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*Research Article*

# Will Port Integration Help Reduce Carbon Emissions and Improve Social Welfare?

**Zhuoqi Teng**,[1] **Xiaoli Li**,[1] **Yuantao Fang**,[2] **and Hailing Fu**[3]

[1]*College of Business Administration, Henan Finance University, Zhengzhou 451464, China*
[2]*College of Finance, Shanghai Lixin University of Accounting and Finance, Shanghai 201209, China*
[3]*College of Applied Science and Technology, Hainan University, Haikou 570228, China*

Correspondence should be addressed to Yuantao Fang; 20190060@lixin.edu.cn and Hailing Fu; fuhailing@hainanu.edu.cn

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In the context of competition between two ports in Cournot, we studied optimal decision-making processes for the government and the port in four different situations before and after the integration of the port based on the subsidy and carbon tax mechanism. We analyzed the impacts of the carbon tax rate and emission reduction subsidy rate on social welfare and determined the optimal carbon tax rate, the optimal emission reduction subsidy rate, the optimal carbon emission level, and the optimal social welfare level in different situations. We also compared the optimal social welfare level and the optimal carbon emission level of the four situations before and after the integration. This research can be used as a policy reference for the government for the formation of environmental policies based on the goal of maximizing social welfare, and it could also be used for the port's internal decision-making when the environmental policy has been set.

## 1. Introduction

With the rapid growth of China's foreign trade, the shipping industry has made considerable progress. According to China's "Statistical Bulletin on the Development of the Transportation Industry in 2019," in 2019, national ports had a cargo throughput of 13.951 billion tons, an increase of 5.7% year on year. Coastal ports had a throughput of 9.188 billion tons, an increase of 4.3%, and inland ports had a throughput of 47.63 Billion tons, an increase of 9.0%, which is still a relatively high growth rate. Thus, there has been a trend for rapid port development. As an indispensable type of infrastructure in economic development, ports can drive the economic development of a region [1–4]. With rapid economic development, pollution problems caused by carbon emissions from ports have gradually become prominent. At the same time, in order to cope with wasted port resources and increase the competitiveness of ports, port integration has become a key concern in the field of port operation and management in China [5–7]. Port integration refers to the creation of a good and open port development environment and the establishment of effective coordination mechanisms to partially improve the constraints of administrative barriers and market barriers, so that their respective advantages and functions are fully utilized, forming a system with reasonable division of labor, complementary advantages, healthy competition, common development, mutual benefit, and win-win situation. And also, the development process of continuous optimization of port resource allocation, continuous improvement of port operation mechanism, continuous enhancement of port comprehensive capacity, and effective utilization could be realized [5]. Since 2015, the integration of ports in many provinces in my country has been intensified. In 2015, Tianjin Port (Group) Co., Ltd., and Hebei Port Group Co., Ltd., signed a framework cooperation agreement; Zhejiang Seaport Investment Operation Group Co., Ltd., was established; and Ningbo-Zhoushan Port, Wenzhou Port, Taizhou Port, and other ports realized integration and unified operation. In 2016, Tianjin Port Group and Tangshan Port Group jointly funded the establishment of Tangshan Container Terminal Co., Ltd.; Hainan Provincial People's Government issued the "Hainan Provincial

Port Resources Integration Plan," proposing to focus on integrating the "four directions and five ports" to build five major sectors. In 2017, Jiangsu Port Group Co., Ltd., was established and included eight state-owned port enterprises in the province. In addition, Liaoning, Hubei, Anhui, and other provinces have also vigorously promoted the integration of port resources in the region, and the scale and scope of port resource integration have continued to expand. This article focuses on whether the integration of ports can help to increase the overall social welfare and reduce carbon emissions.

With the increase in global environmental problems, low-carbon environmental protection has become a mainstream element of social development, and having a low-carbon supply chain is considered a critical direction for sustainable development [8–11]. Both governments and enterprises have attempted to increase green production and the low-carbon supply [12–15]. Many developed countries are gradually transitioning to a low-carbon economy through practical actions [16, 17]. For example, the United Kingdom has implemented a number of carbon emission reduction policies, such as the emission trading mechanism and the climate change tax, and Japan levies environmental taxes for the combustion of petrochemicals such as oil. Scholars' research on the carbon emission supply chain has mostly emerged from governmental policies, which are generally divided into carbon tax policies, carbon quota trading systems, or combinations of multiple policies [18–22]. However, the objects of these studies are limited to ordinary manufacturing companies, and ports are not considered objects of study.

Some scholars have used ports as their research objects and studied issues related to port integration and port environmental issues. Using Liaoning Port as the research object, Wu and Yang explored the influence of port integration. An integration and cooperation scheme, which may be used to achieve systematic optimization of a shipping pattern, has also been proposed [23]. From the perspective of the supply chain, Han explored the impacts of port supply chain integration on port performance [24]. Berechman et al. studied the causes of port environmental problems and explored the factors that affect port environmental problems [25]. Xiao et al. established a model of overall environmental planning and concluded that, overall, environmental planning is conducive to enhancing the competitiveness of a port [26]. Liao et al. used the Taipei container port as an example to establish a model for evaluating the carbon emissions of container ports and found that optimizing the inland container transportation route can reduce carbon emissions [27]. Yu-Chung and Thuy Linh researched Seaport-dry port network design considering multimodal transport and carbon emissions [28]. Some scholars have also considered port privatization and port carbon emissions by analyzing the degree of port privatization and the impacts of port cooperation and competition on the profits and social welfare of port enterprises [29–31].

Although many scholars have conducted separate studies on port integration, port carbon emissions, and carbon tax policies, few scholars have considered the three in combination. Due to the unique characteristics of ports, the research results of the combination of ordinary enterprises and national carbon tax policies cannot be directly applied to port enterprises. Therefore, the use of ports as the research has a certain level of research significance. The innovativeness of this paper is embodied by three aspects. Firstly, considering the unique characteristics of ports, this article investigates both port carbon emissions and national carbon tax policies to fill the gaps left by previous studies. Secondly, this article analyzes how port companies and governments make decisions under four different environmental policies (including situations where there are no environmental policies) and comprehensively considers the different decision-making results that may arise under different environmental policies. Finally, this paper combines port integration with port carbon emissions and social welfare to explore whether port integration can help to improve social welfare and reduce port carbon emissions. The research results of this paper provide a policy reference that can be used by the government to formulate environmental policies to maximize social welfare as well as for the internal decision-making of a port when the environmental policy has been set.

## 2. Model Assumptions

In order to explore the impact of port integration on the decision-making of port companies and governments under different carbon policies, this paper assumes that two port companies are competing in Cournot in the same regional oligopoly market [32, 33]. The two ports are represented by the subscripts. Table 1 shows the symbols used in this paper.

Among customers (consumers) who use port A and port B, the classic consumer utility function [34] can be expressed as

$$U = \alpha q_A + \alpha q_B - \frac{1}{2}\left(q_A^2 + q_B^2 + 2\beta q_A q_B\right). \tag{1}$$

Therefore, the consumer surplus function can be expressed as

$$\mathrm{CS} = U - \theta_A q_A - \theta_B q_B. \tag{2}$$

In order to get the price as a function of demand, using equation (2) to find the respective partial derivatives and make them equal to 0, we can obtain

$$\begin{aligned} \theta_A &= \alpha - q_A - \beta q_B, \\ \theta_B &= \alpha - q_B - \beta q_A. \end{aligned} \tag{3}$$

According to the nature of port enterprise services, the full-service prices of the two ports are

$$\theta_i = p_i + t\frac{q_i}{s_i}, \quad i = A, B. \tag{4}$$

$t(q_i/s_i)$ $(i = A, B)$ represents the waiting time cost of the goods at the port or the time cost of the customer [35].

By combining equations (3) and (4), we get the inverse demand function:

Table 1: Key notations.

| Symbol | Explanation |
|---|---|
| $i$ | Port $i$, $i = A, B$ |
| $j$ | Situation $j$, $j = \text{I, II, III, IV}$ |
| $\alpha(>0)$ | Maximum scheduled service price |
| $\beta(\in(0,1))$ | The fungibility of services of the two ports (The larger the value of $\beta$, the stronger the fungibility of the service) |
| $s_i(>0)$ | The design capacity of the terminal of port $i$ (unit million containers), that is, the service capacity of port $i$ |
| $t$ | Cost parameters of the waiting time of the goods at the terminal |
| $a_i$ | Reduced carbon emissions from port $i$ |
| $p_i$ | Service price of port $i$ |
| $q_i$ | Container handling capacity of port $i$ |
| $\theta_i$ | Full price for port i's services $i$ |
| $x(\geq 0)$ | Carbon tax |
| $c$ | Marginal operating cost of the port |
| $\delta(\in[0,1])$ | Emission reduction subsidy rate ($\delta$ larger means greater subsidy) |

$$p_A = \alpha - q_A - \beta q_B - t\frac{q_A}{s_A},$$
$$p_B = \alpha - q_B - \beta q_A - t\frac{q_B}{s_B}. \tag{5}$$

By substituting formula (5) into formula (2), the consumer surplus function can be reproduced as

$$\text{CS}(q_A, q_B) = \frac{1}{2}\left(q_A^2 + q_B^2 + 2\beta q_A q_B\right). \tag{6}$$

In the context of the Cournot competition between the two port companies, this paper studies optimal decision-making by the government and port companies under different environmental policies before and after the integration (including nonenvironmental policies). For the environmental policies, the optimal social welfare and optimal carbon emission levels are compared before and after integration.

## 3. Port Competition and Environmental Policies before Integration

In order to explore the balanced decision-making of the government and port companies in different situations, this section considers port competition, emission reduction measures, government carbon tax, and subsidy policies under four different situations prior to port integration. The details of the four situations are as follows:

Situation I: port companies do not need to pay carbon emissions taxes and do not take any emission reduction measures.

