Subsidy design in a vessel speed reduction incentive program under government policies

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Abstract

As a green port and shipping-related policy, the vessel speed reduction incentive program (VSRIP) involves using a subsidy to induce ships to reduce their speed in a port area so that the emissions can be reduced at the port. However, this program may attract new ships to visit the port because of the subsidy; in this case, the port's profit will grow due to more ship visits, but its total emissions may also increase, which is counter to the original intention of the subsidy. The government could then intervene by providing part of the subsidy for the VSRIP or by collecting air emission taxes for the increased emission at the port. This paper studies how to design suitable subsidies for ships participating in a VSRIP. Two bilevel subsidy design models are formulated based on a Stackelberg game to maximize the port's profit (related to the profits from original and new ships, the subsidy provided by the port, and air emission taxes) and to minimize the government's cost (related to the damage cost of air emissions, the subsidy provided by the government, and air emission taxes). We determine which policy (including a sharing subsidy policy, no government intervention, and an air emission tax policy) should be implemented by the government in different cases and how much subsidy should be provided by the port under each government policy. We find that these decisions are affected by several practical factors, such as the damage cost of air emissions per ton of fuel and the subsidy sensitivities of original and new ships. We also outline several meaningful insights based on the analysis of these practical factors.

Keywords: Green port and shipping; subsidy game; vessel speed reduction incentive

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program (VSRIP); sharing subsidy; air emission taxes

1. Introduction

A subsidy program adopted by a port may lead to an increase in air pollution even if it appears to be environmentally friendly. Hence, effective government intervention to mitigate the negative influence or promote the positive influence of the program is essential. This paper considers a subsidy program aimed at green environmental protection in shipping, which is used to demonstrate a methodology for the design of suitable government intervention policies and for the determination of the program's subsidies under different policies to deliver economic and environmental benefits for both the ports and society (Du et al., 2015).

Green environmental protection in the shipping industry to reduce emissions has become an increasing concern recently. Shipping emissions are dependent on fuel consumption. The Third International Maritime Organization Greenhouse Gas Study (IMO, 2014) showed that global fuel consumption by ships was estimated to be around 300 million tons per year. Ships emit considerable amounts of gases and particulates from their operations, including nitrogen oxides (NO_x), sulfur dioxide (SO_2), carbon dioxide (CO_2), and particulate matter (PM), and 70% of shipping emissions occur within 400 km of the coast, which may cause a severe environmental problem and damage human health. Many environmental regulations for different industries have been presented and widely discussed (Ančić and Šestan, 2015; Esenduran et al., 2015; Svindland, 2018), and various measures have been adopted to reduce shipping emissions, among which slow steaming has received significant attention (Kontovas and Psaraftis, 2011; Woo and Moon, 2014; Yin et al., 2014; Lee et al., 2015; Psaraftis and Kontovas, 2015; Cariou et al., 2019; Psaraftis, 2019). Although Psaraftis and Kontovas (2010) and Chang and Chang (2013) pointed out that slow steaming may not bring economic benefits, it remains an effective way of reducing emissions due to the approximately cubic relationship between vessel speed and fuel consumption (Corbett et al., 2009; Wang and Meng, 2012; Brouer et al., 2013; Lindstad et al., 2013; Wang and Meng, 2015; Koza, 2019).

Because slow steaming can lead to lower emissions, a voluntary vessel speed reduction program was adopted by the ports of Los Angeles (LSA) and Long Beach (LGB) in 2001. In recent years, each of the two ports has imposed two vessel speed reduction zones (VSRZs): a 20-nautical-mile (nm) VSRZ and a 40-nm VSRZ. A shipping line can receive dockage refunds if 90% or more of its ship visits (a ship visit means that a ship enters and leaves the port once) in a calendar year comply with the 12 nm/h (knots) speed limit in the VSRZs. At LSA, ships participating in the vessel speed reduction incentive program (VSRIP) in the 20-nm and 40-nm VSRZs can receive refunds of 15% and 30% of their first-day dockage, respectively. At LGB, ships participating in the 20-nm and 40-nm VSRZs can receive 15% and 25% reduced dockage rates in the following year, respectively. According to statistics, participation rates for the 20-nm VSRZ were 92% at LSA and 97% at LGB in 2017, and for the 40-nm VSRZ, they were 84% at LSA and 91% at LGB (LSA, 2018; LGB, 2018). The high rate of compliance with the VSRIP is related to the subsidy. According to the analysis results of Ahl et al. (2017), an increase of US$100 in daily dockage savings for each ship visit can induce a 9.27% increase in the compliance rate of mixed-cargo ships, which indicates that the program's financial incentives can encourage more ships to participate.

The VSRIP has been investigated and analyzed by numerous scholars (Zis et al., 2014; Zis, 2015; Bone et al., 2016; Zhuge et al., 2020). Khan et al. (2012) reported that reducing vessel speeds from cruise speed (i.e., 24 or 25 knots) to no higher than 12 knots in VSRZs can lead to reductions in CO_2 and NO_x emissions of approximately 61% and 56%, respectively. Analyzing the VSRIP at LGB, Chang and Jhang (2016) assessed the effects of speed reduction and switching to low-sulfur fuel for bulk and container ships entering the Kaohsiung Port under two scenarios: decreasing the speed to 12 knots in a 20-nm VSRZ and decreasing it to 12 knots combined with switching to low-sulfur fuel in the 20-nm VSRZ. Linder (2018) analyzed the effects of social pressure, regulatory pressure, and economic motivations on the success of the VSRIP. Some studies have focused on other VSRZs similar to those used at LSA and LGB. Cariou and Cheaitou (2012) argued that setting VSRZs at European Union ports may generate more emissions on a global scale because of the increased sailing speed of ships outside the zones. Chang and Wang (2014) estimated SO_2, NO_x, and PM emissions and found that a VSRZ could reduce these emissions by one third. López-Aparicio et al. (2017) developed a comprehensive emission inventory for a Nordic port considering the regulation on the sulfur content of fuel and explored several mitigation measures, i.e., the implementation of onshore power for feasible oceangoing vessels, the combination of onshore power and a VSRZ, and the use of liquefied natural gas (LNG) by domestic ferries based on this combination. Their results showed that onshore power can reduce emissions effectively, as compared with 2013, emissions of NO_x and carbon dioxide equivalent (CO_{2e}) in 2020 could be reduced by up to 15% by the measure of onshore power in combination with the VSRZ, and by up to 23% for NO_x

and 17% for CO_{2e} with the increased use of LNG based on this combination. VSRIPs and VSRZs have received a great deal of attention from academia, and numerous studies have concluded that the design of VSRZs can contribute to the reduction of emissions in local areas. However, few studies have considered that the VSRIP may attract new ships, resulting in additional air emissions, which may decrease the effectiveness of the VSRIP's emission reduction near the port.

