.

If a stringent policy does not occur, carriers A and B can continue to use LNG ships but need to pay carbon emissions fees. In this case, market demand is mainly affected by price and carbon emissions, and the market demands are, respectively,

$$q_{A2}^{LL2} = \alpha m - p_{A2} + \beta p_{B2} - \gamma e \tag{65}$$

$$q_{B2}^{LL2} = (1-\alpha)m - p_{B2} + \beta p_{A2} - \gamma e \tag{66}$$

The profit functions are, respectively,

$$\pi_{A2}^{LL2} = (p_A - c^L - re)q_{A2}^{LL2} \tag{67}$$

$$\pi_{B2}^{LL2} = (p_B - c^L - re)q_{B2}^{LL2} \tag{68}$$

Assuming that the discount factor is δ, then the sum of the profits in the two periods are

$$U_A^{LL} = \pi_{A1}^{LL} + \delta\left[\lambda \mathrm{CVaR}_{A2}^{LL1} + (1-\lambda)\pi_{A2}^{LL2}\right] - F^L - \delta\lambda F^H \tag{69}$$

$$U_B^{LL} = \pi_{B1}^{LL} + \delta\left[\lambda \mathrm{CVaR}_{B2}^{LL1} + (1-\lambda)\pi_{B2}^{LL2}\right] - F^L - \delta\lambda F^H \tag{70}$$

Proposition 4. *The equilibrium price decisions of the two carriers in the scenario (L, L) are shown in Table 5.*

Table 5. The equilibrium solutions of scenario (*L*, *L*).

Period	Policy Severity	The Price of Carrier A	The Price of Carrier B
1	-	$p_{A1}^{LL*} = \dfrac{M_A + (c^L - e\gamma)(2+\beta)}{4-\beta^2}$	$p_{B1}^{LL*} = \dfrac{M_B + (c^L - e\gamma)(2+\beta)}{4-\beta^2}$
2	Stringent	$p_{A2}^{LL1*} = \dfrac{M_A + c^H(2+\beta) + \varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$	$p_{B2}^{LL1*} = \dfrac{M_B + c^H(2+\beta) + \varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$
	Lenient	$p_{A2}^{LL2*} = \dfrac{M_A + c^L(2+\beta) + e(2+\beta)(r-\gamma)}{4-\beta^2}$	$p_{A2}^{LL2*} = \dfrac{M_B + c^L(2+\beta) + e(2+\beta)(r-\gamma)}{4-\beta^2}$

where $M_A = m(2\alpha + \beta - \alpha\beta)$; $M_B = m(2 - 2\alpha + \alpha\beta)$.

5. Comparisons and Equilibriums

5.1. Comparative Analysis of Sub-Games

To simplify the analysis, we assume that carriers A and B maintain the same risk-averse attitude, i.e., $\eta_A = \eta_B = \eta$.

Corollary 1. *In the scenarios (H, H), (H, L), (L, H), and (L, L), the effects of the carriers' risk-averse attitude, the degree of variation in unit operation costs, and the shippers' sensitivity to carbon emissions on the optimal freight rate are as follows:*

(i) Both carriers' equilibrium prices in period 2 decrease with η.

(ii) Both carriers' equilibrium prices in period 2 increase with the degree of variation in unit operation costs under strategy H.

(iii) Both carriers' equilibrium prices decrease with the shippers' carbon emission sensitivity.

Corollary 1 (i) indicates that the equilibrium freight rates for both carriers decrease as η increases and rise as η decreases in period 2. An increase in risk aversion implies that carriers have a greater aversion to potential losses. According to expected utility theory, strongly risk-averse decision-makers tend to secure unit revenue by raising prices in order to hedge against the downside risks associated with uncertainty. Consequently, an increase in risk aversion creates upward pressure on prices, with carriers adopting "safety-first pricing" strategies to avoid extreme loss scenarios. Conversely, when risk aversion decreases, carriers are more willing to take the risk of price competition, using lower prices to compete for market share, seeking to maximize expected profits rather than minimize risk.

Furthermore, changes in the risk-averse behavior of carriers adopting strategy *H* have a significant impact on the freight rates of their competitors. Specifically, when carriers adopting strategy *H* become less risk-averse, the equilibrium prices of competitors adopting strategy *L* also fall. This suggests that carriers adopting strategy *H* enhance their competitiveness and capture market share by lowering freight rates, while competitors are forced to adjust their prices under competitive pressure in order to maintain their market position.

Corollary 1 (ii) reveals the impact of changes in the unit operation costs under strategy *H* on the carrier's freight rate decisions. An increase in unit operation costs directly erodes the carriers' margin of profit. When marginal costs rise, a rational carrier will pass on part of the costs to downstream shippers by raising the equilibrium price in order to maintain the desired profit level. Furthermore, when a carrier adopting strategy *H* raises freight rates in anticipation of increased costs, competitors (regardless of the green strategy they adopt) will engage in strategic follow-up actions to respond to the changing market environment and maintain their competitive position.

Corollary 1 (iii) reveals the relationship between shippers' carbon emission sensitivity and the equilibrium price. When shippers' carbon emission sensitivity increases, carriers lower their prices. When shippers' preferences for environmental attributes strengthen, the effective demand for high-carbon emission services declines, and carriers face intensified competitive pressure in the market. To maintain market share, carriers are compelled to lower the equilibrium price to compensate for the disutility incurred by shippers due to carbon emissions, thereby creating an environment-preference-driven price suppression effect. This finding offers an interesting contrast to the "polluter pays" principle: although high-carbon emission carriers do not directly bear the costs of environmental externalities, market mechanisms indirectly achieve the effects of environmental regulation through shippers' preferences.

Corollary 2. *Given that the competitor adopts a particular strategy, the equilibrium prices are compared when the carrier adopts different strategies.*

(i) In period 1, given that the competitor adopts a certain strategy, $p_{A1}^{Hj*} > p_{A1}^{Lj*}$ *;* $p_{B1}^{iH*} > p_{B1}^{iL*}$ *, where* $i, j \in \{H, L\}$ *.*

(ii) In period 2, assuming that the new carbon emission policy is lenient and given the strategies adopted by competitors, the equilibrium prices for the carrier adopting strategy H and strategy L are compared as follows:

When $c^H - c^L - er + e\gamma < 0$ *and* $\varepsilon \ge \varepsilon_2$ *, or* $c^H - c^L - er + e\gamma > 0$ *,* $p_{A2}^{Hj2*} > p_{A2}^{Lj2*}$ *,* $p_{B2}^{iH2*} > p_{B2}^{iL2*}$*. When* $c^H - c^L - er + e\gamma < 0$ *and* $\varepsilon_1 \le \varepsilon < \varepsilon_2$*, or* $\varepsilon < \varepsilon_1$*,* $p_{A2}^{Hj2*} < p_{A2}^{Lj2*}$*,* $p_{B2}^{iH2*} <$ p_{B2}^{iL2*}*. Where* $\varepsilon_1 = -(c^H - c^L - er + e\gamma)$*,* $\varepsilon_2 = -\dfrac{c^H - c^L - er + e\gamma}{1-\eta}$.

Corollary 2 (i) shows that when there is no uncertainty regarding carbon emission reduction policies in period 1, and carriers base their decisions solely on a certain cost structure; carriers adopting strategy *H* must offset their cost disadvantage through a higher equilibrium price. Since the unit operation cost of strategy *H* is higher than that of strategy *L* ($c^H > c^L$). This result reflects the fundamental logic of cost-driven pricing: in a certain environment, a high-cost strategy directly translates into a high-price strategy.

Corollary 2 (ii) shows that in period 2, when $c^H - c^L - er + e\gamma < 0$ and $\varepsilon \ge \varepsilon_2$ or $c^H - c^L - er + e\gamma > 0$, the high unit operation cost of strategy *H* dominates pricing decisions. Despite the lenient policy, the cost disadvantage of strategy *H* relative to strategy *L* (operation costs) outweighs the environmental benefits derived from its zero carbon emissions. To maintain the desired profit level, the carrier must pass on these costs to shippers via a higher equilibrium price. This result reflects the dominant role of cost-driven pricing mechanisms in a lenient policy environment; when cost disadvantages are significant or operation costs are highly volatile, high-carbon emission reduction strategies struggle to gain an advantage through price competition.

When $c^H - c^L - er + e\gamma < 0$ and $\varepsilon_1 \le \varepsilon < \varepsilon_2$ or $\varepsilon < \varepsilon_1$, the zero-carbon emission advantage of strategy *H* translates into a competitive advantage due to the effect of carbon emission sensitivity (γ). When strategy *H*'s overall cost disadvantage is negative (i.e., $c^H - c^L - er + e\gamma < 0$), this implies that the environmental benefits derived from zero carbon emissions (as reflected by the shippers' carbon emission sensitivity) outweigh the higher operation costs. In this scenario, carriers adopting strategy *H* can attract environmentally conscious shippers through lower equilibrium pricing, thereby realizing a "green discount" effect, wherein environmental advantages are converted into price competitiveness, allowing them to capture market share through their pricing advantage.

In summary, in a deterministic environment, a high-cost strategy translates directly into a high-price strategy. However, in period two, when the policy is lenient, adopting a high-emission reduction strategy does not always result in a higher price than adopting a low-emission reduction strategy, which is counterintuitive.

Corollary 3. *When carriers adopt different green strategies, the equilibrium freight rates for carriers adopting strategy H are compared with those for carriers adopting strategy L.*

(i) In period 1, when $(2\alpha-1)m > c^L - c^H - e\gamma$*,* $p_{A1}^{HL*} > p_{B1}^{HL*}$*; otherwise,* $p_{A1}^{HL*} \le p_{B1}^{HL*}$.

(ii) In period 2, under a stringent policy, when $\alpha > 1/2$ *,* $p_{A2}^{HL1*} > p_{B2}^{HL1*}$*; otherwise,* $p_{A2}^{HL1*} \le p_{B2}^{HL1*}$.

(iii) In period 2, under a lenient policy, the equilibrium freight rates are as follows:

When $(2\alpha-1)m < c^L - c^H - e\gamma + er$ *and* $\varepsilon \ge \varepsilon_4$ *, or* $(2\alpha-1)m > c^L - c^H - e\gamma + er$ *,* $p_{A2}^{HL2*} > p_{B2}^{HL2*}$*; when* $(2\alpha-1)m < c^L - c^H - e\gamma + er$ *and* $\varepsilon_3 \le \varepsilon < \varepsilon_4$*, or* $\varepsilon < \varepsilon_3$*,* $p_{A2}^{HL2*} < p_{B2}^{HL2*}$*, where* $\varepsilon_3 = (1-2\alpha)m - (c^H - c^L - er + e\gamma)$*,* $\varepsilon_4 = -\dfrac{(2\alpha-1)m + c^H - c^L - er + e\gamma}{1-\eta}$.

Since the strategic pairs (*H*, *L*) and (*L*, *H*) are symmetric, the only difference between the two carriers is their market shares, with carrier A holding a market share of α and carrier B holding a market share of $1-\alpha$. The results for the (*L*, *H*) can be obtained simply by interchanging the subscripts and variables. Due to space constraints, these results are omitted.

Corollary 3 (i) indicates that there is no uncertainty regarding carbon emission reduction policies in period 1, and pricing decisions are determined jointly by market position effects, cost structures, and the negative effects of carbon emissions. Market position effects reflect carrier A's market share advantage or disadvantage. In terms of cost structure, strategy L has an operational cost advantage over strategy H, and the relative magnitude of the two determines the net effect of this cost advantage. The negative effects of carbon emissions refer to the adverse impact of carbon emissions on demand. When carrier A's market position advantage exceeds carrier B's net cost advantage (after accounting for the negative effects of carbon emissions), carrier A can maintain strategy H through higher price. Conversely, carrier B's low-cost advantage will translate into price competitiveness. This result reveals the combined influence of market share and cost structure and the negative effects of carbon emissions on pricing decisions.

Corollary 3 (ii) shows that under a stringent policy, both carriers must adopt strategy H in the second stage. In this case, pricing depends solely on market position, and the carrier with the larger market share can set a higher freight rate.