Situation II: the government levies a carbon emission tax on port companies at a rate of $x$, and port companies do not make any emission reduction measures.

Situation III: the government levies a carbon emission tax on port companies at a rate of $x$, and port companies make certain emission reduction measures, the reduction in emissions is $a_i$, and the cost of the emission reductions is $(a_i^2/2)$ [36–38].

Situation IV: the government levies a carbon emission tax on port companies at a rate of $x$, and the port company adopts certain emission reduction measures. The reduction in emissions is $a_i$, the cost of the emission reduction is $(a_i^2/2)$, and the government grants port companies emission reduction subsidies at a subsidy rate of $\delta(\in[0,1])$.

For convenience, the superscripts "I," "II," "III," and "IV" are used below to represent the above four situations, and the superscript "*" is used to represent the equilibrium solution.

*3.1. No Carbon Tax, No Emission Reduction (Situation I).* In Situation I, the government does not implement carbon tax and emission reduction subsidy policies, and the port does not adopt any emission reduction measures. We assume that the carbon emission function is

$$\text{ED}^{\text{I}} = \frac{1}{2}\left(q_A^{\text{I}} + q_B^{\text{I}}\right)^2. \tag{7}$$

The level of carbon emissions can reflect the degree of environmental pollution caused by business operations to a certain extent. Most studies in the related body of literature express carbon emissions as a nonlinear function [39, 40] and a few use a linear function [41]. This paper uses the former.

The profit function of port enterprises is

$$R_i^{\text{I}} = \left(p_i^{\text{I}} - c\right)q_i^{\text{I}}, \quad i = A, B. \tag{8}$$

For convenience, many studies set the marginal costs of the two port companies to be equal [16], and this article follows this assumption. Social welfare refers to all measures taken by members of society to improve their material and cultural life and is a good state of life for members of society [42]. Thus, the social welfare function can be expressed as

$$W^{\text{I}} = \text{CS}^{\text{I}} + R_A^{\text{I}} + R_B^{\text{I}} - \text{ED}^{\text{I}}. \tag{9}$$

Two port companies make decisions at the same time: $\max_{q_A^{\text{I}}} R_A^{\text{I}}$ and $\max_{q_B^{\text{I}}} R_B^{\text{I}}$. According to the first-order optimal condition $((\partial R_A^{\text{I}}/\partial q_A^{\text{I}}) = (\partial R_B^{\text{I}}/\partial q_B^{\text{I}}) = 0)$, we can obtain

$$q_A^{\mathrm{I}^*}=\frac{(c-\alpha)(-2s_B-2t+\beta s_B)s_A}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2s_As_B},$$
$$q_B^{\mathrm{I}^*}=\frac{(c-\alpha)(-2s_A-2t+\beta s_A)s_B}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2s_As_B}. \quad (10)$$

For all optimal solutions obtained in the model in this paper, the second-order conditions were proven to be true. Due to limitations on the length of the article, we do not repeat them. By substituting formula (10) into formulas (7) and (9), we can obtain the optimal carbon emission level and the optimal social welfare level:

$$\mathrm{ED}^{\mathrm{I}^*}=\frac{2(c-\alpha)^2(-2s_As_B-s_At-ts_B+\beta s_As_B)^2}{\left(-4s_As_B-4s_At-4ts_B-4t^2+\beta^2s_As_B\right)^2},$$
$$W^{\mathrm{I}^*}=\frac{(c-\alpha)^2\left[4t^2\left(s_At+s_Bt+s_A^2+s_B^2\right)-4s_As_Bt^2(\beta-3)-\left(s_Bs_A^2t+s_As_B^2t\right)\left(\beta^2+2\beta-8\right)+\left(4-3\beta^2+\beta^3\right)s_A^2s_B^2\right]}{\left(-4s_As_B-4s_At-4ts_B-4t^2+\beta^2s_As_B\right)^2}. \quad (11)$$

*3.2. With Carbon Tax, No Emission Reduction (Situation II).* In Situation II, the government imposes a carbon tax on port companies, but port companies still do not take measures to reduce emissions. The carbon emissions function is

$$\mathrm{ED}^{\mathrm{II}}=\frac{1}{2}\left(q_A^{\mathrm{II}}+q_B^{\mathrm{II}}\right)^2. \quad (12)$$

The government's carbon tax revenue function [31] is

$$T^{\mathrm{II}}=x^{\mathrm{II}}\left(q_A^{\mathrm{II}}+q_B^{\mathrm{II}}\right). \quad (13)$$

The profit function of port enterprises is

$$R_i^{\mathrm{II}}=\left(p_i^{\mathrm{II}}-c\right)q_i^{\mathrm{II}}-xq_i^{\mathrm{II}},\quad i=A,B. \quad (14)$$

Thus, the social welfare function can be expressed as

$$W^{\mathrm{II}}=\mathrm{CS}^{\mathrm{II}}+R_A^{\mathrm{II}}+R_B^{\mathrm{II}}+T^{\mathrm{II}}-\mathrm{ED}^{\mathrm{II}}. \quad (15)$$

The decision-making goal of the two port companies is to maximize profits, while the government's decision-making goal is to maximize social welfare. In Situation II, the decision sequence is as follows: in the first stage, the government determines the optimal carbon tax rate; in the second stage, the port company determines the optimal output. We can use the inverse solution method to solve the equation.

In the second stage, the two port companies make decisions at the same time: $\max_{q_A^{\mathrm{II}}}R_A^{\mathrm{II}}$, $\max_{q_B^{\mathrm{II}}}R_B^{\mathrm{II}}$. According to the first-order optimal condition $((\partial R_A^{\mathrm{II}}/\partial q_A^{\mathrm{II}})=(\partial R_B^{\mathrm{II}}/\partial q_B^{\mathrm{II}})=0)$, we can obtain

$$q_A^{\mathrm{II}}=\frac{(c-\alpha+x)(-2s_B-2t+\beta s_B)s_A}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2s_As_B},$$
$$q_B^{\mathrm{II}}=\frac{(c-\alpha+x)(-2s_A-2t+\beta s_A)s_B}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2s_As_B}. \quad (16)$$

By substituting formula (16) into formula (15), the social welfare function can be reproduced. In the first stage, in order to optimize social welfare, the government makes a decision: $\max_x W^{\mathrm{II}}$. According to the first-order optimal condition $((\partial W^{\mathrm{II}}/\partial x)=0)$, the optimal carbon tax rate can be obtained $x^{\mathrm{II}^*}=(N_1/M_1)$. For this,

$$M_1(>0)=4t^2\left(s_A^2+ts_A+s_B^2+ts_B\right)-\left(ts_As_B^2+ts_Bs_A^2\right)\left(\beta^2+6\beta-16\right)-4t^2s_As_B(\beta-5)+s_A^2s_B^2(\beta+3)(\beta-2)^2,$$
$$N_1(>0)=s_As_B(\alpha-c)(-2s_B+\beta s_B-2t)(\beta s_A-2s_A-2t). \quad (17)$$

After substituting $x^{\mathrm{II}^*}=(N_1/M_1)$ into equation (16) and then substituting the updated equation (16) into equations (12) and (15), the optimal carbon emissions and social welfare values can be obtained:

$$\mathrm{ED}^{\mathrm{II}^*}=\frac{2(c-\alpha)^2(-2s_As_B-s_At-ts_B+\beta s_As_B)^4}{M_1^2},$$
$$W^{\mathrm{II}^*}=\frac{(c-\alpha)^2(\beta s_As_B-2s_As_B-s_At-s_Bt)^2}{M_1}. \quad (18)$$

*3.3. Carbon Tax and Emission Reductions Are Implemented (Situation III).* In Situation III, the government implements a carbon tax policy, and the port adopts certain emission reduction measures. The carbon emission function is

$$\mathrm{ED}^{\mathrm{III}}=\frac{1}{2}\left(q_A^{\mathrm{III}}-a_A^{\mathrm{III}}+q_B^{\mathrm{III}}-a_B^{\mathrm{III}}\right)^2. \quad (19)$$

The government carbon tax revenue function is

$$T^{\mathrm{III}}=x\left(q_A^{\mathrm{III}}-a_A^{\mathrm{III}}+q_B^{\mathrm{III}}-a_B^{\mathrm{III}}\right). \quad (20)$$

The profit function of port enterprises is

$$R_i^{\mathrm{III}}=\left(p_i^{\mathrm{III}}-c\right)q_i^{\mathrm{III}}-x\left(q_i^{\mathrm{III}}-a_i^{\mathrm{III}}\right)-\frac{1}{2}\left(a_i^{\mathrm{III}}\right)^2,\quad i=A,B. \quad (21)$$

Thus, the social welfare function can be expressed as

$$W^{\mathrm{III}}=\mathrm{CS}^{\mathrm{III}}+R_A^{\mathrm{III}}+R_B^{\mathrm{III}}+T^{\mathrm{III}}-\mathrm{ED}^{\mathrm{III}}. \quad (22)$$

The decision-making goal of the two port enterprises is to maximize their profits, while the government's decision-making goal is to maximize social welfare. Compared with Situation II, port companies adopt emission reduction measures. In Situation III, the decision sequence is as follows: in the first stage, the government determines the carbon tax rate; in the second stage, the port company determines the optimal output and optimal reduction in emissions.