Governments play a central role in reducing shipping emissions. Collecting emission tax is a common government intervention measure (Wang and Chen, 2017; Ding et al., 2020; Haehl and Spinler, 2020). Wang and Xu (2015) and Wang et al. (2018) analyzed different carbon tax forms and demonstrated that carbon tax is effective in controlling shipping emissions. The government may also provide subsidies for the construction of green ports and the development of green shipping. Dai et al. (2019) and Wu and Wang (2020) studied how to offer subsidies for promoting investment in shore power and its use. Subsidies can also accelerate fleet replacement so that ship emissions can be reduced (Zheng and Chen, 2018; Yang et al., 2019).

Based on the existing research, our paper investigates how to design a fixed subsidy for every visit of a ship participating in the program at a port, considering new ships attracted by the VSRIP, and introduces two government policies: a sharing subsidy policy, i.e., the government provides part of subsidy for the program, and an air emission tax policy, i.e., the government collects taxes on the increased air emissions from new ships visiting the port. In this paper, the emissions are mainly NO_x, SO_2, CO_2, and PM. Note that in our study, the fixed subsidy per ship visit is assumed to be no higher than the profit obtained from each ship visit to guarantee that the total profit of the port is positive. We study this problem in a one-week period because liner ships usually have a weekly service frequency. A base case without considering the VSRIP at the port (Case 0) is first presented. Our study then considers three main cases: the VSRIP is adopted without government intervention (Case 1), the VSRIP is adopted with the sharing subsidy policy (Case 2), and the VSRIP is adopted with the air emission tax policy (Case 3). The models in Cases 2 and 3 are proposed using a Stackelberg game. The subsidy of the VSRIP can be provided by the port and the government. To differentiate the source of the subsidy, we abbreviate the subsidy offered by the government to "government subsidy," and that by the port to "port subsidy." The subsidy from the VSRIP, that is, the sum of the government and port subsidies, is abbreviated to "program subsidy." The program and port subsidies are identical in Cases 1 and 3. The total profit at the port is abbreviated to "port profit," that is, the profit from original ships in Case 0, the total profit from original and new ships minus the port subsidy in Cases 1 and 2, and the total profit minus the port subsidy and the air emission taxes in Case 3, as shown in Table 1. We use "government cost" in the study to denote the total damage cost of air emissions in the VSRZ in Cases 0 and 1, the sum of the total damage cost and government subsidy in Case 2, and the total damage cost minus air emission taxes in Case 3 (see Table 2).

Table 1: Constructs of port profit under different cases

Terms	Case 0 No VSRIP	Case 1 Normal VSRIP (without government intervention)	Case 2 Sharing subsidy policy (subsidy shared by government)	Case 3 Air emission tax policy (tax collected by government)
Profit from original ships	+	+	+	+
Profit from new ships		+	+	+
Port subsidy		−	−	−
Air emission taxes				−

Note: "+" means that the term in the corresponding row is included in the port profit of the case in the corresponding column and leads to an increase in the port profit, and "−" means that the term in the corresponding row is included in the port profit and leads to a decrease in the port profit.

Table 2: Constructs of government cost under different cases

Terms	Case 0	Case 1	Case 2	Case 3
Damage cost of air emissions	+	+	+	+
Government subsidy			+	
Air emission taxes				−

Our paper investigates the following research questions: 1) Which policy should the government implement to minimize its cost? How much subsidy should the port give for each ship visit to maximize its profit under the government's policy? How many ships will participate in the program given the fixed subsidy per ship visit? 2) How will several important factors, including the damage cost of air emissions per ton of fuel and the subsidy sensitivities of the original and new ships, affect the port profit, the government cost, and the number of ships complying with the rules of the VSRIP?

Three notable findings emerge from our study. 1) For each assumption in the decision function of shipping companies regarding whether to participate in the subsidy program (i.e., linear, convex or concave functions of the number of ships participating in the VSRIP with the program subsidy per ship visit), there are two thresholds of the total change in fuel consumption as a function of the unit subsidy provided for each ship visit: a negative threshold and zero. The optimal decisions for the government are the sharing subsidy policy, no government intervention, and the air emission tax policy when the total change in fuel consumption per unit subsidy for each ship visit is less than the negative threshold, between the two thresholds, and greater than zero, respectively. The port will always adopt the program, and the program subsidy per ship visit varies under different government policies. It is interesting that the subsidy provided by the port for each ship visit is identical when the sharing subsidy policy is implemented or when government intervention is not included. The numbers of original and new ships that participate in the VSRIP are closely related to the program subsidy. 2) The numbers of original and new ships participating in the VSRIP without government intervention increase under the sharing subsidy policy and decrease under the air emission tax policy. The change in the port profit is as follows: the port can always obtain more profit from the VSRIP, and the sharing subsidy policy will further increase its profit, while the air emission tax policy will reduce the increase in profit from the VSRIP. The change in the government cost after the adoption of the VSRIP is as follows: when the total change in fuel consumption per unit subsidy provided for each ship visit is negative, the government can reduce its cost by applying the program; when it is less than the negative threshold, the government can further reduce its cost by implementing a sharing subsidy policy; and when it is positive, the government will implement the air emission tax policy to reduce its cost, as otherwise, the government cost in this case will be higher than that without the VSRIP. 3) Several practical factors will affect the decisions of the government and the port, including the damage cost of air emissions per ton of fuel and the subsidy sensitivities of original and new ships. Note that the values of two important indexes mentioned above, i.e., the total change in fuel consumption per unit subsidy for each ship visit and the negative threshold, are dependent on these factors. Our study suggests that to make wise decisions on intervention policies, the government should evaluate the two indexes by collecting data on these important factors. Using the results of the sensitivity analysis, the port can estimate the effectiveness of the VSRIP in attracting new ships and improving its profit.

The remainder of this paper is organized as follows. Section 2 proposes one model of the port profit and two bilevel Stackelberg game models of the port profit and the government cost under different government policies, and analyzes the equilibrium solution for each player (the government or port). Section 3 examines the effects of the damage cost of air emissions per ton of fuel and the subsidy sensitivities of original and new ships. In Section 4, we investigate two new assumptions on the function of the number of ships participating in the VSRIP. Section 5 concludes the paper.