Corollary 3 (iii) leads to a counterintuitive conclusion: under a lenient policy, carriers adopting the high-emission reduction strategy H may not necessarily have higher freight rates than competitors adopting the low-emission reduction strategy L. This phenomenon stems from the interaction between market share and carbon sensitivity compensation. Specifically, the effective cost of strategy L includes an implicit carbon penalty, manifested in reduced demand ($-\gamma e$) and carbon charges (re), whereas strategy H does not incur such a penalty. When shippers' sensitivity to carbon emissions (γ) is sufficiently high, this penalty will outweigh the operational cost disadvantage of strategy H. This enables carriers adopting strategy H, particularly those with smaller market shares, to attract price sensitive shippers by setting lower prices whilst not sacrificing demand from environmentally conscious shippers. The threshold condition in Corollary 3 formalizes this trade-off: A green discount emerges when the carbon penalty of strategy L exceeds its cost advantage relative to strategy H. This effect becomes more pronounced as the market share gap widens. Consequently, pricing outcomes are determined not by a single factor but by the interaction between market share and carbon sensitivity.

Corollary 4. *In the (H, H), (H, L), (L, H), and (L, L) scenarios, the effects of the carrier's risk-averse attitude, the degree of variation in unit operation costs, and the shippers' sensitivity to carbon emissions on equilibrium demand are as follows:*

(i) In period 2, when the policy is stringent, the demand of all carriers increases with η*. When the policy is lenient, the equilibrium demand of carriers adopting strategy H increases with* η*, and the equilibrium demand of carriers adopting strategy L decreases with* η*.*

(ii) In period 2, regardless of whether the policy is stringent or not, the equilibrium demand of carriers adopting strategy H decreases with the unit operation costs, while the equilibrium demand of carriers adopting strategy L increases with the unit operation costs of strategy H.

(iii) Carriers' equilibrium demand decreases with shippers' sensitivity to carbon emissions.

Corollary 4 (i) shows that an increase in risk aversion implies that carriers have a greater aversion to potential losses, prompting them to adopt defensive pricing strategies. For carriers adopting strategy H, increased risk aversion leads them to raise the equilibrium price in order to hedge against the downside risks associated with uncertainty. In accordance with the law of demand, a rise in price suppresses market demand, and consequently, equilibrium demand decreases. This outcome reflects the market cost of a safety-oriented pricing strategy: whilst securing unit revenue through

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higher prices, market share is sacrificed. For carriers adopting strategy *L*, the change in demand stems from strategic adjustments by the competitor. When the competitor adopting strategy *H* raises prices due to increased risk aversion, the carrier adopting strategy *L* gains a relative price advantage, attracting a portion of price sensitive shippers to shift their demand, thereby increasing the equilibrium demand.

Corollary 4 (ii) shows that for a carrier adopting strategy *H*, an increase in unit operation costs directly erodes their profit margin. To maintain the desired level of revenue, the carrier raises the equilibrium price, passing on part of the costs to shippers. The price increase leads to a contraction in market demand, and consequently, equilibrium demand decreases. This result confirms the demand-suppressing effect of cost-driven pricing. For the carrier adopting strategy *L*, changes in demand also stem from the competitor's price adjustments. When the competitor employing strategy *H* raises prices due to increased costs, the carrier adopting strategy *L* gains a competitive advantage, attracting some shippers to switch. Consequently, the equilibrium demand increases. This outcome reflects the substitution effect in oligopoly: one party's cost disadvantage translates into a market opportunity for the competitor.

Corollary 4 (iii) indicates that increased carbon sensitivity among shippers implies a heightened preference for environmental attributes and reduced acceptance of high-carbon emission services. As shippers' carbon emission sensitivity increases, the carrier adopting strategy *L* faces pressure from shrinking demand: shippers either reduce their demand for these services, switch to zero-emission carriers adopting strategy *H*, or reduce their overall consumption of transport services. When both carriers adopt strategy *H*, carbon sensitivity has no direct impact on equilibrium demand, as their services are both zero-emission. However, when at least one carrier adopts strategy *L*, total market demand declines due to environmental preferences. This result reveals the overall dampening effect of heightened environmental awareness on high-carbon emission industries: even if some firms achieve a green transition, overall industry demand may still contract due to environmental externalities.

5.2. The Equilibrium Green Strategy

Next, we solve for the final equilibrium outcome of the game.

Proposition 5. *The equilibrium green strategy of the two carriers is as follows:*

$$Z^* = \begin{cases} (H,H), & \text{if and only if } F^L - F^H(1-\delta\lambda) > \max\{R_2 - R_1, R_6 - R_5\} \\ (H,L), & \text{if and only if } F^L - F^H(1-\delta\lambda) > R_4 - R_3 \text{ and } F^L - F^H(1-\delta\lambda) < R_6 - R_5 \\ (L,H), & \text{if and only if } F^L - F^H(1-\delta\lambda) < R_2 - R_1 \text{ and } F^L - F^H(1-\delta\lambda) > R_8 - R_7 \\ (L,L), & \text{if and only if } F^L - F^H(1-\delta\lambda) < \min\{R_4 - R_3, R_8 - R_7\} \end{cases}$$

$R_i (i = 1, \ldots, 8)$ *are presented in the Appendix A.1.*

To show the equilibrium results more intuitively, simulations using numerical examples are presented in Section 6.

6. Sensitivity Analysis of the Equilibrium

In order to demonstrate the equilibrium strategy more intuitively, we present a numerical example in this section. The default parameter settings are as follows: $m = 100000, \alpha = 0.6, \beta = 0.6, \gamma = 0.3, c^H = 0.85, c^L = 0.3, e = 0.07, r = 0.2, F^L = 35000, F^H = 20000$, $\delta = 0.4$. Specifically, the market size is set to a larger value ($m = 100000$) in order to account for fixed investment costs (in tens of thousands), ensuring that the carrier's total revenue is commensurate with the scale of investment and avoiding numerical distortion caused by differences in units of measurement. $\alpha = 0.6$ means carrier A holds a 60%

market share, whilst Carrier B holds 40%, reflecting an asymmetry in market position. This scenario enables us to examine the differences in green strategy choices between the market leader and the follower. The cross-price sensitivity β and carbon sensitivity γ are set to 0.6 and 0.3, respectively, following Zheng et al. [5] and Lu et al. [53], which reflect moderate competition intensity and growing environmental awareness among shippers. The cost disadvantage of methanol relative to LNG is quantified by Lee and Kim [59], who find that methanol's high price makes it less competitive under current carbon pricing mechanisms. This supports our baseline assumption $c^H > c^L$ with a ratio of approximately 2.8. The base operational costs are $c^H = 0.85$ and $c^L = 0.3$, consistent with the observation that high-abatement fuels (e.g., green methanol) currently have higher operation expenses than LNG [4,8]. In order to keep carbon costs and carbon effects within a reasonable economic range and to establish a system of dimensions that is intrinsically consistent with parameters such as operation costs, carbon prices, and carbon sensitivity, we set $e = 0.07$. This allows us to examine the coexistence and competition between the two strategies under conditions of policy and cost uncertainty. The carbon emission fee is $r = 0.2$, aligned with early-stage EU ETS prices for shipping (approximately EUR 20–30 per ton CO_2 equivalent). The fixed investment costs are set as $F^H = 20000, F^L = 35000$, acknowledging that green methanol vessels require higher upfront investment but may benefit from future cost reductions [5]. The discount factor is $\delta = 0.4$, a typical value for multi-period maritime investment decisions.

6.1. Impact of Policy Uncertainty on Emission Reductions

(1) The relationship between η and λ .

When the two carriers have the same market share (i.e., $\alpha = 0.5$), the equilibrium green strategies are shown in Figure 2.

Figure 2 shows that when the probability of stringent policy issuance is low, both carriers tend to choose strategy *L*. This strategy has lower emission reduction but is cheaper. However, when the probability of future stringent policy issuance is high, which leads to stranded assets, both carriers choose strategy *H*. This strategy has higher emission reduction but is more expensive. This reflects the importance of stringent policies in guiding the green transformation of the shipping industry.

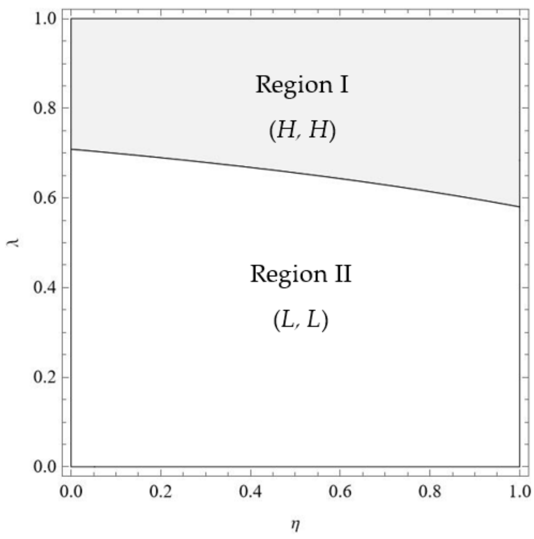

Figure 2. The equilibrium of the green strategy ($\alpha = 0.5$).

When the probability of a stringent policy is moderate, both carriers will choose strategy *L* when η is small, and when η is large, they will choose strategy *H* instead.

In other words, carriers become more risk-averse, favoring strategy *L*, i.e., the strategy with more stable operation costs. When carriers become more optimistic, they tend to choose a strategy with variable operation costs but with greater emission reduction potential.

The results in Figure 3 show that when the market share is asymmetric, both carriers will choose strategy *H* when the probability of stranding due to a stringent policy is high. When the probability of a stringent policies is moderate, the carrier with a larger market share will choose strategy *L*, while the one with a smaller market share will choose strategy *H*, i.e., they will adopt a differentiated strategy. When the probability of a stringent policy is low, both carriers will choose strategy *L*. That is to say, market share provides a certain buffer against stringent policies, and for the carrier with a smaller market share, differentiation can avoid direct competition with the larger carrier. Market share has an important influence on the choice of strategy.

(2) The relationship between λ and ε.

Figure 4 shows that when the probability of a stringent policy is low, regardless of the uncertainty surrounding the operation costs of the strategy *H* (whether it rises or falls), both carriers tend to adopt the low-cost, certain strategy *L*; whereas when the probability of a stringent policy is high, both carriers tend to adopt strategy *H*. In other words, compared to fluctuations in the unit operation costs of the high-emission reduction strategy *H*, carriers' choice of green strategy is more significantly influenced by stringent policies. When the probability of a stringent policy is high, although the unit operation cost of strategy *H* is subject to fluctuations, adopting strategy *L* would result in greater losses due to stranded assets. Consequently, carriers tend to choose strategy *H*. When the probability of a stringent policy is low, adopting strategy *L* is less likely to result in stranded assets, and adopting strategy *H* carries the risk of rising unit operation cost. In this case, carriers are more inclined to choose strategy *L*.

Figure 5 is similar to Figure 4, except that when the probability of a stringent policy is moderate, the two carriers adopt differentiated strategies, with the carrier with the larger market share tending to adopt a low emission reduction strategy. Only when the probability of stringent policies being issued is high do the two carriers' strategies converge, with both adopting strategy *H*.

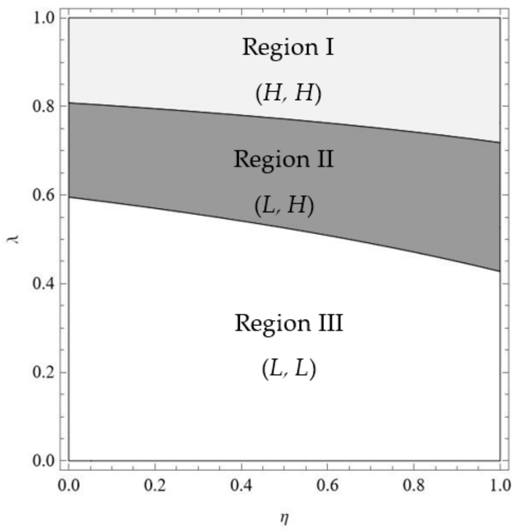

Figure 3. The equilibrium of the green strategy ($\alpha = 0.6$).

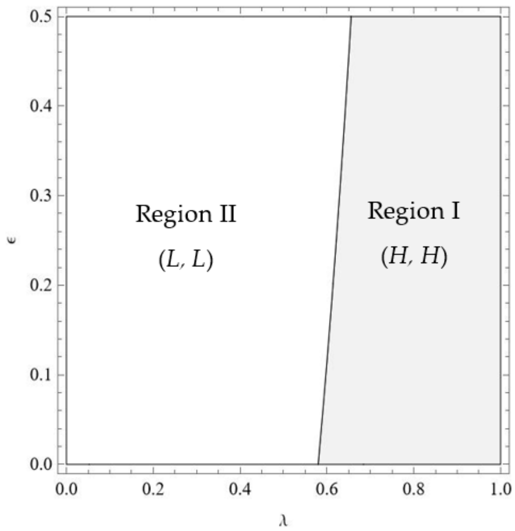

Figure 4. The equilibrium of the green strategy ($\alpha = 0.5$).