In the second stage, the two port companies make the following decisions at the same time: $\max_{q_A^{III}, a_A^{III}} R_A^{III}$ and $\max_{q_B^{III}, a_B^{III}} R_B^{III}$. According to the first-order optimal condition $((\partial R_A^{III}/\partial q_A^{III}) = (\partial R_B^{III}/\partial q_B^{III}) = 0$ and $(\partial R_A^{III}/\partial a_A^{III}) = (\partial R_B^{III}/\partial a_B^{III}) = 0)$, we can obtain

$$q_A^{III} = \frac{(c-\alpha+x)(-2s_B-2t+\beta s_B)s_A}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2 s_As_B},$$
$$q_B^{III} = \frac{(c-\alpha+x)(-2s_A-2t+\beta s_A)s_B}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2 s_As_B}, \tag{23}$$

$$a_A^{III} = a_B^{III} = x. \tag{24}$$

By substituting equations (23) and (24) into equation (22), we can reproduce the social welfare function. In the first stage, in order to optimize social welfare, the government makes a decision: $\max_x W^{III}$. According to the first-order optimal condition $((\partial W^{III}/\partial x) = 0)$, we can find the optimal carbon tax rate $x^{III^*} = (N_2/M_2)$. For this,

$$\begin{aligned}M_2(>0) &= 4t^2\left(12t^2+17s_A^2+29ts_A+17s_B^2+29ts_B\right)-\left(ts_A^2s_B+ts_B^2s_A\right)\left(22\beta+29\beta^2-160\right)\\&\quad -4s_As_Bt^2\left(6\beta^2+5\beta-69\right)+s_A^2s_B^2\left(3\beta^2+17\beta+23\right)(\beta-2)^2,\\ N_2(>0) &= (\alpha-c)\left[8t^2\left(ts_A+ts_B+s_A^2+s_B^2\right)-4s_As_Bt^2(2\beta-9)+s_A^2s_B^2(2\beta+5)(\beta-2)^2-2\left(ts_A^2s_B+ts_B^2s_A\right)\left(\beta^2+5\beta-14\right)\right].\end{aligned} \tag{25}$$

By substituting $x^{III^*} = (N_2/M_2)$ into equations (23) and (24) and then substituting the updated equations (23) and (24) into equations (19) and (22), the optimal carbon emissions level and optimal social welfare level can be determined:

$$\begin{aligned}\mathrm{ED}^{III^*} &= \frac{2(c-\alpha)^2\left[t^2\left(7s_A^2+7s_B^2+4ts_A+4ts_B\right)-\left(ts_A^2s_B+ts_As_B^2\right)(\beta+10)(\beta-2)+s_A^2s_B^2(\beta+4)(\beta-2)^2-2s_As_Bt^2(2\beta-9)\right]}{M_2^2},\\ W^{III^*} &= \frac{3(c-\alpha)^2\left[t^2\left(4ts_A+4ts_B+7s_A^2+7s_B^2\right)-\left(ts_A^2s_B+ts_B^2s_A\right)\left(\beta^2+8\beta-20\right)-2s_As_Bt^2(2\beta-9)+s_A^2s_B^2(\beta+4)(\beta-2)^2\right]}{M_2}.\end{aligned} \tag{26}$$

*3.4. Carbon Taxes, Emission Reductions, and Emission Reduction Subsidies Are Implemented (Situation IV).* To a certain extent, government subsidy policies can generate positive incentives for enterprises. Many scholars have involved government subsidies in their research [43]. In Situation IV, the company implements carbon tax and emission reduction subsidy policies, and the port also adopts certain emission reduction measures. At this time, the carbon emissions function is

$$\mathrm{ED}^{IV} = \frac{1}{2}\left(q_A^{IV}-a_A^{IV}+q_B^{IV}-a_B^{IV}\right)^2. \tag{27}$$

The government's carbon tax revenue function is

$$T^{IV} = x\left(q_A^{IV}-a_A^{IV}+q_B^{IV}-a_B^{IV}\right). \tag{28}$$

The profit function of port enterprises is

$$R_i^{IV} = \left(p_i^{IV}-c\right)q_i^{IV}-x\left(q_i^{IV}-a_i^{IV}\right)-\frac{(1-\delta)}{2}\left(a_i^{IV}\right)^2,\quad i=A,B. \tag{29}$$

Thus, the social welfare function can be expressed as

$$W^{IV} = \mathrm{CS}^{IV}+R_A^{IV}+R_B^{IV}+T^{IV}-\mathrm{ED}^{IV}-\frac{\delta}{2}\left[\left(a_A^{IV}\right)^2+\left(a_B^{IV}\right)^2\right]. \tag{30}$$

Compared with Situation III, Situation IV adds the government's emission reduction subsidies to those of port companies. In this situation, the decision sequence is as follows. In the first stage, the government decides the optimal carbon tax rate and emission reduction subsidy rate; in the second stage, the company determines the optimal output and reduction in carbon emissions.

In the second stage, the two port companies make decisions at the same time: $\max_{q_A^{IV}, a_A^{IV}} R_A^{IV}$ and $\max_{q_B^{IV}, a_B^{IV}} R_B^{IV}$. According to the first-order optimal condition $((\partial R_A^{IV}/\partial q_A^{IV}) = (\partial R_B^{IV}/\partial q_B^{IV}) = 0$ and $(\partial R_A^{IV}/\partial a_A^{IV}) = (\partial R_B^{IV}/\partial a_B^{IV}) = 0)$, we can obtain

$$\begin{aligned} q_A^{IV} &= \frac{(c-\alpha+x)(-2s_B-2t+\beta s_B)s_A}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2 s_As_B}, \\ q_B^{IV} &= \frac{(c-\alpha+x)(-2s_A-2t+\beta s_A)s_B}{4s_As_B+4s_At+4ts_B+4t^2-\beta^2 s_As_B}, \end{aligned} \tag{31}$$

$$a_A^{IV} = a_B^{IV} = \frac{x}{1-\delta}. \tag{32}$$

By substituting formulas (31) and (32) into (30), the social welfare function can be reproduced. In the first stage, in order to optimize social welfare, the government makes the following decisions: $\max_{\delta,x} W^{IV}$.

At this time, the optimal emission reduction subsidy rate and the optimal carbon tax rate can be obtained:

$$\delta^* = \frac{3\left[2t^2\left(s_A^2+s_B^2\right)+s_A^2s_B^2(\beta-2)^2-2s_As_Bt\left(s_A+s_B\right)(\beta-2)\right]}{2\left(\beta s_As_B-2s_As_B-ts_A-ts_B\right)^2}, \tag{33}$$

$$x^{IV*} = \frac{N_3}{M_3}. \tag{34}$$

For this,

$$\begin{aligned} M_3(>0) &= 4t^2\left(2s_A^2+2s_B^2+3ts_A+3ts_B\right)+s_A^2s_B^2(3\beta+5)(\beta-2)^2 \\ &\quad -\left(s_A^2ts_B+s_B^2ts_A\right)\left(3\beta^2+10\beta-32\right), \\ N_3(>0) &= 2(c-\alpha)\left[4t^2\left(s_A^2+s_B^2-s_As_B\right)+s_A^2s_B^2(\beta-2)^2-2\left(s_A^2ts_B+s_B^2ts_A\right)(\beta-2)\right]. \end{aligned} \tag{35}$$

By substituting equations (33) and (34) into equations (31) and (32) and then substituting the updated equations (31) and (32) into equations (27) and (30), we can obtain the optimal carbon emission level and the optimal level of social welfare:

$$\begin{aligned} \mathrm{ED}^{IV*} &= \frac{8(c-\alpha)^2\left(-2s_As_B-s_At-ts_B+\beta s_As_B\right)^4}{M_3^2}, \\ W^{IV*} &= \frac{3(c-\alpha)^2\left(\beta s_As_B-2s_As_B-s_At-s_Bt\right)^2}{M_3}. \end{aligned} \tag{36}$$

*3.5. Social Welfare and Carbon Emissions.* The above analysis shows that the optimal social welfare level and carbon emissions differ under different environmental policies. When analyzed from the perspective of the government, the government's decision-making is often based on optimizing overall social welfare or considering carbon emissions. Therefore, for these four different environmental policies, the decision-making process of the government can be analyzed by comparing social welfare and carbon emissions.

*3.5.1. Social Welfare Comparison.* By comparing the optimal social welfare conditions in the four situations, the following quantitative relationship can be obtained:

$$W^{I*} < W^{II*} < W^{III*} < W^{IV*}. \tag{37}$$

*Proof.*

$$\begin{aligned} W^{I*} - W^{II*} &= -\frac{(c-\alpha)^2 s_A^2 s_B^2\left(s_B\beta-2t-2s_B\right)^2\left(s_A\beta-2s_A-2t\right)^2}{\left(-4s_As_B-4s_At-4s_Bt-4t^2+\beta^2 s_As_B\right)^2 M_1} < 0, \\ W^{II*} - W^{III*} &= -\frac{(c-\alpha)^2 K}{M_1M_2}, \end{aligned} \tag{38}$$

among them,

$$\begin{aligned}
K &= K_1 + K_2 + \cdots + K_{13},\\
K_1 &= -12 s_B^4 s_A^3 t (\beta + 5)(\beta - 2)^3 > 0,\\
K_2 &= -12 s_A^4 s_B^3 t (\beta + 5)(\beta - 2)^3 > 0,\\
K_3 &= -4 s_A^4 s_B t^3 (\beta + 18)(\beta - 2) > 0,\\
K_4 &= -4 s_A s_B^4 t^3 (\beta + 18)(\beta - 2) > 0,\\
K_5 &= s_A^4 s_B^4 (4\beta + 13)(\beta - 2)^4 > 0,\\
K_6 &= -48 s_A^3 s_B t^4 (\beta - 4) > 0,\\
K_7 &= -48 s_B^3 s_A t^4 (\beta - 4) > 0,\\
K_8 &= -16 s_B^2 s_A^2 t^4 (6\beta - 19) > 0,\\
K_9 &= 4 s_B^2 s_A^3 t^3 (\beta - 2)(9\beta - 82) > 0,\\
K_{10} &= 4 s_A^2 s_B^3 t^3 (\beta - 2)(9\beta - 82) > 0,\\
K_{11} &= 8 s_A^3 s_B^3 t^2 (\beta + 30)(\beta - 2)^2 > 0,\\
K_{12} &= 4 s_A^4 s_B^2 t^2 (3\beta + 25)(\beta - 2)^2 > 0,\\
K_{13} &= 4 s_A^2 s_B^4 t^2 (3\beta + 25)(\beta - 2)^2 > 0.
\end{aligned} \tag{39}$$

So, $K = K_1 + K_2 + \cdots + K_{13} > 0$,

$$\begin{aligned}
W^{\mathrm{II}^*} - W^{\mathrm{III}^*} &= -\frac{(c-\alpha)^2 K}{M_1 M_2} < 0,\\
W^{\mathrm{III}^*} - W^{\mathrm{IV}^*} &= -\frac{9(c-\alpha)^2 \left(2s_B^2 t^2 + 4 s_B^2 s_A^2 + 4 s_B^2 s_A t - 4 s_B^2 \beta s_A^2 + 4 t s_B s_A^2 + \beta^2 s_B^2 s_A^2 + 2t^2 s_A^2 - 2t\beta s_B s_A^2 - 2\beta t s_B^2 s_A\right)^2}{M_2 M_3} < 0.
\end{aligned} \tag{40}$$

Then, we obtain the result $W^{\mathrm{I}^*} < W^{\mathrm{II}^*} < W^{\mathrm{III}^*} < W^{\mathrm{IV}^*}$.