2. Subsidy design

This paper analyzes a subsidy design problem of the VSRIP at a port under several government policies. The VSRIP sets a VSRZ with an upper speed limit (e.g., 12 knots). The shape of the VSRZ is similar to a sector with the port as the center of a circle with a fixed radius (e.g., 20 nm). The visit of a ship that follows the speed limit rule in the VSRZ is eligible for a fixed subsidy, which does not exceed the profit that can be obtained from each ship visit. Ships that reduce their sailing speed in the VSRZ will contribute to the reduction of air emissions near the port. However, some new ships attracted by the program will cause extra air emissions. Recall that the damage cost of air emissions is the major term of government cost. Therefore, our paper takes into account two common government policies (i.e., a sharing subsidy policy and an air emission tax policy) to reduce government cost, where the sharing subsidy policy can reduce air emissions by attracting more ships to comply with the rules in the program and the government can increase its tax revenue and limit the number of new ships via the air emission tax policy. We study one case without the VSRIP and three cases in which the program is adopted during a one-week period. The aims of the port and the government are to maximize profit and minimize cost, respectively. The shipping companies decide on the number of original and new ships participating in the VSRIP as a function of the program subsidy per ship visit.

2.1. Case 0: No VSRIP

We first analyze the original profit at the port (called the port profit) and the damage cost of air emissions in the VSRZ (called the government cost) without the VSRIP. We take into account all service charges from ships at the port. We define the average service charge for each ship visit as r and the average variable cost for each ship visit as c^{var}, and we do not consider the fixed cost of serving ships by the port since it has no effect on the design of the subsidies in the program. Therefore, the average profit p obtained from each ship visit can be calculated as $p = r - c^{var}$. We also define the number of original ships visiting the port without the VSRIP as Q_0, the fuel consumption per ship visit in the VSRZ for the ships not participating in the program as f_1, and the damage cost of air emissions resulting from emitting one ton of fuel as c. The port profit Π_0 and the government cost C_0 are then

$$\Pi_0 = pQ_0 \tag{1}$$

and

$$C_0 = cf_1Q_0. \tag{2}$$

2.2. Case 1: No government intervention

The VSRIP is a voluntary program. We consider that the number of original ships visiting the port, i.e., Q_0, will not change after the program is adopted, and that some of them (denoted by $\hat{Q}(x)$) may participate in the program. Referring to Maglaras and Meissner (2006), Adida and DeMiguel (2011), Luo et al. (2012), Chen and Liu (2016), Dong et al. (2016), and Cho and Wang (2017), we assume a linear relationship between $\hat{Q}(x)$ and the program subsidy per ship visit x with subsidy sensitivity a_1:

$$\hat{Q}(x) = a_1x. \tag{3}$$

We define $x \leq p < Q_0/a_1$ because the program subsidy cannot be larger than the profit per ship visit p, and getting all of the original ships to participate in the program may be difficult even if the program subsidy is significantly high. Moreover, it is common for adjacent ports to compete with each other (such as Hong Kong and Shenzhen ports, Singapore and Tanjung Pelepas ports, and Los Angeles and Long Beach ports), and a port may therefore attract more ships when it reduces its charge per ship visit by providing program subsidies. All new ships will participate in the VSRIP to receive the subsidy. The number of new ships, denoted by $\tilde{Q}(x)$, is related to the subsidy per ship visit in the VSRIP, which can be expressed as

$$\tilde{Q}(x) = a_2x, \tag{4}$$

where a_2 is the subsidy sensitivity of new ships. Suppose that $a_1 > a_2 > 0$, i.e., the subsidy sensitivity of the original ships is greater than that of the new ships because the sailing routes and schedules of the original ships have fewer changes than those of the new ships participating in the VSRIP, which means that it is usually more convenient or beneficial for the original ships to participate in the program.

The port aims to maximize its total profit considering the profit from all ships, including original and new ships minus the total program subsidy:

$$[\text{M1}] \quad \max_x \Pi_1(x) = p(Q_0 + \tilde{Q}(x)) - x(\hat{Q}(x) + \tilde{Q}(x)) \tag{5}$$

subject to (3), (4) and

$$0 \le x \le p. \tag{6}$$

The first- and second-order derivatives of $\Pi_1(x)$ are

$$\frac{d\Pi_1(x)}{dx} = a_2 p - 2(a_1 + a_2)x, \tag{7}$$

and

$$\frac{d^2\Pi_1(x)}{dx^2} = -2(a_1 + a_2) < 0, \tag{8}$$

meaning that $\Pi_1(x)$ is a concave function in x. The optimal solution can be obtained when $d\Pi_1(x)/dx = 0$. Hence, the optimal program subsidy for each ship visit x_1^* is

$$x_1^* = \frac{a_2 p}{2(a_1 + a_2)}, \tag{9}$$

which lies between 0 and p.

The numbers of original ships and new ships from different shipping companies participating in the program, denoted by $\hat{Q}_1^*$ and $\tilde{Q}_1^*$, are

$$\hat{Q}_1^* = \frac{a_1 a_2 p}{2(a_1 + a_2)} \tag{10}$$

and

$$\tilde{Q}_1^* = \frac{{a_2}^2 p}{2(a_1 + a_2)}. \tag{11}$$

Plugging x_1^* into objective function (5), the maximum port profit can be expressed as

$$\Pi_1^* = pQ_0 + \frac{a_2^2 p^2}{4(a_1 + a_2)}. \tag{12}$$

Eq. (12) shows that the port profit will increase, i.e., $\Pi_1^* > \Pi_0$, after the adoption of the VSRIP since the profit from new ships is higher than the total port subsidy.

The local government is concerned about the damage cost of air emissions from the incoming and outgoing ships in the VSRZ. We define f_2 as the fuel consumption per ship visit in the VSRZ for the ships participating in the VSRIP. We have $f_1 > f_2$ because a ship not following the rules of the program has a higher sailing speed and consumes more fuel. According to the average profit from each liner ship visit at ports and the damage cost of air emissions, we assume that $p > cf_1 > cf_2$ and $p > 2cf_2$. The government cost C_1^*, i.e., the total damage cost of air emissions from original and new ships, with the designed program subsidy per ship visit x_1^* is

$$\begin{aligned} C_1^* &= cf_1(Q_0 - \hat{Q}_1^*) + cf_2(\hat{Q}_1^* + \tilde{Q}_1^*) \\ &= cf_1 Q_0 + c\left[f_2(a_1 + a_2) - f_1 a_1\right] x_1^* \\ &= cf_1 Q_0 + \frac{a_2 p \cdot c\left[f_2(a_1 + a_2) - f_1 a_1\right]}{2(a_1 + a_2)}. \end{aligned} \tag{13}$$

Define A as the total change in fuel consumption caused by the per-unit subsidy provided for each ship visit:

$$A = f_2(a_1 + a_2) - f_1 a_1, \tag{14}$$

which must be less than $a_2 p/2c$ because $f_1 > f_2$ and $p > 2cf_2$. Note that A can have a positive or negative value in our study. If fuel consumption increases, then $A > 0$; if fuel consumption decreases, then $A < 0$. The VSRIP may attract a large number of new ships to visit the port, or it may not be attractive (i.e., the subsidy sensitivity of new ships a_2 is insignificant) for many reasons. For example, there may be no other ports near the port with the VSRIP, making it difficult to entice ships that always berth at other ports to visit this port; alternatively, some ships may have signed contracts with other ports that offer a lower service charge. It is evident that if $A \leq 0$, which may occur when new ships are not sensitive to the subsidy or when the upper speed limit in the VSRZ is very low, the total damage cost will decrease after the VSRIP is adopted, i.e., $C_1^* \leq C_0$; otherwise, the total damage cost will increase, i.e., $C_1^* > C_0$.