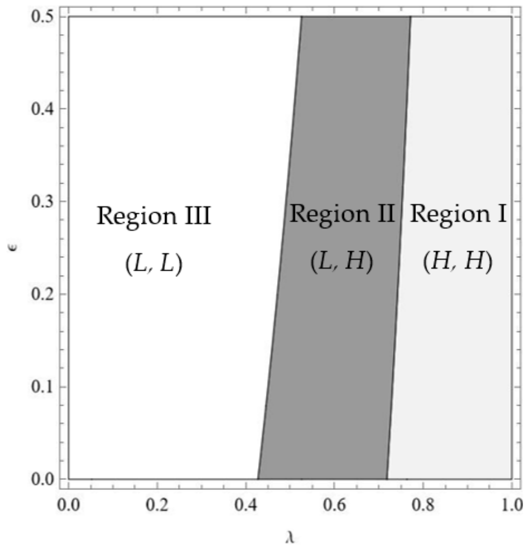

Figure 5. The equilibrium of the green strategy ($\alpha = 0.6$).

6.2. Impact of Carriers' Risk Aversion

Figures 6 and 7 illustrate, respectively, how the risk-averse behavior of carriers influences the strategic equilibrium in symmetric markets ($\alpha = 0.5$) and asymmetric markets ($\alpha = 0.6$). As shown in Figure 6, when the market shares of the two carriers are equal, two strategic equilibria exist: (*L*, *L*) and (*H*, *H*). We find that when carriers are highly risk-averse, they will only choose strategy *H* if the extent of cost fluctuations for strategy *H* is small; otherwise, they will choose strategy *L*. Furthermore, as carriers' risk aversion decreases, they will gradually shift from favoring strategy *L* to favoring strategy *H*, even though the extent of cost fluctuations for strategy *H* is larger. This is because a decrease in carriers' risk aversion increases their tolerance for the extent of cost fluctuations under strategy *H*. Interestingly, Figure 7 presents entirely different results. Only when the carriers are extremely risk-averse and the extent of unit operation cost fluctuations under strategy *H* is extremely high do both carriers tend to adopt strategy *L*; otherwise, the two carriers will adopt different strategies. Specifically, carrier A, with the larger market share, adopts strategy *L*, whilst carrier B, with the smaller market share, adopts strategy *H*. In this scenario, carrier A utilizes its larger market share to avoid the risk of cost increases. Meanwhile, carrier B, with the smaller market share, gains a competitive advantage in the shipping market through a differentiated green strategy whilst avoiding direct competition with carrier A.

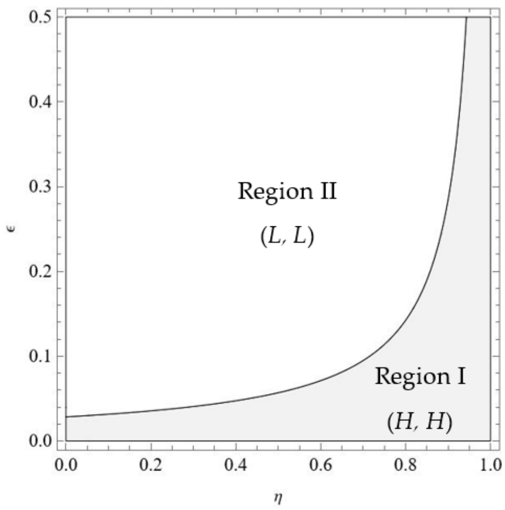

Figure 6. The equilibrium of the green strategy ($\alpha = 0.5$).

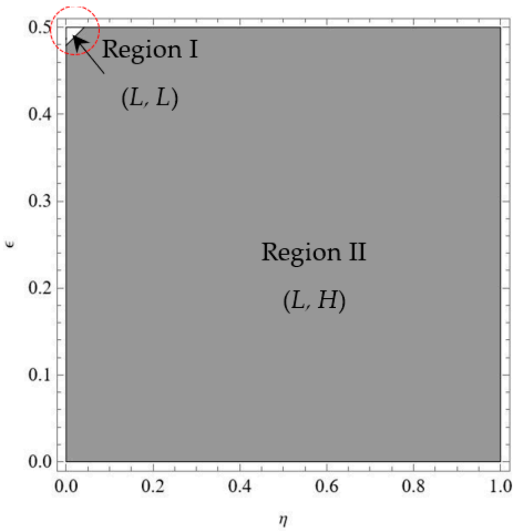

Figure 7. The equilibrium of the green strategy ($\alpha = 0.6$).

6.3. Impact of Market Size

Figure 8 shows that market share divides the equilibrium strategy into symmetric choices. Comparing Region II with Region III, it is clear that carriers with a larger market share choose strategy *L*, whilst those with a smaller market share choose strategy *H*. Taking carrier A's larger market share as an example, Figure 9 shows that when carrier A's market share increases from 0.6 to 0.7, the equilibrium strategy (*L*, *H*) expands. In contrast, the equilibrium strategies (*L*, *L*) and (*H*, *H*) shrink. From the perspective of the industry, the scale effect brought about by the expansion of market demand enables carrier A, even if it adopts strategy *L*, to attract price sensitive shippers through the low-price strategy so as to maintain or expand the market share and consolidate the market position. With the reduction of carrier B's market share, if it adopts strategy *L*, carrier B will face homogeneous competition and profit compression. Therefore, carrier B prefers to adopt strategy *H* to attract shippers with high sensitivity to carbon emissions through its high-emission reduction capability. Then, the two carriers can complement each other and avoid direct competition.

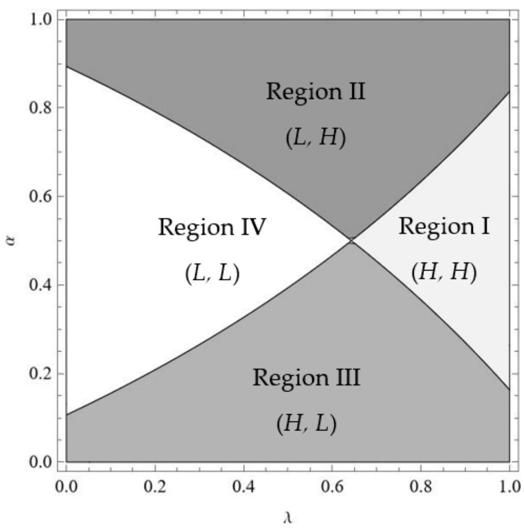

Figure 8. The equilibrium of the green strategy.

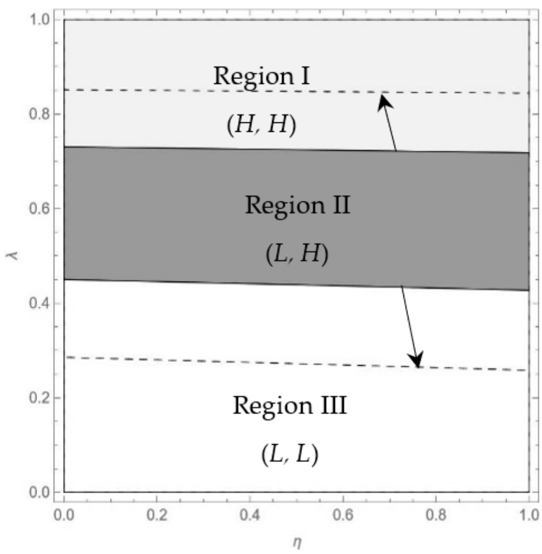

Figure 9. Equilibrium changes when α increases from 0.6 to 0.7.

In addition, as the market share asymmetry widens, policy stringency will have less impact on carriers' strategy choices. Specifically, the differentiated equilibrium strategy (*L*, *H*) gives way to the equilibrium strategy (*L*, *L*) and (*H*, *H*) when the market share of carrier A expands further. In other words, the two carriers will adopt the equilibrium strategy (*L*, *L*) only if the probability of a stringent policy is low, and they will adopt (*H*, *H*) only if the probability of a stringent policy is high; otherwise, they will choose the differentiated equilibrium strategy (*L*, *H*). The impact on the equilibrium region is symmetric when the market share of carrier B increases.

6.4. Impact of Carbon Sensitivity of Shippers

In the green shipping market, an increase in shippers' carbon sensitivity (γ increases from 0.3 to 0.8) can lead to a greater preference for both carriers adopting strategy *H*. As shown in Figure 10, when shippers' carbon sensitivity increases, carriers are more inclined to choose green strategy *H*. This means that carbon emission levels become more important in shippers' choice of shipping services. Consequently, reducing carbon emissions becomes a key competitive factor for the two carriers. When shippers are more concerned about carbon emissions, carriers tend to choose green strategy *H* even if the probability of a stringent policy is low.

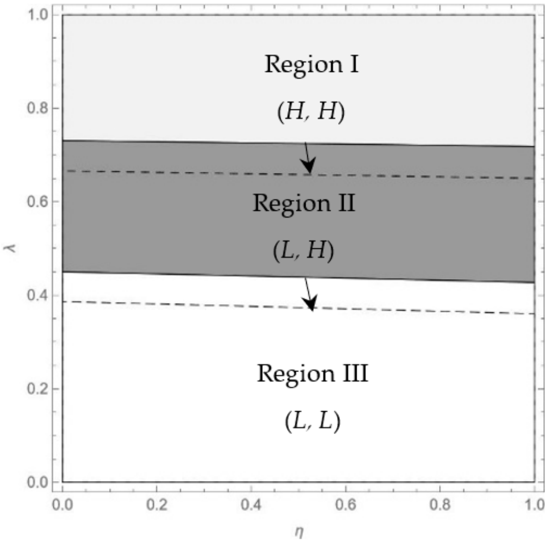

Figure 10. Equilibrium changes when γ increases from 0.3 to 0.8.

6.5. Impact of Carbon Price

The effect of carbon price on the equilibrium is smaller than that of other parameters (α, γ). As shown in Figure 11, as the carbon price r increases from 0.2 to 0.8, the (*L*, *L*) region tends to shrink. When the carbon price increases, carriers need to pay extra for carbon emissions (e.g., EU carbon price, IMO carbon allowances), which leads to a significant increase in the total cost of strategy *L*. As a result, even if the probability of the a stringent policy is low, carriers will tend to choose strategy *H* in order to avoid carbon costs.

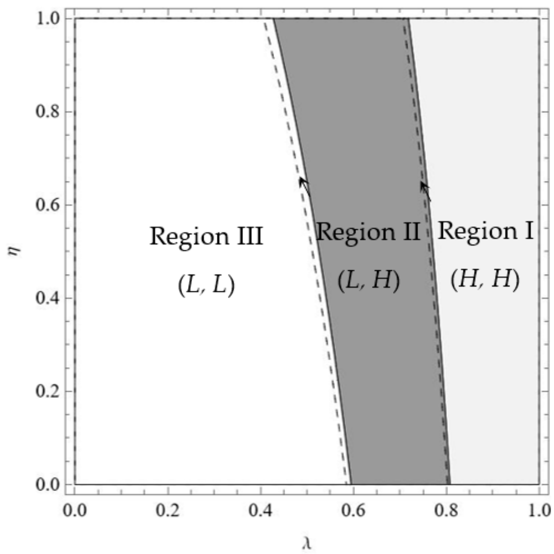

Figure 11. Equilibrium changes when r increases from 0.2 to 0.8.

6.6. Impact of Strategy L's Operation Costs

In the model, the unit operation cost of strategy *L* (denoted by c^L) is treated as a deterministic parameter. However, in practice, the price of LNG, the most representative low-emission reduction strategy fuel, exhibits considerable volatility. As documented in recent industry reports, LNG price fluctuations can be substantial: the annual price volatility in the Chinese LNG market reached 27% in 2024 and remained at 13% in 2025. Geopolitical tensions, such as those in the Strait of Hormuz, have triggered weekly price spikes exceeding 11%. These observations motivate us to examine how variations in c^L affect the equilibrium outcomes.

To this end, we conduct a sensitivity analysis by varying c^L across a reasonable range around its base value ($c^L = 0.3$). Figure 12 and Figure 13 illustrate how the equilibrium strategy regions shift as $c^L = 0.3$ changing. The key findings are summarized as follows.