From this, we can clearly see that when the government implements both carbon tax and emission reduction subsidy policies and enterprises make emission reduction measures, the equilibrium of social welfare is the greatest. This result can be used as a reference for governmental decision-making. □

*3.5.2. Carbon Emissions Comparison.* The quantitative relationship for the optimal carbon emissions levels in the four situations is more complicated. In order to simplify the calculation and clarify the relationships among them, we assumed that the service capabilities of the two ports were the same ($s_A = s_B$), and we combined numerical solutions to analyze the relationships among various situations regarding the optimal carbon emission levels.

By taking $s_A = s_B$ as the optimal carbon emissions in the four different situations, a simplified optimal solution was obtained. By using the symbol "⌢" to represent the simplified optimal solution, it was found that when the two ports have the same design capacity (service capacity), the relationships among the four different situations regarding the optimal carbon emission levels can be expressed as

$$\widehat{\mathrm{ED}^{\mathrm{I}^*}} > \widehat{\mathrm{ED}^{\mathrm{II}^*}} > \widehat{\mathrm{ED}^{\mathrm{IV}^*}} > \widehat{\mathrm{ED}^{\mathrm{III}^*}}. \tag{41}$$

From the above relationship, we can see that when the government implements a carbon tax policy and the company adopts emission reduction measures, the carbon emission level is the lowest. In today's era, as more and more attention is being paid to the environment, environmental protection factors will also become an important factor to be considered in government decision-making. This result can also be used as a reference for governmental decision-making.

For the situation where the capacities of the two ports are not the same, we used numerical solutions. By observing the optimal carbon emissions level in various situations, we found that the optimal carbon emission level has a common factor of different situations $(c-\alpha)^2$. We can remove common factors $(c-\alpha)^2$ and simplify $\mathrm{ED}^{\mathrm{I}^*}$, $\mathrm{ED}^{\mathrm{II}^*}$, $\mathrm{ED}^{\mathrm{III}^*}$, and $\mathrm{ED}^{\mathrm{IV}^*}$ to $Y1$, $Y2$, $Y3$, and $Y4$.

If we let $s_A = 4.3, s_B = 5.0$ and let $\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, we obtain Figure 1.

If we let $s_A = 6.5, s_B = 5.8$ and let $\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, we obtain Figure 2.

From Figures 1 and 2, we can intuitively see that when the service capabilities of the two ports are different, the relationships among the four different situations for the optimal carbon emission levels can be represented by $Y1 > Y2 > Y3 > Y4$. This is in accordance with the conclusion shown when the service capabilities of the two ports are the

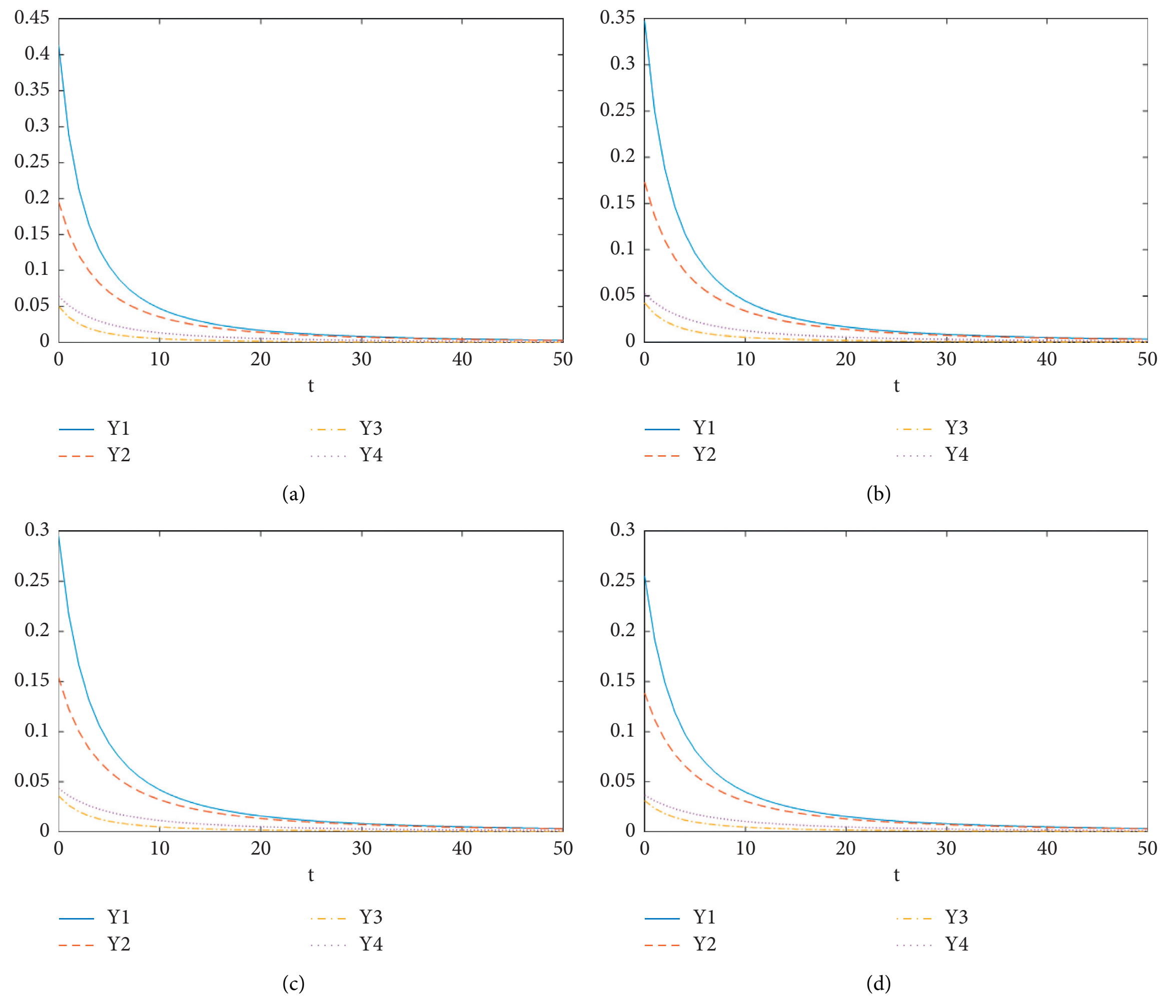


Figure 1: Optimal carbon emissions under different parameter values ($s_A = 4.3$, $s_B = 5.0$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

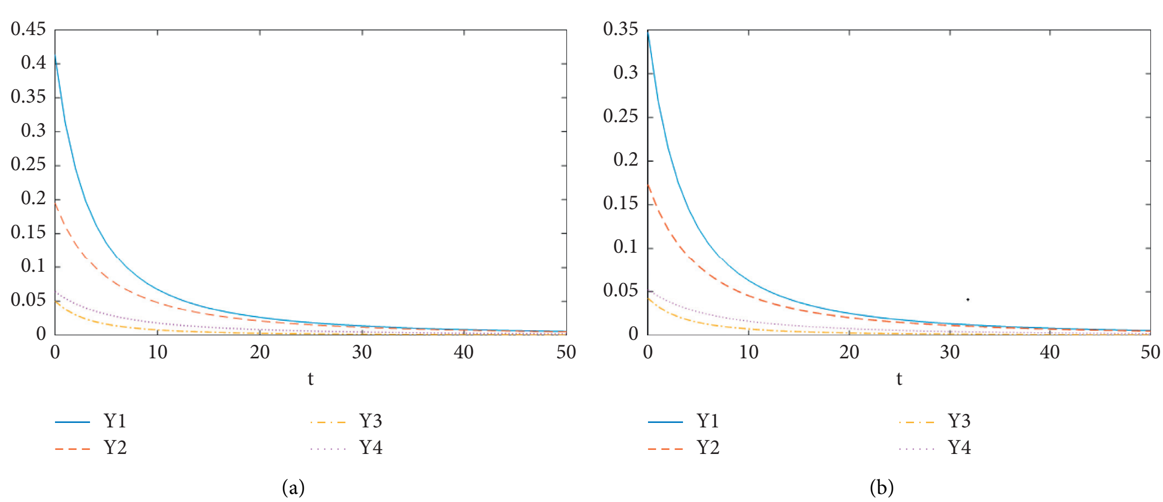


Figure 2: Continued.