2.3. Case 2: Sharing subsidy policy

Two policies can be adopted to reduce the government cost. The first policy is that the local government intervenes in the VSRIP by sharing a certain proportion of the program subsidy (denoted by t) for each ship visit. If $t = 1$, the port will set the program subsidy as high as possible until no new ships will be attracted by the program, which will result in a significant increase in the government cost. Therefore, the government will not pay a full subsidy for the VSRIP. The government cost $C_2(t)$ consists of the total damage cost of air emissions and the government subsidy, and the port profit $\Pi_2(t, x)$ is calculated as the profit from all ships minus the port subsidy. The introduction of a sharing subsidy policy guarantees that the government cost can be reduced after the adoption of the VSRIP. We present a bilevel Stackelberg game model [M2] to minimize the government cost at the upper level and to maximize the port profit at the lower level:

$$\text{[M2]} \quad \min_t C_2(t) = cf_1(Q_0 - a_1x_2^*) + cf_2(a_1x_2^* + a_2x_2^*) + tx_2^*(a_1x_2^* + a_2x_2^*) \tag{15}$$

$$\text{subject to} \quad C_2(t) \leq C_1^* \tag{16}$$

$$x_2^* \in \arg\max_x \Pi_2(t, x) \tag{17}$$

$$\max_x \Pi_2(t, x) = p(Q_0 + \tilde{Q}(x)) - (1 - t)x(\hat{Q}(x) + \tilde{Q}(x)) \tag{18}$$

subject to (3), (4) and

$$0 < t < 1 \tag{19}$$

$$0 \leq x \leq p. \tag{20}$$

The government is the leader and can forecast the response of the port (the follower) for a given proportion of the program subsidy offered by the government. Based on the response of the port, the government can make the best decision for the shared proportion of the program subsidy to minimize the government cost. Hence, we analyze the lower level of model [M2] first and focus on $\Pi_2(t, x)$, which is also a concave function in x. When the first partial derivative of $\Pi_2(t, x)$ in x is 0, we can obtain the optimal program subsidy per ship visit x_2^* on t:

$$x_2^* = \frac{a_2p}{2(1 - t)(a_1 + a_2)}. \tag{21}$$

Defining $\tilde{t} = 1/(1-t)$, we have

$$x_2^* = \frac{a_2 p \cdot \tilde{t}}{2(a_1 + a_2)}. \tag{22}$$

The government cost model with x_2^* is

$$C_2(\tilde{t}) = cf_1 Q_0 + \frac{{a_2}^2 p^2 \cdot \tilde{t}^2 + 2cA \cdot a_2 p \cdot \tilde{t} - {a_2}^2 p^2 \cdot \tilde{t}}{4(a_1 + a_2)}. \tag{23}$$

It is easy to prove that $C_2(\tilde{t})$ is convex in $\tilde{t}$. The optimal solution $\tilde{t}^*$ can be obtained when the first-order derivative of $C_2(\tilde{t})$ is 0:

$$\tilde{t}^* = \frac{a_2 p - 2cA}{2a_2 p}, \tag{24}$$

and hence, the optimal proportion of program subsidy shared by the government t^* is

$$t^* = \frac{a_2 p + 2cA}{-a_2 p + 2cA}. \tag{25}$$

Only when $A < -a_2 p/2c$ is t^* within its domain. Here, $A < -a_2 p/2c$ means that a unit increase in program subsidy per ship visit will lead to a decrease in the total fuel consumption of more than $a_2 p/2c$ units, which could be a result of a low subsidy sensitivity of new ships or of a low speed limit in the VSRZ. We derive x_2^* as

$$x_2^* = \frac{a_2 p - 2cA}{4(a_1 + a_2)}. \tag{26}$$

It is inferred that $x_2^* > [a_2(p - 2cf_2)]/[4(a_1 + a_2)] > 0$ and $x_2^* < 3pa_1/[4(a_1 + a_2)] < p$. Therefore, x_2^* is always within its domain.

Proposition 1. *If $A < -a_2 p/2c$, the government will intervene in the VSRIP by providing subsidy $t^* x_2^*$ for each ship visit, and the port will provide $(1 - t^*)x_2^* = x_1^*$ for each ship visit; otherwise, the government will not provide a subsidy for the VSRIP, but the port will still provide x_1^* for each ship visit.*

Proof. See Appendix B. □

We find that the optimal solutions for the port subsidy per ship visit is identical under no government intervention (Case 1) and under the sharing subsidy policy (Case 2). The maximum port profit in Case 1 can be obtained at x_1^*, which indicates that the port subsidy will increase faster than the profit from new ships when the port subsidy per ship visit is greater than x_1^*, and this relationship between the port subsidy and the profit from new ships will not change when the government subsidy is introduced in Case 2. Therefore, the optimal port subsidy per ship visit in Case 2 is still x_1^*. The phenomenon that the port will provide the same amount of subsidy per ship visit (i.e., x_1^*) in Cases 1 and 2 can also be explained as follows: 1) there is a quadratic term of the port subsidy per ship visit in the port profit functions in Cases 1 and 2; 2) the first-order derivative of the port profit function with the port subsidy per ship visit in Case 1 is proportional ($1/(1-t)$ times) to that in Case 2, the proof of which is shown in Appendix C; 3) we can derive that both $\Pi_1(x)$ and $\Pi_2(t, \tilde{x})$ are concave functions of the port subsidy per ship visit, and hence, the maximum port profits in the two cases can be obtained when the first-order derivatives of their profit functions with the port subsidy per ship visit are equal to 0.