From Figure 12, we can see that as c^L increases, the strategic equilibrium for carriers gradually shifts from (*L*, *L*) to (*H*, *H*). This result is intuitive: the higher the operation costs of strategy *L*, the weaker its cost advantage relative to strategy *H*, thereby making the high-emission reduction strategy more competitive. Figure 13 demonstrates that carriers with a larger market share are better able to absorb higher operation costs. Even when c^L rises, carriers may still adopt strategy *L*, whilst carriers with smaller market shares will switch to strategy *H* to avoid a cost disadvantage. This suggests that market power acts as a buffer against cost fluctuations, enabling dominant carriers to maintain their preferred strategy, whilst smaller competitors are forced to adopt differentiated strategies.

These sensitivity analysis results confirm that the qualitative conclusions of our paper remain valid even if the operation costs of strategy *L* change. Furthermore, these results reveal an important practical implication: fluctuations in liquefied natural gas (LNG) prices erode the cost advantage of low-emission strategies, thereby accelerating the adoption of zero-emission technologies and prompting risk-averse shipping companies to switch to strategy *H*. For policymakers, this suggests that measures to stabilize LNG fuel prices, whilst beneficial for operational predictability, may inadvertently delay the green transition by maintaining the cost attractiveness of low-emission reduction strategy fuels such as LNG.

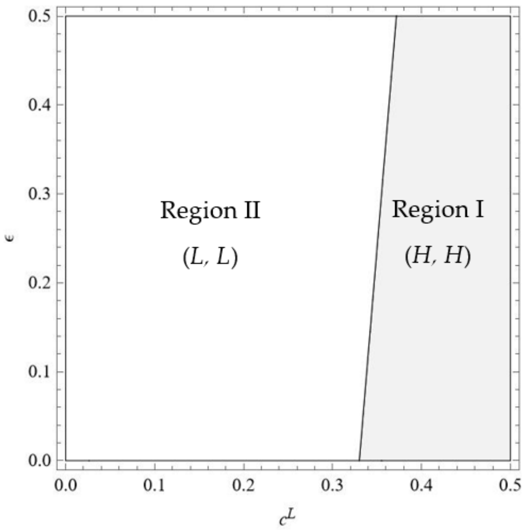

Figure 12. The equilibrium of the green strategy ($\alpha = 0.5$).

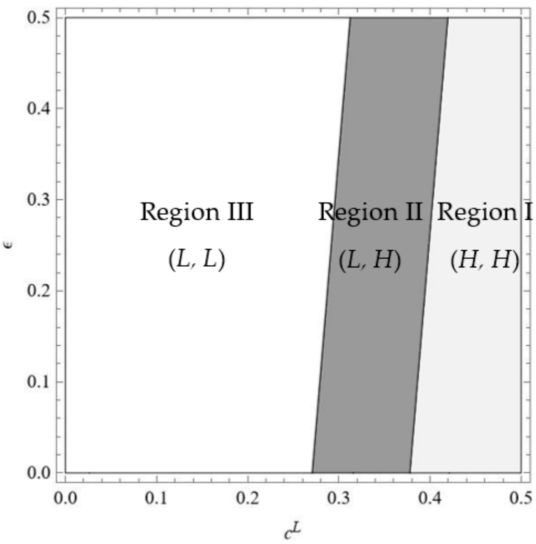

Figure 13. The equilibrium of the green strategy ($\alpha = 0.6$).

7. Extension

In the basic model, we assumed that the salvage value of strategy *L* assets is zero when a stringent policy is enforced in period 2. While this simplification is common in strategic game models under policy uncertainty, vessels rarely become completely worthless in maritime economics. They may be sold to secondary markets (e.g., routes with less stringent regulations) or scrapped for metal recycling. To examine the robustness of our findings, we now relax this assumption by introducing a salvage rate $\varphi \in [0,1)$, such that the recoverable value of the strategy *L* asset is φF^L when a stringent policy materializes. Consequently, the net upgrade cost from strategy *L* to strategy *H* under a stringent policy becomes $F^H - \varphi F^L$ instead of F^H in the basic case. When $\varphi = 0$, our model reduces to the original formulation.

To examine how the residual value rate affects the strategic equilibrium, we revisit the utility differences that determine the carriers' strategic choices. We illustrate this difference using a numerical example that employs the same basic parameters as in Section 6. Figures 14 and 15 compare the differences in the equilibrium region when the market share is symmetric and asymmetric, respectively, as the residual value of strategy *L* changes from 0 to 0.3. Intuitively, a higher residual value makes strategy *L* more attractive ex ante, as carriers can recoup part of their initial investment even if strict regulations come into force. Consequently, the equilibrium region where both carriers choose strategy H shrinks, whilst the equilibrium region where both choose strategy *L* expands. When market shares are asymmetric, a higher residual value also expands the differentiated equilibrium regions (*L*, *H*) or (*H*, *L*), as the smaller carrier can utilize the residual value as a "safety net" to adopt a low-cut strategy without bearing the full downside risk of asset stranding.

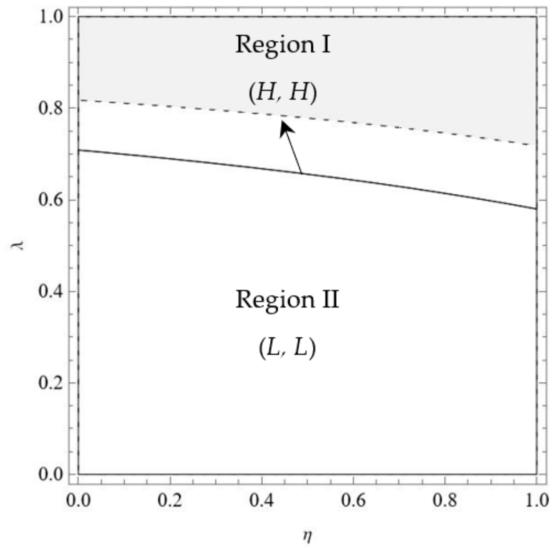

Figure 14. Equilibrium changes when φ increases from 0 to 0.2 ($\alpha = 0.5$).

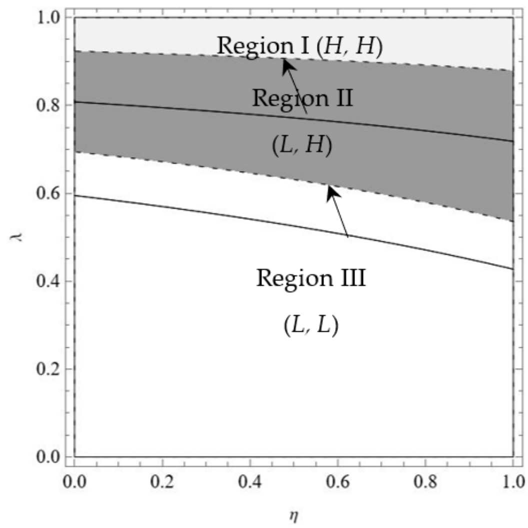

Figure 15. Equilibrium changes when φ increases from 0 to 0.2 ($\alpha = 0.6$).

By relaxing the assumption that the net residual value of stranded assets is zero, we find that the results are essentially consistent with the baseline model, namely that policy uncertainty, cost volatility, market share, and risk aversion collectively determine the choice of green strategy. Furthermore, when designing stringent regulations, policymakers should take into account the second-hand market value of vessels, as a higher residual value may delay shipping companies' voluntary transition to zero-emission technologies.

8. Conclusions

This study contributes to the sustainability transition of the maritime industry by focusing on shipping carriers' green strategy choices under dual uncertainty risks. Dual uncertainty risks are the stringency of future carbon emission reduction policies and the operation cost volatility associated with high-emission reduction strategies (strategy *H*). Strategy *H* achieves significant emission reductions but carries technology- or supply-related cost risks (e.g., green methanol-fueled vessels, carbon capture devices). Strategy *L* offers moderate abatement with no such risks (e.g., LNG-fueled vessels). Using a game-theoretic model, the key findings of our research are as follows:

Firstly, some counterintuitive results are derived. In a deterministic environment, a high-cost strategy directly translates into a high price. However, under a lenient policy, adopting strategy *H* does not always lead to a higher price than adopting strategy *L*. Pricing is determined by a combination of market share advantages, differences in operation costs, the cost of carbon emissions, and the negative effect of carbon emissions on demand. Consequently, the carrier adopting strategy *H* does not necessarily set a higher price than the competitor who adopts strategy *L*. These findings challenge conventional wisdom and highlight the need for carriers to carefully evaluate their competitive position when pursuing sustainability goals.

Secondly, there is a "Masking effect" of the probability of a stringent policy. When the probability of a stringent policy is low, both carriers tend to choose the low-cost, risk-free strategy *L* to avoid uncertainty-driven losses. In this case, cost volatility risks of strategy *H* are "masked": concerns about policy risk dominate over technological cost fluctuations, leading to a wait-and-see, conservative approach. Only when the probability of a stringent policy exceeds a certain threshold do the cost characteristics of strategy *H* enter the decision-making scope. From a sustainability perspective, this masking effect implies that weak or ambiguous policy signals can inadvertently lock the industry into a low-ambition equilibrium, delaying the sustainability transition and increasing the long-term costs of decarbonization.

Thirdly, the degree of cost volatility associated with strategy *H* is fundamental. When volatility is low, both carriers may opt for strategy *H*, forming an ideal (*H*, *H*) strategic equilibrium. When volatility is extremely high, both are forced to choose strategy *L*. Under asymmetric market shares and moderate volatility, a differentiated equilibrium emerges: the carrier with a higher market share prefers the lower-risk strategy *L* to maintain stable returns, while the lower-share carrier may adopt strategy *H* to seek competitive advantage. This reveals a "band effect" of cost risk. Finally, carriers' risk-averse attitudes have a decisive influence on strategic choices within a specific range. When the increase in unit operation cost associated with strategy *H* is extreme (either very high or very low), risk attitudes have no significant impact on the strategic equilibrium because economic rationality far outweighs subjective risk preferences. However, when the cost increase is moderate, carriers' risk-averse attitudes become a key determinant: carriers with a lower degree of risk aversion are more willing to adopt strategy *H* to pursue long-term gains, while those with a higher degree of risk aversion tend to opt conservatively for strategy *L*. An increase in the industry's overall risk tolerance helps to reduce competitive pricing in the green shipping market, which is advantageous for shippers. Moreover, the risk-averse behavior of carriers adopting strategy *H* also significantly affects the freight rates of their competitors who adopt strategy *L*.

To motivate most carriers to adopt high-emission reduction green strategies and accelerate the green transformation of the shipping industry, we provide the following important insights for relevant managers based on the above analyses:

For carriers, the probability of stringent policies and future cost uncertainty of strategy *H* should be considered in green transitions. When the probability is high, carriers should choose strategy *H* in period 1 to avoid double investment costs, even if operation cost risks exist. When the probability is low, carriers can choose according to their risk attitude. Proactive green strategy selection enhances long-term competitiveness and contributes to the broader sustainability agenda by reducing the industry's carbon footprint.

For policymakers, sufficient subsidies for high-abatement green strategies could be provided to help reduce investment costs or unit operation cost, making the (*H*, *H*) equilibrium more attainable. In addition, policymakers may also consider phased policy announcements or risk-sharing mechanisms such as guaranteed minimum carbon prices

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or technology transition funds to reduce perceived policy uncertainty, especially when the probability of a stringent policy is still low.

Based on the research findings and theoretical contributions of this paper, future research could be further deepened and expanded in the following directions. Dynamic game models could incorporate technological evolution (learning effects, cost curves, technological lock-in). Firm heterogeneity (scale, financing capacity, ownership structure) could also be introduced to examine differentiated responses to policy interventions.