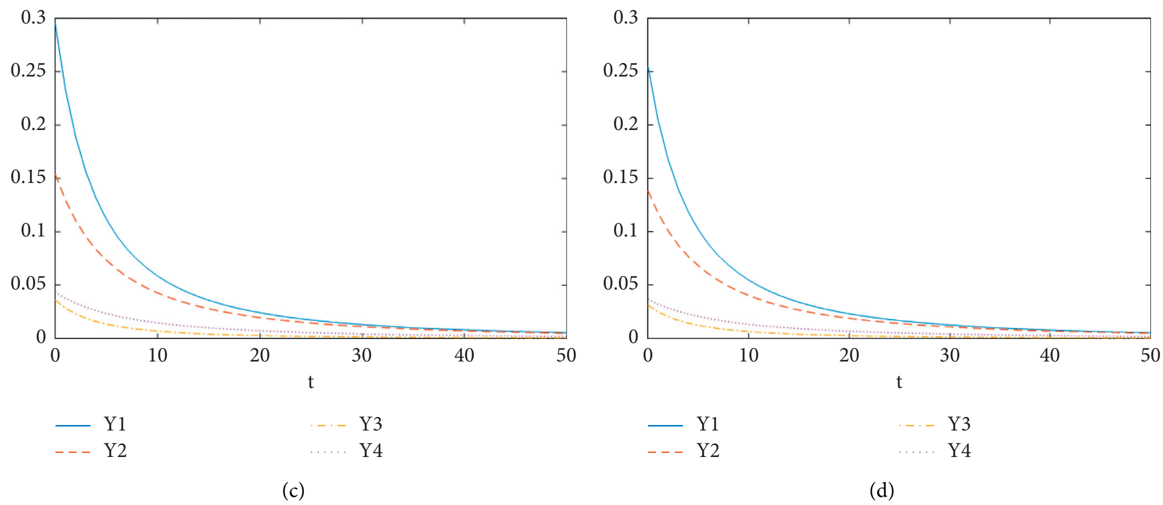


FIGURE 2: Optimal carbon emissions under different parameter values ($s_A = 6.5$, $s_B = 5.8$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

same. From this, it can be concluded that no matter whether the service capabilities of the two ports are equal, the optimal carbon emission levels in different situations always have the following relationship before port integration: $ED^{I^*} > ED^{II^*} > ED^{IV^*} > ED^{III^*}$.

In the relationship, we can see that the optimal carbon emission level in Situation IV is higher than that in Situation III, which may be contrary to our ideal situation. In Situation IV, the emission reduction subsidy policy is added, and the port naturally increases the reduction in emissions. Thus, the question of why the level of carbon emissions is higher arises. In fact, this phenomenon is easy to explain. For port companies, the increase in the subsidy policy is equivalent to encouraging "production," and it increases the port's service volume, which inevitably leads to an increase in carbon emissions.

## 4. Environmental Policy after Port Integration

In order to explore the balanced decision-making of the government and port companies in different situations, this section studies how ports and enterprises make decisions in the four situations described in Section 3 under the premise of port integration. In this section, the overline "—" is used to indicate the parameters after integration.

*4.1. No Carbon Tax, No Reduction in Emissions (Situation I).* In Situation I, the government has not implemented environmental policies, and the port has not made any emission reduction measures. When the port is integrated, the port's decision-making goal is no longer to maximize its own profits, but instead, it is consistent with the government's decision-making goal, that is, to maximize social welfare. At this time, the social welfare function is

$$\overline{W}^I = \overline{CS}^I + \overline{R}_A^I + \overline{R}_B^I - \overline{ED}^I. \tag{42}$$

By substituting formulas (5)–(8) into formula (42), we can obtain

$$\begin{aligned}\overline{W}^I = {} & (\beta - 1)\overline{q}_A^I \overline{q}_B^I + \left(\alpha - \overline{q}_A^I - \beta\overline{q}_B^I - t\frac{\overline{q}_A^I}{s_A^I} - c\right)\overline{q}_A^I \\ & + \left(\alpha - \overline{q}_B^I - \beta\overline{q}_A^I - t\frac{\overline{q}_B^I}{s_B^I} - c\right)\overline{q}_B^I.\end{aligned} \tag{43}$$

At this time, the decision-making goals of the port and the government are $\max_{\overline{q}_A^I, \overline{q}_B^I} \overline{W}^I$. According to the first-order optimal condition $((\partial\overline{W}^I/\partial\overline{q}_A^I) = (\partial\overline{W}^I/\partial\overline{q}_B^I) = 0)$, we can obtain

$$\begin{aligned}\overline{q}_A^{I^*} &= \frac{(\alpha - c)(-s_B - 2t + \beta s_B)s_A}{-3s_As_B - 4s_At - 4s_Bt - 4t^2 + \beta^2 s_As_B + 2\beta s_As_B}, \\ \overline{q}_B^{I^*} &= \frac{(\alpha - c)(-s_A - 2t + \beta s_A)s_B}{-3s_As_B - 4s_At - 4s_Bt - 4t^2 + \beta^2 s_As_B + 2\beta s_As_B}.\end{aligned} \tag{44}$$

By substituting equation (44) into equations (7) and (42), we can determine the optimal carbon emission level and optimal social welfare level after integration:

$$\begin{aligned}\overline{ED}^{I^*} &= \frac{2(c-\alpha)^2(-s_As_B - s_At - s_Bt + \beta s_As_B)^2}{(-3s_As_B - 4s_At - 4s_Bt - 4t^2 + \beta^2 s_As_B + 2\beta s_As_B)^2}, \\ \overline{W}^{I^*} &= \frac{(c-\alpha)^2(-s_As_B - s_At - s_Bt + \beta s_As_B)}{-3s_As_B - 4s_At - 4s_Bt - 4t^2 + \beta^2 s_As_B + 2\beta s_As_B}.\end{aligned} \tag{45}$$

*4.2. There Is a Carbon Tax but No Reduction in Emissions (Situation II).* In Situation II, the government implements a carbon tax policy, but the port still does not take measures to reduce emissions. At this time, the port is integrated. As in Situation I, the port's decision-making goal is to maximize social welfare. At this time, the social welfare function is

$$\overline{W}^{\mathrm{II}} = \overline{\mathrm{CS}}^{\mathrm{II}} + \overline{R}_A^{\mathrm{II}} + \overline{R}_B^{\mathrm{II}} + \overline{T}^{\mathrm{II}} - \overline{\mathrm{ED}}^{\mathrm{II}}. \quad (46)$$

By substituting formulas (5), (6), and (12)–(14) into formula (46), we can obtain

$$\overline{W}^{\mathrm{II}} = (\beta - 1)\overline{q}_A^{\mathrm{II}}\overline{q}_B^{\mathrm{II}} + \left(\alpha - \overline{q}_A^{\mathrm{II}} - \beta\overline{q}_B^{\mathrm{II}} - t\frac{\overline{q}_A^{\mathrm{II}}}{s_A} - c\right)\overline{q}_A^{\mathrm{II}} + \left(\alpha - \overline{q}_B^{\mathrm{II}} - \beta\overline{q}_A^{\mathrm{II}} - t\frac{\overline{q}_B^{\mathrm{II}}}{s_B} - c\right)\overline{q}_B^{\mathrm{II}}. \quad (47)$$

It is easy to see that the social welfare function of the integrated Situation II is the same as that of Situation I, which indicates that optimal decision-making is the same in Situation I and Situation II, so the optimal carbon emissions and social welfare levels for Situation II are $\overline{\mathrm{ED}}^{\mathrm{II}^*} = \overline{\mathrm{ED}}^{\mathrm{I}^*}$, $\overline{W}^{\mathrm{II}^*} = \overline{W}^{\mathrm{I}^*}$.

*4.3. Carbon Tax and a Reduction in Emissions Are Implemented (Situation III).* In Situation III, the government implements a carbon tax policy and the port adopts emission reduction measures. When the port is integrated, the decision-making goal of the port is to maximize social welfare. At this time, the social welfare function is

$$\overline{W}^{\mathrm{III}} = \overline{\mathrm{CS}}^{\mathrm{III}} + \overline{R}_A^{\mathrm{III}} + \overline{R}_B^{\mathrm{III}} + \overline{T}^{\mathrm{III}} - \overline{\mathrm{ED}}^{\mathrm{III}}. \quad (48)$$

By substituting formulas (5), (6), and (19)–(21) into formula (48), we can obtain

$$\overline{W}^{\mathrm{III}} = \frac{\left(\overline{q}_A^{\mathrm{III}}\right)^2 + \left(\overline{q}_B^{\mathrm{III}}\right)^2 + 2\beta\overline{q}_A^{\mathrm{III}}\overline{q}_B^{\mathrm{III}} - \overline{a}\left(\overline{a}_A^{\mathrm{III}}\right)^2 - \left(\overline{a}_B^{\mathrm{III}}\right)^2 - \left(\overline{q}_A^{\mathrm{III}} + \overline{q}_B^{\mathrm{III}} - \overline{a}_A^{\mathrm{III}} - \overline{a}_B^{\mathrm{III}}\right)^2}{2} + \left(\alpha - \overline{q}_A^{\mathrm{III}} - \beta\overline{q}_B^{\mathrm{III}} - t\frac{\overline{q}_A^{\mathrm{III}}}{s_A} - c\right)\overline{q}_A^{\mathrm{III}} + \left(\alpha - \overline{q}_B^{\mathrm{III}} - \beta\overline{q}_A^{\mathrm{III}} - t\frac{\overline{q}_B^{\mathrm{III}}}{s_B} - c\right)\overline{q}_B^{\mathrm{III}}. \quad (49)$$

At this time, the decision-making goals of the port and the government are $\max_{\overline{q}_A^{\mathrm{III}},\overline{q}_B^{\mathrm{III}}}\overline{W}^{\mathrm{III}}$ and $\max_{\overline{a}_A^{\mathrm{III}},\overline{a}_B^{\mathrm{III}}}\overline{W}^{\mathrm{III}}$.