According to Proposition 1, the sharing subsidy policy will be enforced only when $A < -a_2p/2c$. Therefore, based on the decisions of the port and the government, we can determine that when $A < -a_2p/2c$, the numbers of original ships and new ships attracted by the VSRIP (i.e., $\hat{Q}_2^*$ and $\tilde{Q}_2^*$) are

$$\hat{Q}_2^* = \frac{a_1(a_2p - 2cA)}{4(a_1 + a_2)} \tag{27}$$

and

$$\tilde{Q}_2^* = \frac{a_2(a_2p - 2cA)}{4(a_1 + a_2)}, \tag{28}$$

and the minimum government cost and the maximum port profit are

$$C_2^* = cf_1Q_0 - \frac{(a_2p - 2cA)^2}{16(a_1 + a_2)} \tag{29}$$

and

$$\Pi_2^* = pQ_0 + \frac{a_2p(a_2p - 2cA)}{8(a_1 + a_2)}. \tag{30}$$

Proposition 2. *When $A < -a_2p/2c$, we have $C_2^* < C_1^* < C_0$ and $\Pi_2^* > \Pi_1^* > \Pi_0$.*

Proof. See Appendix D. □

We have explained the rationality of the relationships between C_1^* and C_0 and between Π_1^* and Π_0 in Section 2.2. The relationships between C_2^* and C_1^* and between Π_2^* and Π_1^* in Proposition 2 are also reasonable for the following reason. When $A < -a_2p/2c$, the government can reduce its cost (i.e., $C_2^* < C_1^*$) by sharing a part of the program subsidy per ship visit (i.e., $t^* x_2^*$) since the decreased damage cost of air emissions is greater than the increased government subsidy, and the port will also benefit from government intervention (i.e., $\Pi_2^* > \Pi_1^*$).

2.4. Case 3: Air emission tax policy

The second policy is that the government will collect taxes on the air emissions which increase after the adoption of the VSRIP, that is, a fixed tax s for the increased air emissions from one ton of fuel. Hence, the total air emission tax S is

$$S = \begin{cases} 0 & \text{if } A \leq 0, \\ sxA & \text{if } 0 < A < \frac{a_2 p}{2c}. \end{cases} \tag{31}$$

When $A \leq 0$, the port does not need to pay any air emission tax. The optimal port subsidy will still be x_1^*. Therefore, we focus on the case of $A > 0$ in this section. Recall that $A < a_2 p/2c$ because $f_1 > f_2$ and $p > 2cf_2$. $C_3(s)$ is the government cost function, including the total damage cost of air emissions minus the total air emission tax. $\Pi_3(s, x)$ is the port profit function considering the port subsidy and air emission taxes. We propose another bilevel Stackelberg game model [M3], where the aim of the upper level is to minimize the government cost and the target of the lower level is to maximize the port profit:

$$[\text{M3}] \quad \min_s C_3(s) = cf_1(Q_0 - a_1 x_3^*) + cf_2(a_1 x_3^* + a_2 x_3^*) - s x_3^* A \tag{32}$$

$$\text{subject to} \quad C_3(s) \leq C_1^* \tag{33}$$

$$x_3^* \in \arg\max_x \Pi_3(s, x) \tag{34}$$

$$\max_x \Pi_3(s, x) = p(Q_0 + \tilde{Q}(x)) - x(\hat{Q}(x) + \tilde{Q}(x)) - S \tag{35}$$

subject to (3), (4) and

$$s \geq 0 \tag{36}$$

$$0 \leq x \leq p. \tag{37}$$

The government is still the leader and determines the tax by predicting the response of the port (the follower). $\Pi_3(s, x)$ is a concave function in x. Denote by x_3^* the optimal solution to $\Pi_3(s, x)$. When $x = x_3^*$, the first partial derivative is equal to 0. Therefore, x_3^* on the tax s can be calculated as

$$x_3^* = \frac{a_2 p - sA}{2(a_1 + a_2)}. \tag{38}$$

Plugging x_3^* into $C_3(s)$, we obtain

$$C_3(s) = cf_1 Q_0 + \frac{A(c - s)(a_2 p - sA)}{2(a_1 + a_2)}, \tag{39}$$

which is a convex function in s. The optimal air emission tax s^* can be obtained by letting the first-order derivative of $C_3(s)$ be equal to 0. Then s^* is

$$s^* = \frac{a_2 p + cA}{2A} > 0. \tag{40}$$

The optimal program subsidy per ship visit x_3^* is

$$x_3^* = \frac{a_2 p - cA}{4(a_1 + a_2)}. \tag{41}$$

It is easy to show that $0 < x_3^* < p$.

Considering the optimal program subsidy, $\hat{Q}_3^*$ original ships and $\tilde{Q}_3^*$ new ships will be attracted:

$$\hat{Q}_3^* = \frac{a_1(a_2 p - cA)}{4(a_1 + a_2)} \tag{42}$$

and

$$\tilde{Q}_3^* = \frac{a_2(a_2 p - cA)}{4(a_1 + a_2)}. \tag{43}$$

The minimum government cost and the maximum port profit are

$$C_3^* = cf_1 Q_0 - \frac{(a_2 p - cA)^2}{8(a_1 + a_2)} \tag{44}$$

and

$$\Pi_3^* = pQ_0 + \frac{(a_2 p - cA)^2}{16(a_1 + a_2)}. \tag{45}$$

Proposition 3. *When $0 < A < a_2 p/2c$, we have $C_3^* < C_0 < C_1^*$ and $\Pi_1^* > \Pi_3^* > \Pi_0$.*

Proof. See Appendix E. □

In this section, focusing on the case of $0 < A < a_2p/2c$, the government will enact an air emission tax policy to minimize its cost, where the tax must be sufficiently large to guarantee that the government cost of Case 3 will not exceed that of Case 0; otherwise, the government will increase the tax. Based on this policy, the port aims to maximize its total profit by designing an optimal program subsidy for the VSRIP, and the program will be cancelled if it cannot improve the total profit. Note that the increased profit related to the VSRIP will decrease due to the air emission tax policy. We can achieve an equilibrium between the two players in which the tax revenue received by the government is higher than the increased damage cost of air emissions and the port's profit from new ships is higher than the air emission tax and the total port subsidy. Therefore, the government cost in Case 3 will be lower than that in Case 0 (i.e., $C_3^* < C_0$), and the port profit in Case 3 will be lower than that in Case 1 (i.e., $\Pi_3^* < \Pi_1^*$) but still higher than that in Case 0 (i.e., $\Pi_3^* > \Pi_0$) in the equilibrium state.