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Appendix A

Appendix A.1. The Expressions of Parameters in Proposition 5

$$R_1 = \frac{\left[M_A - c^H(2-\beta-\beta^2)\right]^2}{(4-\beta^2)^2} + \frac{\delta\left[M_B - c^H(2-\beta-\beta^2) - 2\varepsilon(1-\eta_A) + \beta\varepsilon(1+\beta-\beta\eta_A-\eta_B)\right]^2}{(4-\beta^2)^2}$$

$$R_2 = \frac{1}{(4-\beta^2)^2}\delta\Big\{\left[M_A - (c^L+er)(2-\beta^2) - 2e\gamma + \beta(c^H+\varepsilon-\varepsilon\eta_B)\right]^2(1-\lambda) + \Big[M_A - c^H$$

$$(2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B) - 2(1-\eta_A))\Big]^2\lambda\Big\} + \frac{\left[c^H\beta + M_A - c^L(2-\beta^2) - 2e\gamma\right]^2}{(4-\beta^2)^2}$$

$$R_3 = \frac{1}{(4-\beta^2)^2}\Big\{\delta\left[M_A + \beta(c^L+er-e\gamma) - (2-\beta^2)(c^H+\varepsilon-\varepsilon\eta_A)\right]^2(1-\lambda) + \delta\Big[M_B - c^H$$

$$(2-\beta-\beta^2) - 2\varepsilon(1-\eta_A) + \beta\varepsilon(1+\beta-\beta\eta_A-\eta_B)\Big]^2\lambda\Big\} + \frac{\left[M_A - c^H(2-\beta^2) + \beta(c^L-e\gamma)\right]^2}{(4-\beta^2)^2}$$

$$R_4 = \frac{1}{(4-\beta^2)^2}\delta\Big\{\left[M_A - c^L(2-\beta-\beta^2) - e(2+\beta)(r(1-\beta)+\gamma)\right]^2(1-\lambda) + \Big[M_A - c^H$$

$$(2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B) - 2(1-\eta_A))\Big]^2\lambda\Big\} + \frac{\left[M_A - c^L(2-\beta-\beta^2) - (2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}$$

$$R_5 = \frac{\left[M_B - c^H(2-\beta-\beta^2)\right]^2}{(4-\beta^2)^2} + \frac{\delta\left[M_B - c^H(2-\beta-\beta^2) - 2\varepsilon(1-\eta_B) + \beta\varepsilon(1+\beta-\eta_A-\beta\eta_B)\right]^2}{(4-\beta^2)^2}$$

$$R_6 = \frac{1}{(4-\beta^2)^2}\Big\{\delta\left[M_B - (c^L+er)(2-\beta^2) - 2e\gamma + \beta(c^H+\varepsilon-\varepsilon\eta_A)\right]^2(1-\lambda) + \delta\Big[M_B - c^H$$

$$(2-\beta-\beta^2) - 2\varepsilon(1-\eta_B) + \beta\varepsilon(1+\beta-\eta_A-\beta\eta_B)\Big]^2\lambda\Big\} + \frac{\left[M_B - c^L(2-\beta^2) + c^H\beta - 2e\gamma\right]^2}{(4-\beta^2)^2}$$

$$R_7 = \frac{1}{(4-\beta^2)^2}\delta\Big\{\Big[M_B + \beta(c^L + er - e\gamma) - (2-\beta^2)(c^H + \varepsilon - \varepsilon\eta_B)\Big]^2(1-\lambda) + \Big[M_B - c^H (2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B) - 2(1-\eta_B))\Big]^2\lambda\Big\} + \frac{\Big[M_B - c^H(2-\beta^2) + \beta(c^L - e\gamma)\Big]^2}{(4-\beta^2)^2}$$

$$R_8 = \frac{1}{(4-\beta^2)^2}\delta\Big\{\Big[M_B - c^L(2-\beta-\beta^2) - e(2+\beta)(r(1-\beta)+\gamma)\Big]^2(1-\lambda) + \Big[M_B - c^H (2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B) - 2(1-\eta_B))\Big]^2\lambda\Big\} + \frac{\Big[M_B - c^L(2-\beta-\beta^2) - (2+\beta)e\gamma\Big]^2}{(4-\beta^2)^2}$$

where $M_A = m(2\alpha+\beta-\alpha\beta)$; $M_B = m(2-2\alpha+\alpha\beta)$.

Appendix A.2. Proof of Proposition 1

Firstly, we analyze period 2. Since carriers A and B adopt strategy H in period 2 and there is uncertainty regarding the unit operation cost of strategy H, we analyze the CVaR for carriers A and B.

Let $G_A^{HH}(v) = v + \frac{1}{\eta}\mathrm{E}[\min\{(p_{A2}-\xi)q_{A2}^{HH} - v, 0\}]$. Since it is assumed that ξ is uniformly distributed between $[c^H-\varepsilon, c^H+\varepsilon]$, i.e., the probability density is $1/2\varepsilon$, therefore,

$$G_A^{HH}(v) = v + \frac{1}{\eta}\int_{p_{A2}-v/q_{A2}^{HH}}^{c^H+\varepsilon}[(p_{A2}-\xi)q_{A2}^{HH} - v]\frac{1}{2\varepsilon}d\xi \tag{A1}$$

Then, $\mathrm{CVaR}_A^{HH}(\eta_A) = \max_v \mathrm{G}_A^{HH}(v)$. The first-order condition on v for Equation (A1) can be obtained as follows:

$$\frac{\partial G_A^{HH}(v)}{\partial v} = -\frac{v + q_{A2}^{HH}(c^H - p_{A2} + \varepsilon - 2\varepsilon\eta)}{2q_{A2}^{HH}\varepsilon\eta} \tag{A2}$$

In addition, the second-order condition on v for Equation (A1) is $\frac{\partial^2 G_A^{HH}(v)}{\partial v^2} = -\frac{1}{2q_{A2}^{HH}\varepsilon\eta} < 0$. Setting Equation (A2) to zero, we obtain

$$\bar{v} = -q_{A2}^{HH}(c^H - p_{A2} + \varepsilon - 2\varepsilon\eta) \tag{A3}$$

According to Equation (A1) and Equation (A3), we can derive

$$\mathrm{CVaR}_{A2}^{HH} = [p_{A2} - c^H - \varepsilon(1-\eta_A)]q_{A2}^{HH} \tag{A4}$$

Similarly, the CVaR value for carrier B can be calculated as follows:

$$\mathrm{CVaR}_{B2}^{HH} = [p_{B2} - c^H - \varepsilon(1-\eta_B)]q_{B2}^{HH} \tag{A5}$$

Substituting the demand functions into Equations (A4) and (A5), respectively, and deriving the first-order conditions for p_{A2} and p_{B2}, respectively, we obtain

$$\frac{d\mathrm{CVaR}_{A2}^{HH}}{dp_{A2}} = \alpha m + \beta p_{B2} - 2p_{A2} + c^H + \varepsilon(1-\eta_A) \tag{A6}$$

$$\frac{d\mathrm{CVaR}_{B2}^{HH}}{dp_{B2}} = (1-\alpha)m + \beta p_{A2} - 2p_{B2} + c^H + \varepsilon(1-\eta_B) \tag{A7}$$

Subject to the second-order conditions $\frac{d^2\mathrm{CVaR}_{A2}^{HH}}{dp_{A2}^2} = \frac{d^2\mathrm{CVaR}_{B2}^{HH}}{dp_{B2}^2} = -2 < 0$, this implies that CVaR_{A2}^{HH} and CVaR_{B2}^{HH} are concave functions. Setting Equations (A6) and (A7) to zero and solving the system of equations yields the equilibrium price as

$$p_{A2}^{HH*}=\frac{m(2\alpha+\beta-\alpha\beta)+c^{H}(2+\beta)+\varepsilon(2+\beta-2\eta_{A}-\beta\eta_{B})}{4-\beta^{2}}$$

$$p_{B2}^{HH*}=\frac{m(2-2\alpha+\alpha\beta)+c^{H}(2+\beta)+\varepsilon(2+\beta-\beta\eta_{A}-2\eta_{B})}{4-\beta^{2}}$$

Next, we calculate the equilibrium solution for period 1. The decisions and profits in period 2 do not affect the equilibrium price and profit in period 1. Therefore, the objective of carriers A and B in period 1 is to maximize profit. Solving the first-order conditions for π_{A1}^{HH} and π_{B1}^{HH}, respectively, yields

$$\frac{d\pi_{A1}^{HH}}{dp_{A1}}=\alpha m-2p_{A1}+\beta p_{B1}+c^{H} \tag{A8}$$

$$\frac{d\pi_{B1}^{HH}}{dp_{B1}}=\left(1-\alpha\right)m+\beta p_{A1}-2p_{B1}+c^{H} \tag{A9}$$

According to second-order conditions $\frac{d^{2}\pi_{A1}^{HH}}{dp_{A1}^{2}}=\frac{d^{2}\pi_{B1}^{HH}}{dp_{B1}^{2}}=-2<0$, it implies that π_{A1}^{HH} and π_{B1}^{HH} are concave functions with respect to p_{A1} and p_{B1}.

Setting Equations (A8) and (A9) to zero and solving the system of equations yields an equilibrium price of

$$p_{A1}^{HH*}=\frac{(2\alpha+\beta-\alpha\beta)m+c^{H}(2+\beta)}{4-\beta^{2}}$$

$$p_{B1}^{HH*}=\frac{(2-2\alpha+\alpha\beta)m-c^{H}(2+\beta)}{4-\beta^{2}}$$

Finally, the total utility for carrier A and B is

$$U_{A}^{HH*}=\frac{\delta\left[m(2\alpha-\alpha\beta+\beta)-c^{H}(2-\beta-\beta^{2})-2\varepsilon(1-\eta_{A})+\beta\varepsilon(1+\beta-\beta\eta_{A}-\eta_{B})\right]^{2}}{(4-\beta^{2})^{2}}$$
$$+\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^{H}(2-\beta-\beta^{2})\right]^{2}}{(4-\beta^{2})^{2}}-F^{H}$$

$$U_{B}^{HH*}=\frac{\delta\left[m(2-2\alpha+\alpha\beta)-c^{H}(2-\beta-\beta^{2})-2\varepsilon(1-\eta_{B})+\beta\varepsilon(1+\beta-\eta_{A}-\beta\eta_{B})\right]^{2}}{(4-\beta^{2})^{2}}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^{H}(2-\beta-\beta^{2})\right]^{2}}{(4-\beta^{2})^{2}}-F^{H}$$

□

Appendix A.3. Proof of Proposition 2

Firstly, we will analyze period 2. Since period 2 involves the introduction of new emission reduction policies, we categorize these into stringent and lenient policies. We therefore analyze each of these separately below.

(i) When carbon emission reduction policies are strict, carrier A must purchase new green methanol fueled vessels (i.e., adopt strategy *H*). As in the scenario (*H*, *H*), the CVaR functions for carriers A and B can be expressed as

$$\text{CVaR}_{A2}^{LH1}=[p_{A2}-c^{H}-\varepsilon(1-\eta_{A})]q_{A2}^{LH1} \tag{A10}$$

$$\text{CVaR}_{B2}^{LH1}=[p_{B2}-c^{H}-\varepsilon(1-\eta_{B})]q_{B2}^{LH1} \tag{A11}$$

Substituting the demand functions into Equations (A10) and (A11), respectively, and deriving the first-order conditions for p_{A2} and p_{B2}, respectively, we obtain

$$\frac{d\text{CVaR}_{A2}^{LH1}}{dp_{A2}} = \alpha m - 2p_{A2} + \beta p_{B2} + c^H + \varepsilon\left(1-\eta_A\right) \tag{A12}$$

$$\frac{d\text{CVaR}_{B2}^{LH1}}{dp_{B2}} = \left(1-\alpha\right)m + \beta p_{A2} - 2p_{B2} + c^H + \varepsilon\left(1-\eta_B\right) \tag{A13}$$

Based on the second-order conditions $\frac{d^2\text{CVaR}_{A2}^{LH1}}{dp_{A2}^2} = \frac{d^2\text{CVaR}_{B2}^{LH1}}{dp_{B2}^2} = -2 < 0$, this implies that CVaR_{A2}^{LH1} and CVaR_{B2}^{LH1} are concave functions. Setting Equations (A12) and (A13) to zero and solving the system of equations yields the equilibrium price as

$$p_{A2}^{LH1*} = \frac{m(2\alpha+\beta-\alpha\beta) + c^H(2+\beta) + \varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$$

$$p_{B2}^{LH1*} = \frac{m(2-2\alpha+\alpha\beta) + c^H(2+\beta) + \varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$$

At this point, the CVaR values for the two carriers are

$$\text{CVaR}_{A2}^{LH1*} = \frac{\left[m\left(2\alpha-\alpha\beta+\beta\right) - c^H\left(2-\beta-\beta^2\right) - 2\varepsilon(1-\eta_A) + \beta\varepsilon(1+\beta-\beta\eta_A-\eta_B)\right]^2}{\left(4-\beta^2\right)^2}$$

$$\text{CVaR}_{B2}^{LH1*} = \frac{\left[m(2-2\alpha+\alpha\beta) - c^H\left(2-\beta-\beta^2\right) - 2\varepsilon(1-\eta_B) + \beta\varepsilon(1+\beta-\eta_A-\beta\eta_B)\right]^2}{\left(4-\beta^2\right)^2}$$