According to the first-order optimal condition ($(\partial\overline{W}^{\mathrm{III}}/\partial\overline{q}_A^{\mathrm{III}}) = (\partial\overline{W}^{\mathrm{III}}/\partial\overline{q}_B^{\mathrm{III}}) = 0$ and $(\partial\overline{W}^{\mathrm{III}}/\partial\overline{a}_A^{\mathrm{III}}) = (\partial\overline{W}^{\mathrm{III}}/\partial\overline{a}_B^{\mathrm{III}}) = 0$), we can obtain

$$\overline{q}_A^{\mathrm{III}^*} = \frac{3s_A(\alpha - c)(-2t + bs_B - s_B)}{-5s_As_B - 8s_At - 8s_Bt - 12t^2 + 3\beta^2s_As_B + 2\beta s_As_B},$$
$$\overline{q}_B^{\mathrm{III}^*} = \frac{3s_A(\alpha - c)(-2t + bs_A - s_A)}{-5s_As_B - 8s_At - 8s_Bt - 12t^2 + 3\beta^2s_As_B + 2\beta s_As_B}, \quad (50)$$

$$\overline{a}_A^{\mathrm{III}^*} = \overline{a}_B^{\mathrm{III}^*} = \frac{2(\alpha - c)(-s_At - s_Bt + \beta s_As_B - s_As_B)}{-5s_As_B - 8s_At - 8s_Bt - 12t^2 + 3\beta^2s_As_B + 2\beta s_As_B}. \quad (51)$$

By substituting equations (50) and (51) into equations (19) and (48), we can determine the optimal carbon emissions and social welfare levels after integration:

$$\overline{\mathrm{ED}}^{\mathrm{III}^*} = \frac{2(c - \alpha)^2(-s_At - s_Bt + \beta s_As_B - s_As_B)^2}{\left(-5s_As_B - 8s_At - 8s_Bt - 12t^2 + 3\beta^2s_As_B + 2\beta s_As_B\right)^2},$$
$$\overline{W}^{\mathrm{III}^*} = \frac{3(c - \alpha)^2(-s_At - s_Bt + \beta s_As_B - s_As_B)}{-5s_As_B - 8s_At - 8s_Bt - 12t^2 + 3\beta^2s_As_B + 2\beta s_As_B}. \quad (52)$$

*4.4. Carbon Taxes, Emission Reductions, and Emission Reduction Subsidies Are Implemented (Situation IV).* In Situation IV, the government implements carbon tax and emission reduction subsidy policies, and the port adopts emission reduction measures. When the port is integrated, the decision-making goal of both the port and the government is to maximize social welfare. At this time, the social welfare function is

$$\overline{W}^{\mathrm{IV}} = \overline{\mathrm{CS}}^{\mathrm{IV}} + \overline{R}_A^{\mathrm{IV}} + \overline{R}_B^{\mathrm{IV}} + \overline{T}^{\mathrm{IV}} - \overline{\mathrm{ED}}^{\mathrm{IV}} - \frac{\delta}{2}\left[\left(\overline{a}_A^{\mathrm{IV}}\right)^2 + \left(\overline{a}_B^{\mathrm{IV}}\right)^2\right]. \quad (53)$$

By substituting formulas (5), (6), and (27)–(29) into formula (53), we can obtain

Table 2: Social welfare balance before and after port integration.

| | Before port integration | After port integration | Compared |
|---|---|---|---|
| Situation I | $W^{I^*}$ | $\overline{W}^{I^*}$ | $W^{I^*} < \overline{W}^{I^*}$ |
| Situation II | $W^{II^*}$ | $\overline{W}^{II^*}$ | $W^{II^*} < \overline{W}^{II^*}$ |
| Situation III | $W^{III^*}$ | $\overline{W}^{III^*}$ | $W^{III^*} < \overline{W}^{III^*}$ |
| Situation IV | $W^{IV^*}$ | $\overline{W}^{IV^*}$ | $W^{IV^*} < \overline{W}^{IV^*}$ |

Table 3: Comparison of balanced carbon emissions before and after port integration.

| | Before port integration | After port integration | Compared |
|---|---|---|---|
| Situation I | $\widehat{ED}^{I^*}$ | $\overline{\widehat{ED}}^{I^*}$ | $\widehat{ED}^{I^*} > \overline{\widehat{ED}}^{I^*}$ |
| Situation II | $\widehat{ED}^{II^*}$ | $\overline{\widehat{ED}}^{II^*}$ | $\widehat{ED}^{II^*} = \overline{\widehat{ED}}^{II^*}$ |
| Situation III | $\widehat{ED}^{III^*}$ | $\overline{\widehat{ED}}^{III^*}$ | $\widehat{ED}^{III^*} < \overline{\widehat{ED}}^{III^*}$ |
| Situation IV | $\widehat{ED}^{IV^*}$ | $\overline{\widehat{ED}}^{IV^*}$ | $\widehat{ED}^{IV^*} < \overline{\widehat{ED}}^{IV^*}$ |

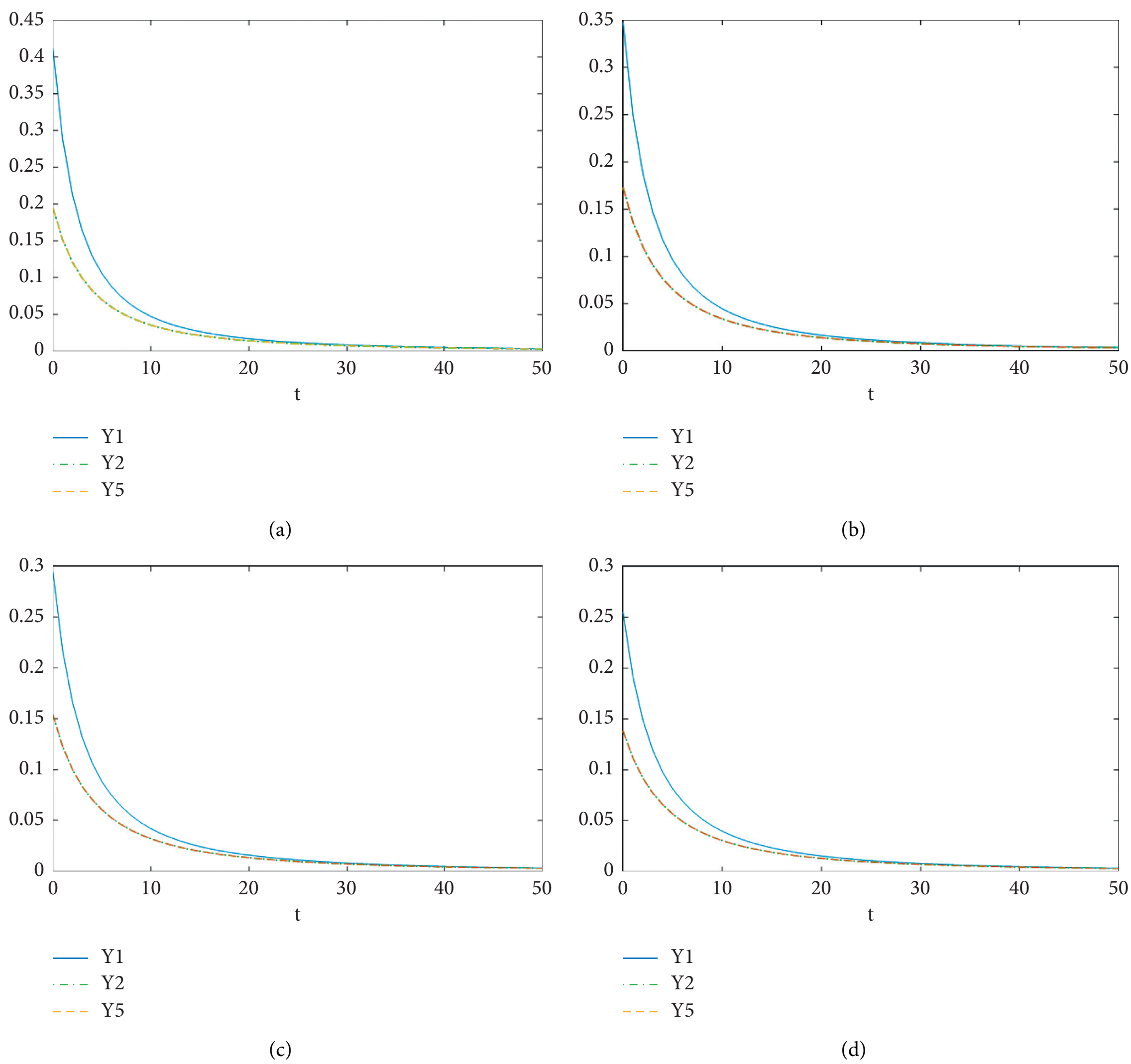


Figure 3: Balanced carbon emissions before and after the integration of Situation I and Situation II ($s_A = 4.3$, $s_B = 5.0$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