The decisions and effects of the government policy and program subsidy are summarized in Table 3. We observe a surprising result: there exists an interval of A without government intervention between two intervals with different intervention policies. The reason may lie in the different concerns of the two government intervention policies. The sharing subsidy policy is relevant to the numbers of original and new ships following the rules of the VSRIP, and the air emission taxes are dependent on the increase in air emissions. In addition, when $-a_2p/2c \leq A \leq 0$, meaning that the decrease in the total fuel consumption is significantly small for each unit increase of the program subsidy per ship visit, the government subsidy cannot be offset by the decreased damage cost of air emissions, and hence, the contribution of the VSRIP to the reduction in the damage cost is insufficient to motivate the government to provide a subsidy. For simplification of expression, we define

$$(x^*, \Pi^*, C^*, \hat{Q}^*, \tilde{Q}^*) = \begin{cases} (x_2^*, \Pi_2^*, C_2^*, \hat{Q}_2^*, \tilde{Q}_2^*) & \text{if } A < -\frac{a_2p}{2c}, \\ (x_1^*, \Pi_1^*, C_1^*, \hat{Q}_1^*, \tilde{Q}_1^*) & \text{if } -\frac{a_2p}{2c} \leq A \leq 0, \\ (x_3^*, \Pi_3^*, C_3^*, \hat{Q}_3^*, \tilde{Q}_3^*) & \text{if } 0 < A < \frac{a_2p}{2c}. \end{cases} \quad (46)$$

3. Analysis

In this section, we examine the impacts of the damage cost of air emissions from one ton of fuel and the subsidy sensitivities of original and new ships on the decisions made by the shipping companies, the maximum port profit, and the minimum government cost.

Table 3: The decisions and effects of government policy and program subsidy

Intervals of A	$A < -\frac{a_2 p}{2c}$	$-\frac{a_2 p}{2c} \leq A \leq 0$	$0 < A < \frac{a_2 p}{2c}$
Optimal government policy	Sharing subsidy policy	No intervention	Air emission tax policy
Optimal program subsidy per ship visit	x_2^*	x_1^*	x_3^*
Number of original ships participating in the VSRIP comparison	$\hat{Q}_2^* > \hat{Q}_1^*$	N.A.	$\hat{Q}_3^* < \hat{Q}_1^*$
Number of new ships participating in the VSRIP comparison	$\tilde{Q}_2^* > \tilde{Q}_1^*$	N.A.	$\tilde{Q}_3^* < \tilde{Q}_1^*$
Port profit comparison	$\Pi_2^* > \Pi_1^* > \Pi_0$	$\Pi_1^* > \Pi_0$	$\Pi_1^* > \Pi_3^* > \Pi_0$
Government cost comparison	$C_2^* < C_1^* < C_0$	$C_1^* \leq C_0$	$C_3^* < C_0 < C_1^*$

3.1. Effects of the damage cost of air emissions per ton of fuel

The value of the damage cost c of air emissions per ton of fuel is related to several factors, including population density near the port, wind direction, and fuel quality. Eqs. (10) and (11) show that c has no effect on the numbers of original and new ships that will participate in the VSRIP when there is no government intervention. Referring to the optimal policy in each interval of A, as shown in Table 3, we see that when c grows, the shipping companies will increase the numbers of original and new ships participating in the program if the government shares the subsidy, and they will reduce these numbers if the government collects air emission taxes, which can be easily derived from Eqs. (27), (28), (42), and (43). The reasons for the above findings are as follows. The shipping companies determine participation depending on the optimal program subsidy per ship visit x^* when we analyze the effect of c. We observe that x^* will not change, will rise, and will fall with the increase of c when the government does not intervene, offers a subsidy, and collects air emission taxes, respectively, and the number of ships participating in the program will have the same change tendency with c.

As shown in Table 4, whether the values of two first-order derivatives dC_2^*/dc and dC_1^*/dc in c are greater than 0 cannot be estimated directly, which requires further analysis, and we obtain $dC_2^*/dc > 0$ and $dC_1^*/dc > 0$ by the results in Appendix F. Therefore, as shown in Table 4, we have the following proposition.

Proposition 4. *The impacts of c on Π^* and C^* are as follows: 1) when $A < -a_2p/2c$, Π_2^* will increase in c; when $-a_2p/2c \leq A \leq 0$, a change in c will not affect Π_1^*; when $0 < A < a_2p/2c$, Π_3^* will decrease in c; 2) C^* will increase in c within each interval of A.*

To interpret the results of Proposition 4, we focus on the terms of each Π^* and C^* with an increase in c as follows. When $A < -a_2p/2c$, the government will provide a larger subsidy per ship visit, but the port subsidy per ship visit will not change; hence, the numbers of original and new ships participating in the program will increase. The added profit is greater than the increased subsidy at the port, so the total profit Π_2^* will rise. When $-a_2p/2c \leq A \leq 0$, the port profit will not be affected by c because c is not included in any term of Π_1^*. When $0 < A < a_2p/2c$, the tax per ship visit will increase, and the program subsidy per ship visit will decrease, leading to a reduction in the numbers of the two types of ships following the rules of the program. Then, the profit from new ships will shrink, and the reduced profit will become greater than the total reduced subsidy and tax provided by the port. Therefore, the total profit Π_3^* will decrease. In addition, as the total damage cost of air emissions is a major term of C^*, it makes sense that the increase of c will always result in an expansion of C^*, even if the government can adjust the subsidy and the tax to find a new equilibrium when $A < -a_2p/2c$ and $0 < A < a_2p/2c$, respectively.

Table 4: Impact of c on Π^* and C^*

Intervals of A	$\frac{d\Pi^*}{dc}$	$\frac{dC^*}{dc}$
$A < -\frac{a_2p}{2c}$	$-\frac{a_2pA}{4(a_1+a_2)} > 0$	$f_1Q_0 + \frac{(a_2p-2cA)A}{4(a_1+a_2)} > 0^{[*]}$
$-\frac{a_2p}{2c} \leq A \leq 0$	0	$f_1Q_0 + \frac{a_2pA}{2(a_1+a_2)} > 0^{[*]}$
$0 < A < \frac{a_2p}{2c}$	$-\frac{(a_2p-cA)A}{8(a_1+a_2)} < 0$	$f_1Q_0 + \frac{(a_2p-cA)A}{4(a_1+a_2)} > 0$

Notes: 1) "> 0" or "< 0" is shown after a first-order derivative if its value is always positive or negative, respectively, with the increase of c. 2) "[$*$]" is shown as a right superscript of "> 0" if the value interval of a first-order derivative is greater than 0 but cannot be estimated directly. 3) "$\frac{d\Pi^*}{dc}$" is the first-order derivative of Π^* in c, and "$\frac{dC^*}{dc}$" is the first-order derivative of C^* in c.

3.2. Effects of the subsidy sensitivities of original and new ships

We now analyze the impacts of the subsidy sensitivities of original and new ships (i.e., a_1 and a_2) on the numbers of the two types of ships participating in the program (i.e., $\hat{Q}^*$ and $\tilde{Q}^*$) using the related first-order derivatives. Based on the findings in Tables 5 and 6, we present Proposition 5.