(ii) When carbon emission reduction policies are lenient, carrier A can maintain its original strategy *L*. Similarly, carrier B's CVaR remains unchanged, whilst carrier A's CVaR is equal to its profit, that is,

$$\pi_{A2}^{LH2} = \left(p_{A2} - c^L - re\right)q_{A2}^{LH2} \tag{A14}$$

Carrier B's CVaR is

$$\text{CVaR}_{B2}^{LH2} = [p_{B2} - c^H - \varepsilon(1-\eta_B)]q_{B2}^{LH2} \tag{A15}$$

Substituting the demand functions into Equations (A14) and (A15), respectively, and deriving the first-order conditions for p_{A2} and p_{B2}, respectively, we obtain

$$\frac{d\pi_{A2}^{LH2}}{dp_{A2}} = m\alpha - 2p_{A2} + \beta p_{B2} + c^L + e\left(r-\gamma\right) \tag{A16}$$

$$\frac{d\text{CVaR}_{B2}^{LH2}}{dp_{B2}} = \left(1-\alpha\right)m + \beta p_{A2} - 2p_{B2} + c^H + \varepsilon\left(1-\eta_B\right) \tag{A17}$$

Based on the second-order conditions $\frac{d^2\pi_{A2}^{LH2}}{dp_{A2}^2} = \frac{d^2\text{CVaR}_{B2}^{LH2}}{dp_{B2}^2} = -2 < 0$, this implies that π_{A2}^{LH2} and CVaR_{B2}^{LH2} are concave functions. Setting Equations (A16) and (A17) to zero and solving the system of equations yields the equilibrium price as

$$p_{A2}^{LH2*} = \frac{m(2\alpha+\beta-\alpha\beta) + 2\left[c^L + e(r-\gamma)\right] + \beta(c^H + \varepsilon - \varepsilon\eta_B)}{4-\beta^2}$$

$$p_{B2}^{LH2*} = \frac{m(2-2\alpha+\alpha\beta) + \beta\left[c^L + e(r-\gamma)\right] + 2(c^H + \varepsilon - \varepsilon\eta_B)}{4-\beta^2}$$

At this point, the CVaR values for the two carriers are

$$\pi_{A2}^{LH2*} = \frac{\left[m(2\alpha+\beta-\alpha\beta) - (c^L+er)(2-\beta^2) - 2e\gamma + \beta(c^H+\varepsilon-\varepsilon\eta_B)\right]^2}{(4-\beta^2)^2}$$

$$\text{CVaR}_{B2}^{LH2*} = \frac{\left[m(2-2\alpha+\alpha\beta) + \beta(c^L+er-e\gamma) - (2-\beta^2)(c^H+\varepsilon-\varepsilon\eta_B)\right]^2}{(4-\beta^2)^2}$$

Next, we calculate the equilibrium solution for period 1. The decisions and profits in period 2 do not affect the equilibrium price and profit in period 1. Therefore, the objective of carriers A and B in period 1 is to maximize profit. By solving the first-order conditions for π_{A1}^{LH} and π_{B1}^{LH} in terms of p_{A1} and p_{B1}, respectively, we obtain

$$\frac{d\pi_{A1}^{LH}}{dp_{A1}} = m\alpha - 2p_{A1} + \beta p_{B1} + c^L - e\gamma \tag{A18}$$

$$\frac{d\pi_{B1}^{LH}}{dp_{B1}} = m(1-\alpha) + \beta p_{A1} - 2p_{B1} + c^H \tag{A19}$$

From the second-order condition $\frac{d^2\pi_{A1}^{LH}}{dp_{A1}^2} = \frac{d^2\pi_{B1}^{LH}}{dp_{B1}^2} = -2 < 0$, it follows that π_{A1}^{LH} and π_{B1}^{LH} are concave functions of p_{A1} and p_{B1}.

Setting Equations (A18) and (A19) to zero, the system of equations yields an equilibrium price of

$$p_{A1}^{LH*} = \frac{m(2\alpha+\beta-\alpha\beta)+\beta c^H + 2(c^L - e\gamma)}{4-\beta^2}$$

$$p_{B1}^{LH*} = \frac{m(2-2\alpha+\alpha\beta)+2c^H + \beta(c^L - e\gamma)}{4-\beta^2}$$

At this point, the utility of carriers A and B is

$$\pi_{A1}^{LH*} = \frac{\left[m(2\alpha+\beta-\alpha\beta) - c^L(2-\beta^2) + \beta c^H - 2e\gamma\right]^2}{(4-\beta^2)^2}$$

$$\pi_{B1}^{LH*} = \frac{\left[m(2-2\alpha+\alpha\beta) - c^H(2-\beta^2) + \beta(c^L - e\gamma)\right]^2}{(4-\beta^2)^2}$$

Assuming the discount factor is δ, the sums of the utilities for carriers A and B in the two periods are, respectively,

$$U_A^{LH*} = \Big\{\left[m(2\alpha+\beta-\alpha\beta) - (c^L + er)(2-\beta^2) - 2e\gamma + \beta(c^H + \varepsilon - \varepsilon\eta_B)\right]^2 (1-\lambda) + \big[m (2\alpha+\beta-\alpha\beta) - c^H(2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B) - 2(1-\eta_A))\big]^2 \lambda\Big\}\frac{1}{(4-\beta^2)^2}\delta + \frac{\left[c^H\beta + m(2\alpha+\beta-\alpha\beta) - c^L(2-\beta^2) - 2e\gamma\right]^2}{(4-\beta^2)^2} - F^H\delta\lambda - F^L$$

$$U_B^{LH*} = \Big\{\left[m(2-2\alpha+\alpha\beta) + \beta(c^L + er - e\gamma) - (2-\beta^2)(c^H + \varepsilon - \varepsilon\eta_B)\right]^2 (1-\lambda) + \big[m (2-2\alpha+\alpha\beta) - c^H(2-\beta-\beta^2) + \varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B) - 2(1-\eta_B))\big]^2 \lambda\Big\}\frac{1}{(4-\beta^2)^2}\delta + \frac{\left[m(2-2\alpha+\alpha\beta) - c^H(2-\beta^2) + \beta(c^L - e\gamma)\right]^2}{(4-\beta^2)^2} - F^H$$

□

Appendix A.4. Proof of Proposition 3

Since the scenario (*H*, *L*) is similar to the scenario (*L*, *H*), we omit its equilibrium proof to save space. Therefore, we present only the equilibrium results.

(i) When policies are strict, the equilibrium outcome is as follows:

$$p_{A2}^{HL1*} = \frac{m(2\alpha-\beta-\alpha\beta) + c^H(2+\beta) + \varepsilon(2+\beta-2\eta_A-\beta\eta_B)}{4-\beta^2}$$

$$p_{B2}^{HL1*} = \frac{m(2-2\alpha+\alpha\beta) + c^H(2+\beta) + \varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$$

$$\text{CVaR}_{A2}^{HL1*}=\frac{\left\{m(2\alpha+\beta-\alpha\beta)-c^{H}(2-\beta-\beta^{2})+\varepsilon\left[\beta(1+\beta-\beta\eta_{A}-\eta_{B})-2(1-\eta_{A})\right]\right\}^{2}}{(4-\beta^{2})^{2}}$$

$$\text{CVaR}_{B2}^{HL1*}=\frac{\left\{m(2-2\alpha+\alpha\beta)-c^{H}(2-\beta-\beta^{2})+\varepsilon\left[\beta(1+\beta-\eta_{A}-\beta\eta_{B})-2(1-\eta_{B})\right]\right\}^{2}}{(4-\beta^{2})^{2}}$$

(ii) When the policies are lenient, the equilibrium outcome is as follows:

$$p_{A2}^{HL2*}=\frac{m(2\alpha+\beta-\alpha\beta)+\beta\left[c^{L}+e(r-\gamma)\right]+2(c^{H}+\varepsilon-\varepsilon\eta_{A})}{4-\beta^{2}}$$

$$p_{B2}^{HL2*}=\frac{m(2-2\alpha+\alpha\beta)+2\left[c^{L}+e(r-\gamma)\right]+\beta(c^{H}+\varepsilon-\varepsilon\eta_{A})}{4-\beta^{2}}$$

$$\text{CVaR}_{A2}^{HL2*}=\frac{\left\{m(2\alpha+\beta-\alpha\beta)+\beta\left[c^{L}+e(r-\gamma)\right]-(2-\beta^{2})(c^{H}+\varepsilon-\varepsilon\eta_{A})\right\}^{2}}{(4-\beta^{2})^{2}}$$

$$\pi_{B2}^{HL2*}=\frac{\left[m(2-2\alpha+\alpha\beta)-(2-\beta^{2})(c^{L}+er)-2e\gamma+\beta(c^{H}+\varepsilon-\varepsilon\eta_{A})\right]^{2}}{(4-\beta^{2})^{2}}$$

(iii) The equilibrium outcome for period 1 is as follows:

$$p_{A1}^{HL*}=\frac{m(2\alpha+\beta-\alpha\beta)+2c^{H}+\beta(c^{L}-e\gamma)}{4-\beta^{2}}$$

$$p_{B1}^{HL*}=\frac{m(2-2\alpha+\alpha\beta)+\beta c^{H}+2(c^{L}-e\gamma)}{4-\beta^{2}}$$

$$\pi_{A1}^{HL*}=\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^{H}(2-\beta^{2})+c^{L}\beta-\beta e\gamma\right]^{2}}{(4-\beta^{2})^{2}}$$

$$\pi_{B1}^{HL*}=\frac{\left[m(2-2\alpha+\alpha\beta)-c^{L}(2-\beta^{2})+c^{H}\beta-2e\gamma\right]^{2}}{(4-\beta^{2})^{2}}$$

The final total utility is as follows:

$$U_{A}^{HL*}=\Big\{\left[m(2\alpha+\beta-\alpha\beta)+\beta(c^{L}+er-e\gamma)-(2-\beta^{2})(c^{H}+\varepsilon-\varepsilon\eta_{A})\right]^{2}(1-\lambda)+\Big[m$$
$$(2\alpha-\alpha\beta+\beta)-c^{H}(2-\beta-\beta^{2})-2\varepsilon(1-\eta_{A})+\beta\varepsilon(1+\beta-\beta\eta_{A}-\eta_{B})\Big]^{2}\lambda\Big\}\frac{\delta}{(4-\beta^{2})^{2}}+$$
$$\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^{H}(2-\beta^{2})+\beta(c^{L}-e\gamma)\right]^{2}}{(4-\beta^{2})^{2}}-F^{H}$$

$$U_{B}^{HL*}=\Big\{\left[m(2-2\alpha+\alpha\beta)-(c^{L}+er)(2-\beta^{2})-2e\gamma+\beta(c^{H}+\varepsilon-\varepsilon\eta_{A})\right]^{2}(1-\lambda)+\Big[m$$
$$(2-2\alpha+\alpha\beta)-c^{H}(2-\beta-\beta^{2})-2\varepsilon(1-\eta_{B})+\beta\varepsilon(1+\beta-\eta_{A}-\beta\eta_{B})\Big]^{2}\lambda\Big\}\frac{\delta}{(4-\beta^{2})^{2}}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^{L}(2-\beta^{2})+c^{H}\beta-2e\gamma\right]^{2}}{(4-\beta^{2})^{2}}-F^{H}\delta\lambda-F^{L}$$

□

Appendix A.5. Proof of Proposition 4

In order to save space, we omit the proof of the equilibrium and present only the equilibrium results.