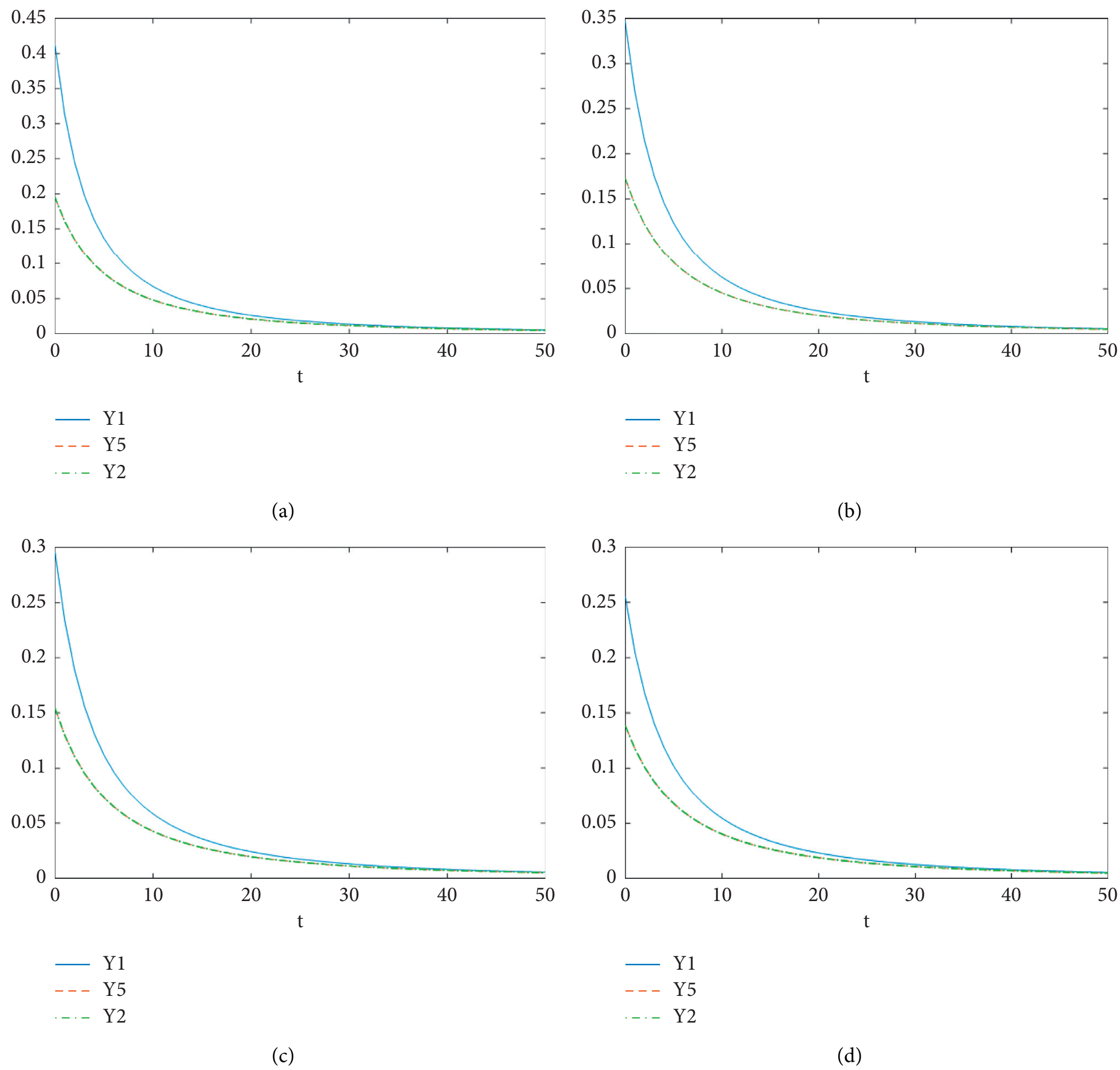


Figure 4: Balanced carbon emissions before and after the integration of Situation I and Situation II ($s_A = 6.5$, $s_B = 5.8$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

$$\begin{aligned}\overline{W}^{\mathrm{IV}} = {} & \frac{\left(\overline{q}_A^{\mathrm{IV}}\right)^2 + \left(\overline{q}_B^{\mathrm{IV}}\right)^2 + 2\beta\overline{q}_A^{\mathrm{IV}}\overline{q}_B^{\mathrm{IV}} - \left(\overline{a}_A^{\mathrm{IV}}\right)^2 - \left(\overline{a}_B^{\mathrm{IV}}\right)^2 - \left(\overline{q}_A^{\mathrm{IV}} + \overline{q}_B^{\mathrm{IV}} - \overline{a}_A^{\mathrm{IV}} - \overline{a}_B^{\mathrm{IV}}\right)^2}{2} \\ & + \left(\alpha - \overline{q}_A^{\mathrm{IV}} - \beta\overline{q}_B^{\mathrm{IV}} - t\frac{\overline{q}_A^{\mathrm{IV}}}{s_A} - c\right)\overline{q}_A^{\mathrm{IV}} + \left(\alpha - \overline{q}_B^{\mathrm{IV}} - \beta\overline{q}_A^{\mathrm{IV}} - t\frac{\overline{q}_B^{\mathrm{IV}}}{s_B} - c\right)\overline{q}_B^{\mathrm{IV}}.\end{aligned} \tag{54}$$

It is easy to see that the social welfare functions of Case IV and Case III are the same after integration. Therefore, it is easy to obtain the optimal carbon emissions and social welfare levels of Case IV: $\overline{\mathrm{ED}}^{\mathrm{IV}^*} = \overline{\mathrm{ED}}^{\mathrm{III}^*}$ and $\overline{W}^{\mathrm{IV}^*} = \overline{W}^{\mathrm{III}^*}$.

*4.5. Social Welfare and Carbon Emissions Levels.* The above analysis shows that Situation I and Situation II and Situation III and Situation IV have the same decision-making goal and the same equilibrium result after integration. We are very interested in the relationship between the results of port integration and the results obtained before the integration. Therefore, this section analyzes the relationship for the equilibrium results before and after port integration.

*4.5.1. Social Welfare Comparison.* The social welfare balance in the four situations before and after integration is shown in Table 2. The calculation process is the same as above and is omitted here.

It is easy to see from Table 2 that in the four situations discussed in this article, the optimal social welfare level of the port after integration is greater than the optimal social welfare level before integration. Therefore, we can conclude

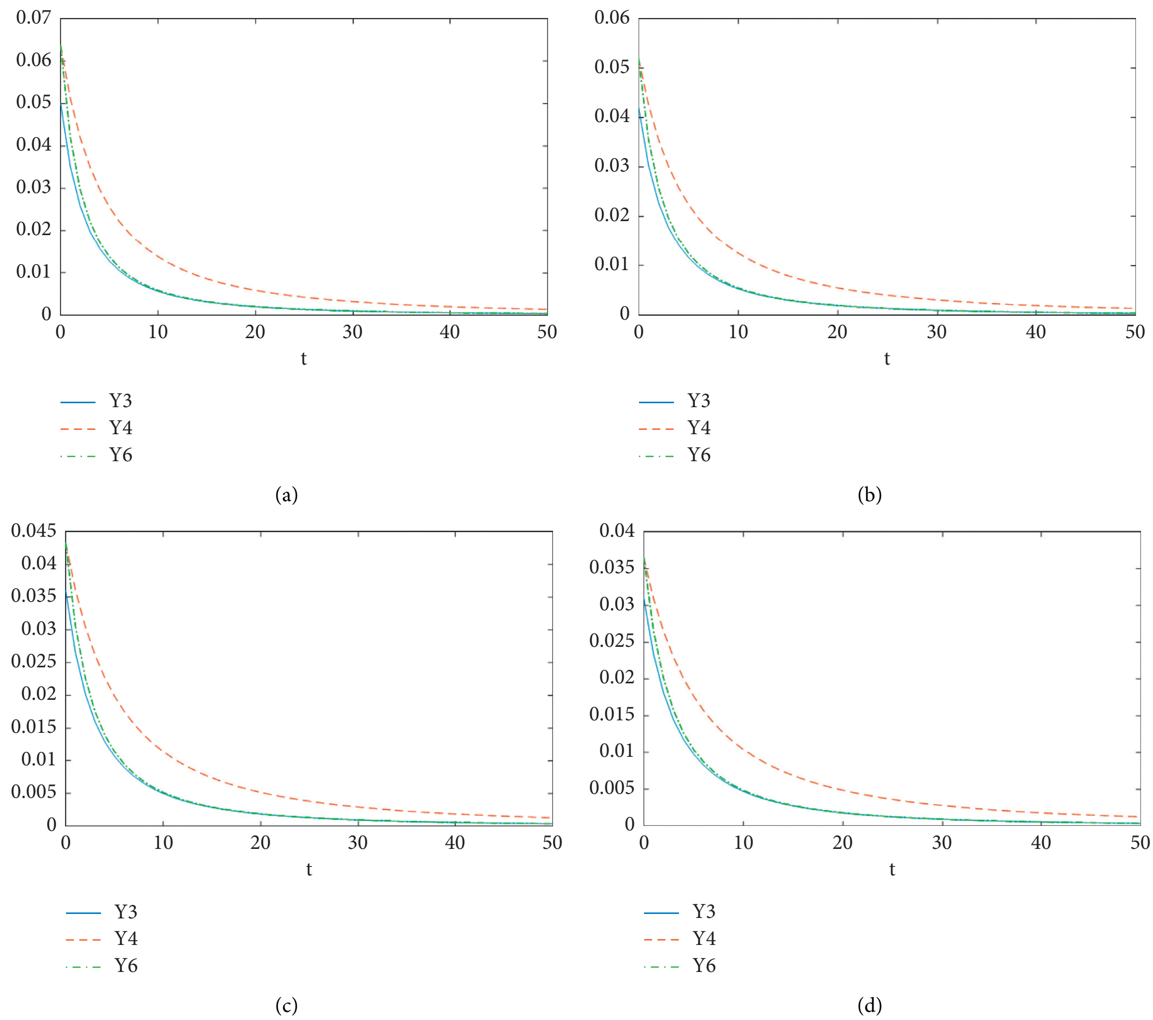


Figure 5: Balanced carbon emissions before and after the integration of Situation III and Situation IV ($s_A = 4.3$, $s_B = 5.0$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

that in the four situations studied in this article, port integration helps to improve social welfare. This conclusion can theoretically prove that port integration can help improve overall social welfare. Under China's national conditions, it is feasible and beneficial to realize port integration. Therefore, the country and various regions should actively explore ways of port integration, realize port integration, and improve social welfare.