Proposition 5. *The impacts of a_1 on $\hat{Q}^*$, a_1 on $\tilde{Q}^*$, a_2 on $\hat{Q}^*$, and a_2 on $\tilde{Q}^*$ are as follows: 1) an increase in a_1 or a_2 will lead to a larger $\hat{Q}^*$ or $\tilde{Q}^*$, respectively, during each domain of A; 2) $\tilde{Q}^*$ will decrease in a_1 and $\hat{Q}^*$ will increase in a_2 when $-a_2p/2c \leq A \leq 0$ or $0 < A < a_2p/2c$; 3) when $A < -a_2p/2c$, the monotonicity of $\tilde{Q}^*$ in a_1 and that of $\hat{Q}^*$ in a_2 are opposite, dependent on the relationship between $2cf_1$ and p (i.e., if $p > 2cf_1$, $\hat{Q}^*$ will increase with a_2 and $\tilde{Q}^*$ will decrease with a_1; if $p = 2cf_1$, $\hat{Q}^*$ and $\tilde{Q}^*$ are constant with the change of a_2 and a_1, respectively; otherwise, $\hat{Q}^*$ will decrease with a_2 and $\tilde{Q}^*$ will increase with a_1).*

It should be noted that the change in $\tilde{Q}^*$ with a_1 is determined by the relationship between x^* and a_1, and the increase or decrease in $\hat{Q}^*$ and x^* with a_2 is identical, while the monotonicity of $\hat{Q}^*$ in a_1 and $\tilde{Q}^*$ in a_2 may be different from the monotonicity of x^* in a_1 and x^* in a_2.

Table 5: Impact of a_1 on $\hat{Q}^*$ and $\tilde{Q}^*$

Intervals of A (Intervals of a_1)	$\frac{d\hat{Q}^*}{da_1}$	$\frac{d\tilde{Q}^*}{da_1}$
$A < -\frac{a_2p}{2c}$ $(a_1 > \overline{a}_1)$	$\frac{a_2(a_2p-2cA)+2a_1c(f_1-f_2)(a_1+a_2)}{4(a_1+a_2)^2} > 0$	$\frac{{a_2}^2(2cf_1-p)}{4(a_1+a_2)^2}$
$-\frac{a_2p}{2c} \leq A \leq 0$ $(\overline{a}_1 \geq a_1 \geq \underline{a}_1)$	$\frac{{a_2}^2p}{2(a_1+a_2)^2} > 0$	$-\frac{{a_2}^2p}{2(a_1+a_2)^2} < 0$
$0 < A < \frac{a_2p}{2c}$ $(\underline{a}_1 > a_1 > 0)$	$\frac{a_2(a_2p-cA)+a_1c(f_1-f_2)(a_1+a_2)}{4(a_1+a_2)^2} > 0$	$\frac{{a_2}^2(cf_1-p)}{4(a_1+a_2)^2} < 0$

Notes: 1) "$\underline{a}_1$" is defined as $\frac{f_2a_2}{f_1-f_2}$ and "$\overline{a}_1$" is defined as $\frac{a_2p+2cf_2a_2}{2c(f_1-f_2)}$. 2) "$\frac{d\hat{Q}^*}{da_1}$" is the first-order derivative of $\hat{Q}^*$ in a_1, and "$\frac{d\tilde{Q}^*}{da_1}$" is the first-order derivative of $\tilde{Q}^*$ in a_1.

The changes in the maximum port profit Π^* and the minimum government cost C^* with a_1 in each interval of A are shown in Table 7. Summarizing the results in Table 7 yields Proposition 6.

Table 6: Impact of a_2 on $\hat{Q}^*$ and $\tilde{Q}^*$

Intervals of A (Intervals of a_2)	$\frac{d\hat{Q}^*}{da_2}$	$\frac{d\tilde{Q}^*}{da_2}$
$A < -\frac{a_2 p}{2c}$ $(0 < a_2 < \underline{a}_2)$	$\frac{a_1^2(p-2cf_1)}{4(a_1+a_2)^2}$	$\frac{a_1(a_2p-2cA)+a_2(p-2cf_2)(a_1+a_2)}{4(a_1+a_2)^2} > 0$
$-\frac{a_2 p}{2c} \le A \le 0$ $(\underline{a}_2 \le a_2 \le \overline{a}_2)$	$\frac{{a_1}^2 p}{2(a_1+a_2)^2} > 0$	$\frac{2a_1a_2p+{a_2}^2p}{2(a_1+a_2)^2} > 0$
$0 < A < \frac{a_2 p}{2c}$ $(a_2 > \overline{a}_2)$	$\frac{a_1^2(p-cf_1)}{4(a_1+a_2)^2} > 0$	$\frac{a_1(a_2p-cA)+a_2(p-cf_2)(a_1+a_2)}{4(a_1+a_2)^2} > 0$

Notes: 1) "$\underline{a}_2$" is defined as $\frac{2c(f_1-f_2)a_1}{p+2cf_2}$ and "$\overline{a}_2$" is defined as $\frac{(f_1-f_2)a_1}{f_2}$. 2) "$\frac{d\hat{Q}^*}{da_2}$" is the first-order derivative of $\hat{Q}^*$ in a_2, and "$\frac{d\tilde{Q}^*}{da_2}$" is the first-order derivative of $\tilde{Q}^*$ in a_2.

Proposition 6. *The impacts of a_1 on Π^* and C^* are as follows: 1) when $A < -a_2p/2c$, the monotonicity of Π_2^* in a_1 is related to the relationship between $2cf_1$ and p (i.e., Π_2^* will increase with a_1 if $2cf_1 > p$, a_1 has no effect on Π_2^* if $2cf_1 = p$, and otherwise Π_2^* will decrease with a_1), and an increase in a_1 will cause a decrease in C_2^*; 2) when $-a_2p/2c \le A \le 0$, an increase of a_1 will cause a decrease of Π_1^* and C_1^* simultaneously; 3) when $0 < A < a_2p/2c$, the values of the first-order derivatives of Π_3^* and C_3^* in a_1 are related to their corresponding parameter values.*