(i) When the policies are strict, the equilibrium outcome is as follows:

$$p_{A2}^{LL1*}=\frac{m(2\alpha+\beta-\alpha\beta)+c^{H}(2+\beta)+\varepsilon(2+\beta-2\eta_{A}-\beta\eta_{B})}{4-\beta^{2}}$$

$$p_{B2}^{LL1*} = \frac{m(2-2\alpha+\alpha\beta)+c^H(2+\beta)+\varepsilon(2+\beta-\beta\eta_A-2\eta_B)}{4-\beta^2}$$

$$\mathrm{CVaR}_{A2}^{LL1*} = \frac{\left\{m(2\alpha+\beta-\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon\left[\beta(1+\beta-\beta\eta_A-\eta_B)-2(1-\eta_A)\right]\right\}^2}{(4-\beta^2)^2}$$

$$\mathrm{CVaR}_{B2}^{LL1*} = \frac{\left\{m(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon\left[\beta(1+\beta-\eta_A-\beta\eta_B)-2(1-\eta_B)\right]\right\}^2}{(4-\beta^2)^2}$$

(ii) When the policies are lenient, the equilibrium outcome is as follows:

$$p_{A2}^{LL2*} = \frac{m(2\alpha+\beta-\alpha\beta)+c^L(2+\beta)+e(2+\beta)(r-\gamma)}{4-\beta^2}$$

$$p_{B2}^{LL2*} = \frac{m(2-2\alpha+\alpha\beta)+c^L(2+\beta)+e(2+\beta)(r-\gamma)}{4-\beta^2}$$

$$\pi_{A2}^{LL2*} = \frac{\left\{m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)\left[r(1-\beta)+\gamma\right]\right\}^2}{(4-\beta^2)^2}$$

$$\pi_{B2}^{LL2*} = \frac{\left\{m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)\left[r(1-\beta)+\gamma\right]\right\}^2}{(4-\beta^2)^2}$$

(iii) The equilibrium outcome for period 1 is as follows:

$$p_{A1}^{LL*} = \frac{m(2\alpha+\beta-\alpha\beta)+(c^L-e\gamma)(2+\beta)}{4-\beta^2}$$

$$p_{B1}^{LL*} = \frac{m(2-2\alpha+\alpha\beta)+(c^L-e\gamma)(2+\beta)}{4-\beta^2}$$

$$\pi_{A1}^{LL*} = \frac{\left[m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}$$

$$\pi_{B1}^{LL*} = \frac{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}$$

The final total utility is as follows:

$$U_A^{LL*} = \Big\{\left[m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)(r(1-\beta)+\gamma)\right]^2(1-\lambda)+\big[m$$
$$(2\alpha+\beta-\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B)-2(1-\eta_A))\big]^2\lambda\Big\}\frac{\delta}{(4-\beta^2)^2}$$
$$+\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}-F^H\delta\lambda-F^L$$

$$U_B^{LL*} = \Big\{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)(r(1-\beta)+\gamma)\right]^2(1-\lambda)+\big[m$$
$$(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B)-2(1-\eta_B))\big]^2\lambda\Big\}\frac{\delta}{(4-\beta^2)^2}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}-F^H\delta\lambda-F^L$$

□

Appendix A.6. Proof of Corollary 1

The first-order conditions of the equilibrium prices with respect to η, ε, and γ are obtained as follows:

(i) In scenario (*H*, *H*), $\frac{\mathrm{d}p_{A2}^{HH*}}{\mathrm{d}\eta}=\frac{\mathrm{d}p_{B2}^{HH*}}{\mathrm{d}\eta}=-\frac{(2+\beta)\varepsilon}{4-\beta^2}<0$. In scenario (*H*, *L*) or (*L*, *H*), $\frac{\mathrm{d}p_{A2}^{HL1*}}{\mathrm{d}\eta}=\frac{\mathrm{d}p_{B2}^{HL1*}}{\mathrm{d}\eta}=-\frac{(2+\beta)\varepsilon}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{HL2*}}{\mathrm{d}\eta}=-\frac{2\varepsilon}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B2}^{HL2*}}{\mathrm{d}\eta}=-\frac{\beta\varepsilon}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{LH1*}}{\mathrm{d}\eta}=\frac{\mathrm{d}p_{B2}^{LH1*}}{\mathrm{d}\eta}=-\frac{(2+\beta)\varepsilon}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{LH2*}}{\mathrm{d}\eta}=-\frac{\varepsilon\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B2}^{LH2*}}{\mathrm{d}\eta}=-\frac{2\varepsilon}{4-\beta^2}<0$. In scenario (*L*, *L*), $\frac{\mathrm{d}p_{A2}^{LL1*}}{\mathrm{d}\eta}=\frac{\mathrm{d}p_{B2}^{LL1*}}{\mathrm{d}\eta}=-\frac{(2+\beta)\varepsilon}{4-\beta^2}<0$.

(ii) In scenario (*H*, *H*), $\frac{\mathrm{d}p_{A2}^{HH*}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}p_{B2}^{HH*}}{\mathrm{d}\varepsilon}=\frac{1-\eta}{2-\beta}>0$. In scenario (*H*, *L*) or (*L*, *H*), $\frac{\mathrm{d}p_{A2}^{HL1*}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}p_{B2}^{HL1*}}{\mathrm{d}\varepsilon}=\frac{1-\eta}{2-\beta}>0$, $\frac{\mathrm{d}p_{A2}^{HL2*}}{\mathrm{d}\varepsilon}=\frac{2(1-\eta)}{4-\beta^2}>0$, $\frac{\mathrm{d}p_{B2}^{HL2*}}{\mathrm{d}\varepsilon}=\frac{\beta(1-\eta)}{4-\beta^2}>0$, $\frac{\mathrm{d}p_{A2}^{LH1*}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}p_{B2}^{LH1*}}{\mathrm{d}\varepsilon}=\frac{1-\eta}{2-\beta}>0$, $\frac{\mathrm{d}p_{A2}^{LH2*}}{\mathrm{d}\varepsilon}=\frac{\beta(1-\eta)}{4-\beta^2}>0$, $\frac{\mathrm{d}p_{B2}^{LH2*}}{\mathrm{d}\varepsilon}=\frac{2(1-\eta)}{4-\beta^2}>0$. In scenario (*L*, *L*), $\frac{\mathrm{d}p_{A2}^{LL1*}}{\mathrm{d}\varepsilon}=\frac{\mathrm{d}p_{B2}^{LL1*}}{\mathrm{d}\varepsilon}=\frac{1-\eta}{2-\beta}>0$.

(iii) In scenario (*H*, *H*), $\frac{\mathrm{d}p_{A2}^{HH*}}{\mathrm{d}\gamma}=\frac{\mathrm{d}p_{B2}^{HH*}}{\mathrm{d}\gamma}=0$. In scenario (*H*, *L*) or (*L*, *H*), $\frac{\mathrm{d}p_{A1}^{HL*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B1}^{HL*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{HL2*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B2}^{HL2*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A1}^{LH*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B1}^{LH*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{LH2*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{B2}^{LH2*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$. In scenario (*L*, *L*), $\frac{\mathrm{d}p_{A1}^{LL*}}{\mathrm{d}\gamma}=\frac{\mathrm{d}p_{B1}^{LL*}}{\mathrm{d}\gamma}=-\frac{e(2+\beta)}{4-\beta^2}<0$, $\frac{\mathrm{d}p_{A2}^{LL2*}}{\mathrm{d}\gamma}=\frac{\mathrm{d}p_{B2}^{LL2*}}{\mathrm{d}\gamma}=-\frac{e(2+\beta)}{4-\beta^2}<0$.

□

Appendix A.7. Proof of Corollary 2

(i) In period 1, assuming competitors' strategies remain unchanged, the difference between the equilibrium price when the carrier adopts strategy *H* and the equilibrium price when it adopts strategy *L* is as follows:

$$p_{A1}^{HH*}-p_{A1}^{LH*}=p_{A1}^{HL*}-p_{A1}^{LL*}=p_{B1}^{HH*}-p_{B1}^{HL*}=p_{B1}^{LH*}-p_{B1}^{LL*}=\frac{2\left(\mathrm{c}^H-\mathrm{c}^L+e\gamma\right)}{4-\beta^2}>0$$

(ii) In period 2, given that the policies are stringent and competitors' strategies remain unchanged, the carrier must adopt strategy *H*, at which point there is no price differential.

(iii) In period 2, assuming that the policies are lenient and competitors' strategies remain unchanged, the relationship between the equilibrium price for carrier adopting strategy *H* and the equilibrium price for carrier adopting strategy *L* is as follows:

$$p_{A2}^{HH*}-p_{A2}^{LH2*}=p_{A2}^{HL2*}-p_{A2}^{LL2*}=p_{B2}^{HH*}-p_{B2}^{HL2*}=p_{B2}^{LH2*}-p_{B2}^{LL2*}=\frac{2\left(\mathrm{c}^H-\mathrm{c}^L-er+e\gamma+\varepsilon-\varepsilon\eta\right)}{4-\beta^2}$$

Let $f_1(\eta)=\frac{2\left(\mathrm{c}^H-\mathrm{c}^L-er+e\gamma+\varepsilon-\varepsilon\eta\right)}{4-\beta^2}$. Then, because of $\varepsilon>0$, $\beta<1$, and $\frac{\mathrm{d}f_2(\eta)}{\mathrm{d}\eta}=-\frac{2\varepsilon}{4-\beta^2}<0$, $f_1(\eta)$ is monotonically decreasing in the interval. Setting $f_1(\eta)=0$ yields $\eta_1=\frac{\mathrm{c}^H-\mathrm{c}^L-er+e\gamma+\varepsilon}{\varepsilon}$. There are three scenarios:

When $\eta_1 < 0$, i.e., $\varepsilon < \varepsilon_1 = -(c^H - c^L - er + e\gamma)$, since $f_1(\eta_1) = 0$ and $f_1(\eta)$ is strictly decreasing, then $f_1(\eta) < 0$ between the interval $\eta \in (0,1)$. Therefore, $p_{A2}^{HH*} < p_{A2}^{LH2*}$, $p_{A2}^{HL2*} < p_{A2}^{LL2*}$, $p_{B2}^{HH*} < p_{B2}^{HL2*}$, and $p_{B2}^{LH2*} < p_{B2}^{LL2*}$, i.e., $p_{A2}^{Hj2*} < p_{A2}^{Lj2*}$, $p_{B2}^{iH2*} < p_{B2}^{iL2*}$.

When $0 \le \eta_1 < 1$, i.e., $\varepsilon_1 \le \varepsilon$ and $c^H - c^L - er + e\gamma < 0$, since $f_1(\eta)$ is a monotonically decreasing function of η, $f_1(\eta)$ is positive on the interval $\eta \in (0,\eta_1)$. When $\eta < \eta_1$, i.e., $\varepsilon > \varepsilon_2 = -\dfrac{c^H - c^L - er + e\gamma}{1-\eta}$, then $p_{A2}^{HH*} > p_{A2}^{LH2*}$, $p_{A2}^{HL2*} > p_{A2}^{LL2*}$, $p_{B2}^{HH*} > p_{B2}^{HL2*}$, and $p_{B2}^{LH2*} > p_{B2}^{LL2*}$, i.e., $p_{A2}^{Hj2*} > p_{A2}^{Lj2*}$, $p_{B2}^{iH2*} > p_{B2}^{iL2*}$. $f_1(\eta)$ is negative within the interval $\eta \in (\eta_1, 1)$. When $\eta > \eta_1$, i.e., $\varepsilon < \varepsilon_2 = -\dfrac{c^H - c^L - er + e\gamma}{1-\eta}$, then $p_{A2}^{HH*} < p_{A2}^{LH2*}$, $p_{A2}^{HL2*} < p_{A2}^{LL2*}$, $p_{B2}^{HH*} < p_{B2}^{HL2*}$, and $p_{B2}^{LH2*} < p_{B2}^{LL2*}$, i.e., $p_{A2}^{Hj2*} < p_{A2}^{Lj2*}$, $p_{B2}^{iH2*} < p_{B2}^{iL2*}$.

Note that since $\varepsilon > 0$ and $0 < \eta < 1$, we have $1 - \eta > 0$. Furthermore, we obtain $\varepsilon_1 < \varepsilon_2$. In summary, when $c^H - c^L - er + e\gamma < 0$ and $\varepsilon \ge \varepsilon_2$, we have $p_{A2}^{Hj2*} > p_{A2}^{Lj2*}$ and $p_{B2}^{iH2*} > p_{B2}^{iL2*}$; when $c^H - c^L - er + e\gamma < 0$ and $\varepsilon_1 \le \varepsilon < \varepsilon_2$, we have $p_{A2}^{Hj*} < p_{A2}^{Lj2*}$ and $p_{B2}^{iH*} < p_{B2}^{iL2*}$.

When $\eta_1 > 1$, i.e., $c^H - c^L - er + e\gamma > 0$, since $f_1(\eta)$ is monotonically decreasing of η, it holds that $f_1(\eta) > 0$ within the interval $\eta \in (0,1)$. Therefore, $p_{A2}^{Hj2*} > p_{A2}^{Lj2*}$ and $p_{B2}^{iH2*} > p_{B2}^{iL2*}$.