*4.5.2. Carbon Emissions Comparison.* This is the same as the comparison of the average emission levels prior to integration. Due to the complex quantity relationship, in order to simplify the calculation, we assumed that the service capability was the same for both ports ($s_A = s_B$). This meant that the relationship shown in Table 3 could be obtained.

Table 3 shows that when the service capabilities of the two ports are the same, the impact of port integration on the optimal carbon emission level differs among the four situations. In Situation I, port integration can reduce carbon emissions, while in Situation II, the port's carbon emission levels remain unchanged before and after port integration. Situations III and IV are contrary to Situation I, whereby port integration can increase carbon emissions. It can be explained that although port integration can improve the overall welfare of society, it may not necessarily reduce carbon emissions. Therefore, when making port integration decisions, the government needs to pay attention to port carbon emissions and adopt more effective policies to achieve economic benefits and development in the same direction with environmental benefits.

Next, we used numerical solutions to analyze the changes in carbon emission levels before and after integration when the service capabilities of the two ports are different. First, we removed the common factor $(c-\alpha)^2$ in the optimal carbon emission level after integration. We simplified $\overline{ED}^{I^*}$, $\overline{ED}^{II^*}$ to $Y5$ and, at the same time, simplified $\overline{ED}^{III^*}$, $\overline{ED}^{IV^*}$ to $Y6$. In order to express this more clearly, we discuss Situations I and II together and Situations III and IV together.

If we let $s_A = 4.3$, $s_B = 5.0$ and let $\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, by plotting $Y_1$, $Y_2$, and $Y_5$ into the same coordinate axis, we obtain Figure 3.

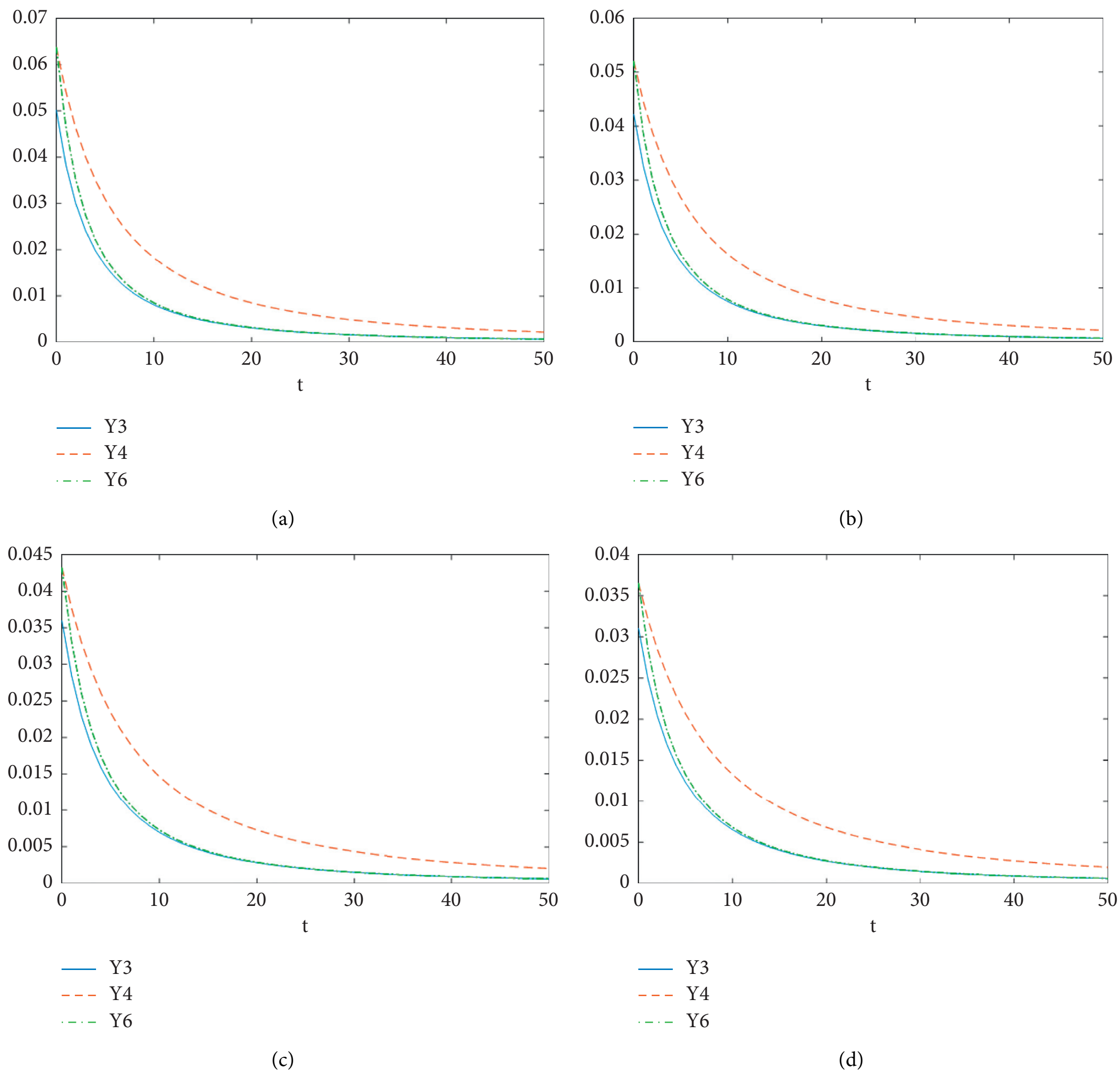


Figure 6: Balanced carbon emissions before and after the integration of Situation III and Situation IV ($s_A = 6.5$, $s_B = 5.8$). (a) $\beta = 0.2$. (b) $\beta = 0.4$. (c) $\beta = 0.6$. (d) $\beta = 0.8$.

If we let $s_A = 6.5, s_B = 5.8$ and let $\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, by plotting $Y_1$, $Y_2$, and $Y_5$ into the same coordinate axis, we obtain Figure 4.

It can be clearly seen from Figures 3 and 4 that when the service capabilities of the two ports differ, $Y1 > Y5$, $Y2 = Y5$. This is the same as the conclusion obtained for two ports with the same service capacity.

If we let $s_A = 4.3, s_B = 5.0$ and let$\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, by plotting $Y_3$, $Y_4$, and $Y_6$ into the same coordinate axis, we obtain Figure 5.

If we let $s_A = 6.5, s_B = 5.8$ and let $\beta$ be equal to 0.2, 0.4, 0.6, and 0.8, respectively, by plotting $Y_3$, $Y_4$, and $Y_6$ into the same coordinate axis, we obtain Figure 6.

From Figures 5 and 6, we can easily see that when the service capabilities of the two ports differ, when $t < 20$, $Y_6 > Y_3$, and when $t > 20$, $Y_6$ and $Y_3$ have an equal trend. The relationship between $Y_4$ and $Y_6$ is very clear: $Y_4 < Y_6$. This result is largely consistent with the situation where the two ports have the same service capacity. Specific problems can be analyzed in detail. In actual problems, when the service capacity of the two ports is known, a comparison of their optimal carbon emission levels is relatively easy.

## 5. Conclusions

Using the context of competition between two ports in Cournot, we studied optimal decision-making by the government and the port in four different situations before and after the integration of the port based on the subsidy and carbon tax mechanism. We analyzed the impacts of having a carbon tax rate and emission reduction subsidy rate on social welfare and determined the optimal carbon tax rate, optimal emission reduction subsidy rate, optimal carbon emission level, and optimal social welfare level in different situations.

In the context of competition in Cournot, optimal decision-making by the government and the port are not the same in the four different situations. Although optimal decision-making differs, both carbon tax and emission reduction subsidy policies can encourage companies to make emission reduction measures to a certain extent, and both policies can have positive impacts on the environment. By comparing optimal social welfare and the optimal carbon emission level, we obtained the following results.

Before port integration, the optimal social welfare level gradually increased from Situation I to Situation IV. Therefore, from the perspective of social welfare, the government's optimal choice should be the environmental policy corresponding to Situation IV. It can be seen that before the port integration, the government's de facto carbon tax policy will help improve social welfare. Prior to port integration, Situation III was associated with the lowest carbon emission level, and Situation I was associated with the highest carbon emission level. For social welfare, port integration helps to improve social welfare; for port carbon emissions, port integration does not necessarily reduce port carbon emissions. Therefore, when the government makes port integration decisions, it needs to pay attention to port carbon emissions and adopt more effective policies to achieve the same development of economic and environmental benefits.

Studies have shown that port integration can always improve the overall social welfare of the port, but sometimes at the expense of the environment. However, if port pollution is considered and has a relatively large impact, port integration will be meaningful in producing better green social welfare. This discovery provides strong support for China's current trend of port integration. The reason is that its main cities are facing an environmental crisis. Port integration is how to effectively control air and water pollution caused by port activities and better manage pollution problems in port cities.

The research results presented in this paper can be used as a policy reference that can be used by the government to formulate environmental policies based on the goal of maximizing social welfare. They could also be used by the port to make internal decisions when environmental policies have been set. The research presented in this article has also certain limitations. We only considered optimal social welfare conditions resulting from government decision-making and did not consider difficulties with policy implementation. Due to quantification difficulties, we did not add the cost of policy implementation to the social welfare function. The demand considered in this paper is to determine the demand. In the future, the research can be expanded to the field of uncertain demand. At the same time, because some companies are facing the problem of funding difficulties, the relevant factors of the financial system can also be taken into consideration.

## Data Availability

Data are from "Statistical Bulletin on the Development of the Transportation Industry in 2019". The datasets used to support the findings of this study can be downloaded from the public websites whose references are provided in this paper. And the datasets are also available from the corresponding author upon request.

## Disclosure

Hailing Fu and Yuantao Fang are co-corresponding authors. Zhuoqi Teng and Xiaoli Li are co-first authors.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

## Authors' Contributions

Zhuoqi Teng and Xiaoli Li contributed equally to this study.

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