□

Appendix A.8. Proof of Corollary 3

The proof is similar to that in Appendix A.6, and it is omitted here to save space. □

Appendix A.9. Proof of Corollary 4

(i) In scenario (*H*, *H*), $\dfrac{dq_{A2}^{HH*}}{d\eta} = \dfrac{dq_{B2}^{HH*}}{d\eta} = \dfrac{(2-\beta(1+\beta))\varepsilon}{4-\beta^2} > 0$. In scenario (*H*, *L*) or (*L*, *H*), $\dfrac{dq_{A2}^{HL1*}}{d\eta} = \dfrac{dq_{B2}^{HL1*}}{d\eta} = \dfrac{(2-\beta(1+\beta))\varepsilon}{4-\beta^2} > 0$, $\dfrac{dq_{A2}^{HL2*}}{d\eta} = \dfrac{(2-\beta^2)\varepsilon}{4-\beta^2} > 0$, $\dfrac{dq_{B2}^{HL2*}}{d\eta} = -\dfrac{\beta\varepsilon}{4-\beta^2} < 0$, $\dfrac{dq_{A2}^{LH1*}}{d\eta} = \dfrac{dq_{B2}^{LH1*}}{d\eta} = \dfrac{(2-\beta(1+\beta))\varepsilon}{4-\beta^2} > 0$, $\dfrac{dq_{A2}^{LH2*}}{d\eta} = -\dfrac{\varepsilon\beta}{4-\beta^2} < 0$, $\dfrac{dq_{B2}^{LH2*}}{d\eta} = \dfrac{(2-\beta^2)\varepsilon}{4-\beta^2} > 0$. In scenario (*L*, *L*), $\dfrac{dq_{A2}^{LL1*}}{d\eta} = \dfrac{dq_{B2}^{LL1*}}{d\eta} = \dfrac{(2-\beta(1+\beta))\varepsilon}{4-\beta^2} > 0$.

(ii) In scenario (*H*, *H*), $\dfrac{dq_{A2}^{HH*}}{d\varepsilon} = \dfrac{dq_{B2}^{HH*}}{d\varepsilon} = -\dfrac{(1-\beta)(1-\eta)}{2-\beta} < 0$. In scenario (*H*, *L*) or (*L*, *H*), $\dfrac{dq_{A2}^{HL1*}}{d\varepsilon} = \dfrac{dq_{B2}^{HL1*}}{d\varepsilon} = -\dfrac{(1-\beta)(1-\eta)}{2-\beta} < 0$, $\dfrac{dq_{A2}^{HL2*}}{d\varepsilon} = -\dfrac{(2-\beta^2)(1-\eta)}{4-\beta^2} < 0$, $\dfrac{dq_{B2}^{HL2*}}{d\varepsilon} = \dfrac{\beta(1-\eta)}{4-\beta^2} > 0$, $\dfrac{dq_{A2}^{LH1*}}{d\varepsilon} = \dfrac{dq_{B2}^{LH1*}}{d\varepsilon} = -\dfrac{(1-\beta)(1-\eta)}{2-\beta} < 0$, $\dfrac{dq_{A2}^{LH2*}}{d\varepsilon} = \dfrac{\beta(1-\eta)}{4-\beta^2} > 0$, $\dfrac{dq_{B2}^{LH2*}}{d\varepsilon} = -\dfrac{(2-\beta^2)(1-\eta)}{4-\beta^2} < 0$. In scenario (*L*, *L*), $\dfrac{dq_{A2}^{LL1*}}{d\varepsilon} = \dfrac{dq_{B2}^{LL1*}}{d\varepsilon} = -\dfrac{(1-\beta)(1-\eta)}{2-\beta} < 0$.

(iii) In scenario *(H, L)* or *(L, H)*, $\frac{\mathrm{d}q_{A1}^{HL*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}q_{B1}^{HL*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$; $\frac{\mathrm{d}q_{A2}^{HL2*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}q_{B2}^{HL2*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$, $\frac{\mathrm{d}q_{A1}^{LH*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$; $\frac{\mathrm{d}q_{B1}^{LH*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$, $\frac{\mathrm{d}q_{A2}^{LH2*}}{\mathrm{d}\gamma}=-\frac{2e}{4-\beta^2}<0$; $\frac{\mathrm{d}q_{B2}^{LH2*}}{\mathrm{d}\gamma}=-\frac{e\beta}{4-\beta^2}<0$. In scenario (*L*, *L*), $\frac{\mathrm{d}q_{A1}^{LL*}}{\mathrm{d}\gamma}=\frac{\mathrm{d}q_{B1}^{LL*}}{\mathrm{d}\gamma}=-\frac{e(2+\beta)}{4-\beta^2}<0$, $\frac{\mathrm{d}q_{A2}^{LL2*}}{\mathrm{d}\gamma}=\frac{\mathrm{d}q_{B2}^{LL2*}}{\mathrm{d}\gamma}=-\frac{e(2+\beta)}{4-\beta^2}<0$. □

Appendix A.10. Proof of Proposition 5

(i) When carrier B chooses strategy *H*.

If $U_A^{HH*}>U_A^{LH*}$, carrier A chooses strategy *H*; otherwise, they will choose strategy *L*. Then, we can determine a threshold and the following conditions.

When carrier B chooses strategy *H* and if $F^L-F^H(1-\delta\lambda)>R_2-R_1$, carrier A chooses strategy *H*; otherwise, strategy *L* is chosen, where

$$R_1=\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^H(2-\beta-\beta^2)\right]^2}{(4-\beta^2)^2}+\frac{\delta\left[m(2\alpha-\alpha\beta+\beta)-c^H(2-\beta-\beta^2)-2\varepsilon(1-\eta_A)+\beta\varepsilon(1+\beta-\beta\eta_A-\eta_B)\right]^2}{(4-\beta^2)^2}$$

$$R_2=\left\{\left[m(2\alpha+\beta-\alpha\beta)-(c^L+er)(2-\beta^2)-2e\gamma+\beta(c^H+\varepsilon-\varepsilon\eta_B)\right]^2(1-\lambda)+\left[m(2\alpha+\beta-\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B)-2(1-\eta_A))\right]^2\lambda\right\}\frac{\delta}{(4-\beta^2)^2}+\frac{\left[c^H\beta+m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta^2)-2e\gamma\right]^2}{(4-\beta^2)^2}$$

(ii) When carrier B chooses strategy *L*.

If $U_A^{HL*}>U_A^{LL*}$, carrier A chooses strategy *H*; otherwise, strategy *L* is chosen. Then we can determine a threshold and the following conditions.

When carrier B decides to adopt strategy *L* and if $F^L-F^H(1-\delta\lambda)>R_4-R_3$, carrier A chooses strategy *H*; otherwise, strategy *L* is chosen, where

$$R_3=\left\{\left[m(2\alpha+\beta-\alpha\beta)+\beta(c^L+er-e\gamma)-(2-\beta^2)(c^H+\varepsilon-\varepsilon\eta_A)\right]^2(1-\lambda)+\left[m(2\alpha-\alpha\beta+\beta)-c^H(2-\beta-\beta^2)-2\varepsilon(1-\eta_A)+\beta\varepsilon(1+\beta-\beta\eta_A-\eta_B)\right]^2\lambda\right\}\frac{\delta}{(4-\beta^2)^2}+\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^H(2-\beta^2)+\beta(c^L-e\gamma)\right]^2}{(4-\beta^2)^2}$$

$$R_4=\left\{\left[m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)(r(1-\beta)+\gamma)\right]^2(1-\lambda)+\left[m(2\alpha+\beta-\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\beta\eta_A-\eta_B)-2(1-\eta_A))\right]^2\lambda\right\}\frac{\delta}{(4-\beta^2)^2}+\frac{\left[m(2\alpha+\beta-\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}$$

(iii) When carrier A chooses strategy *H*.

Similarly, when carrier A chooses strategy *H* and if $F^L-F^H(1-\delta\lambda)>R_6-R_5$, carrier B chooses strategy *H*; otherwise, strategy *L* is chosen, where

$$R_5=\frac{\left[m(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)\right]^2}{(4-\beta^2)^2}+$$
$$\frac{\delta\left[m(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)-2\varepsilon(1-\eta_B)+\beta\varepsilon(1+\beta-\eta_A-\beta\eta_B)\right]^2}{(4-\beta^2)^2}$$

$$R_6=\Big\{\left[m(2-2\alpha+\alpha\beta)-(c^L+er)(2-\beta^2)-2e\gamma+\beta(c^H+\varepsilon-\varepsilon\eta_A)\right]^2(1-\lambda)+\big[m$$
$$(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)-2\varepsilon(1-\eta_B)+\beta\varepsilon(1+\beta-\eta_A-\beta\eta_B)\big]^2\lambda\Big\}\frac{\delta}{(4-\beta^2)^2}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta^2)+c^H\beta-2e\gamma\right]^2}{(4-\beta^2)^2}$$

(iv) When carrier A chooses strategy *L*.

Similarly, when carrier A decides to adopt strategy *L* and if $F^L-F^H(1-\delta\lambda)>R_8-R_7$, carrier B chooses strategy *H*; otherwise, strategy *L* is chosen, where

$$R_7=\Big\{\left[m(2-2\alpha+\alpha\beta)+\beta(c^L+er-e\gamma)-(2-\beta^2)(c^H+\varepsilon-\varepsilon\eta_B)\right]^2(1-\lambda)+\big[m$$
$$(2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B)-2(1-\eta_B))\big]^2\lambda\Big\}\frac{\delta}{(4-\beta^2)^2}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^H(2-\beta^2)+\beta(c^L-e\gamma)\right]^2}{(4-\beta^2)^2}$$

$$R_8=\Big\{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-e(2+\beta)(r(1-\beta)+\gamma)\right]^2(1-\lambda)+\big[m$$
$$2-2\alpha+\alpha\beta)-c^H(2-\beta-\beta^2)+\varepsilon(\beta(1+\beta-\eta_A-\beta\eta_B)-2(1-\eta_B))\big]^2\lambda\Big\}\frac{\delta}{(4-\beta^2)^2}$$
$$+\frac{\left[m(2-2\alpha+\alpha\beta)-c^L(2-\beta-\beta^2)-(2+\beta)e\gamma\right]^2}{(4-\beta^2)^2}$$

The following are concluded from the comparison of subgames:

Given that carrier B adopts strategy *H*, carrier A chooses strategy *H* if and only if $F^L-F^H(1-\delta\lambda)>R_2-R_1$; given that carrier A adopts strategy *H*, carrier B chooses strategy *H* if and only if $F^L-F^H(1-\delta\lambda)>R_6-R_5$. Then, the optimal strategy combination is (*H*, *H*) when $F^L-F^H(1-\delta\lambda)>\max\{R_2-R_1,R_6-R_5\}$.

Given that carrier B chooses strategy *L*, carrier A chooses strategy *H* if and only if $F^L-F^H(1-\delta\lambda)>R_4-R_3$; given that carrier A adopts strategy *H*, carrier B chooses strategy *L* if and only if $F^L-F^H(1-\delta\lambda)<R_6-R_5$. Then, when $F^L-F^H(1-\delta\lambda)>R_4-R_3$ and $F^L-F^H(1-\delta\lambda)<R_6-R_5$, the optimal strategy combination is (*H*, *L*).

Given that carrier B adopts strategy *H*, if and only if $F^L-F^H(1-\delta\lambda)<R_2-R_1$, carrier A chooses strategy *L*; given that carrier A adopts strategy *L*, if and only if $F^L-F^H(1-\delta\lambda)>R_8-R_7$, carrier B chooses strategy *H*. Then, when $F^L-F^H(1-\delta\lambda)<R_2-R_1$ and $F^L-F^H(1-\delta\lambda)>R_8-R_7$, the optimal strategy combination is (*L*, *H*).

Given that carrier B adopts strategy *L*, carrier A chooses strategy *L* if and only if $F^L-F^H(1-\delta\lambda)<R_4-R_3$; given that carrier A adopts strategy *L*, carrier B chooses strategy *L* if and only if $F^L-F^H(1-\delta\lambda)<R_8-R_7$. Then, the optimal strategy combination is (*L*, *L*) when $F^L-F^H(1-\delta\lambda)<\min\{R_4-R_3,R_8-R_7\}$. □

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