The findings in Proposition 6 make practical sense. A look at Eqs. (25), (26), (27), and (28) reveals that when a_1 increases after $\overline{a}_1$ (see Table 7), the government subsidy per ship visit will increase and the port subsidy per ship visit will decrease, and the total number of ships participating in the VSRIP will increase. The added government subsidy is less than the reduced damage cost of air emissions, leading to a decrease in the government cost, and the change in the port profit cannot be determined, as the changes in the port subsidy and the profit from new ships are relevant to the corresponding parameter values. When $-a_2p/2c \le A \le 0$, an increase in a_1 will result in a decrease in the program subsidy per ship visit; the number of original ships participating in the program will then increase and the number of new ships attracted by the program will decrease, but the total number of ships in the program will not change. Comparing the reduced profit from new ships and the decreased port subsidy and considering the reduction in the damage cost of air emissions, we conclude that both Π_1^* and C_1^* will decrease. When $0 < A < a_2p/2c$, the second derivatives of Π_3^* and C_3^* are

$$\frac{d^2\Pi_3^*}{d{a_1}^2} = \frac{{a_2}^2(p - cf_1)^2}{8(a_1 + a_2)^3} > 0, \tag{47}$$

and

$$\frac{d^2C_3^*}{d{a_1}^2} = -\frac{{a_2}^2(p - cf_1)^2}{4(a_1 + a_2)^3} < 0. \tag{48}$$

Therefore, Π_3^* is a convex function and C_3^* is a concave function in a_1, and there may exist three change tendencies of Π_3^* with an increase in a_1 (i.e., decrease, decrease first and then increase, or increase) and C_3^* with a_1 (i.e., increase, increase first and then decrease, or decrease), as shown in Figs. 1 and 2, respectively. We conclude that with an increase in a_1, the tax per ship visit will increase, the program subsidy per ship visit will decrease, and the total number of ships attracted by the VSRIP will increase with the increase in the number of original ships and the decrease in the number of new ships. However, since we cannot compare the first-order derivatives of its terms, the monotonicity of the port profit (the government cost) in a_1 cannot be derived, which can also be confirmed by Fig. 1 (Fig. 2).

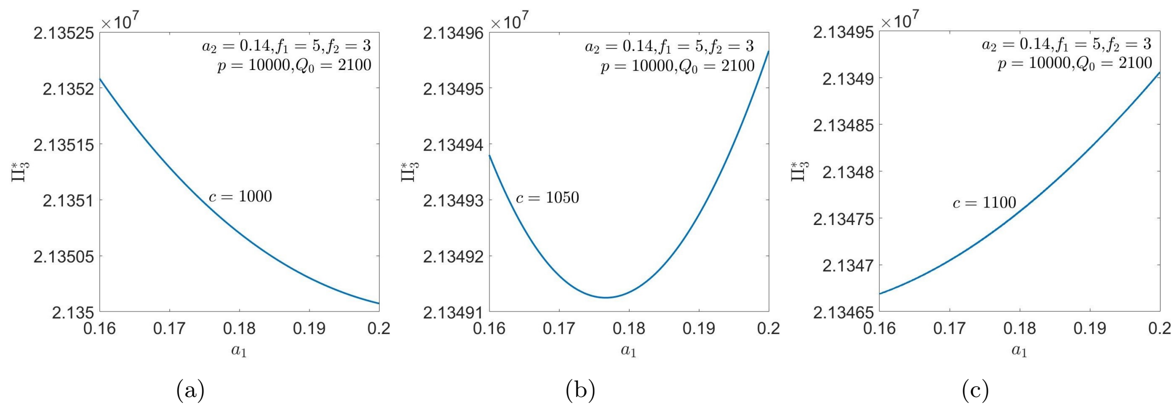
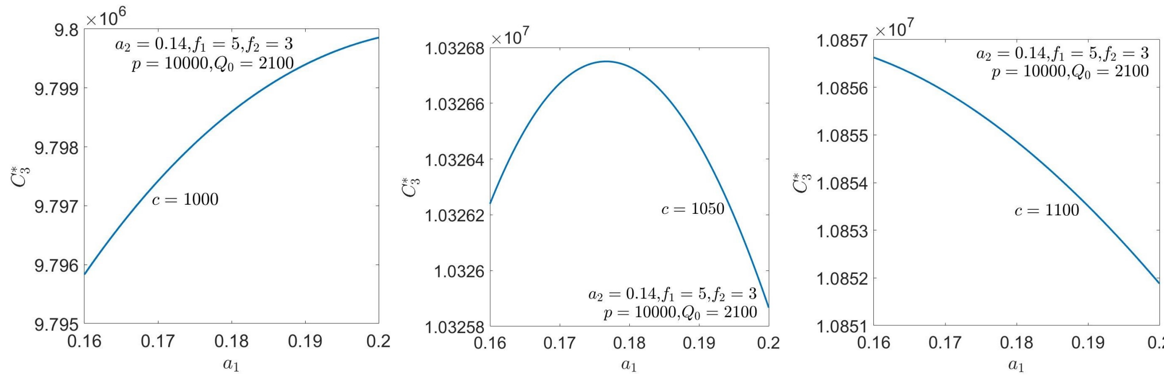


Figure 1: Three change tendencies of Π_3^* with the increase of a_1

Table 8 reports the first-order derivatives of Π^* and C^* in a_2 within each interval. We summarize the results of this table in the following proposition.

Proposition 7. *The impacts of a_2 on Π^* and C^* are as follows: 1) Π_1^*, Π_2^* and Π_3^* are all increasing monotonically in a_2 in the related intervals of A; 2) when $A < -a_2p/2c$ or*



(a) (b) (c)

Figure 2: Three change tendencies of C_3^* with the increase of a_1

Table 7: Impact of a_1 on Π^* and C^*

Intervals of A (Intervals of a_1)	$\frac{d\Pi^*}{da_1}$	$\frac{dC^*}{da_1}$
$A < -\frac{a_2 p}{2c}$ ($a_1 > \overline{a}_1$)	$\frac{{a_2}^2 p(2cf_1 - p)}{8(a_1+a_2)^2}$	$\frac{(a_2 p - 2cA)(a_2 p + 2cA - 4cf_1 a_2)}{16(a_1+a_2)^2} < 0$
$-\frac{a_2 p}{2c} \leq A \leq 0$ ($\overline{a}_1 \geq a_1 \geq \underline{a}_1$)	$-\frac{{a_2}^2 p^2}{4(a_1+a_2)^2} < 0$	$-\frac{{a_2}^2 p \cdot cf_1}{2(a_1+a_2)^2} < 0$
$0 < A < \frac{a_2 p}{2c}$ ($\underline{a}_1 > a_1 > 0$)	$\frac{(a_2 p - cA)(2cf_1 a_2 - a_2 p - cA)}{16(a_1+a_2)^2}$	$\frac{(a_2 p - cA)(a_2 p + cA - 2cf_1 a_2)}{8(a_1+a_2)^2}$

Notes: 1) See Table 5 for the definitions of $\underline{a}_1$ and $\overline{a}_1$. 2) "$\frac{d\Pi^*}{da_1}$" is the first-order derivative of Π^* in a_1, and "$\frac{dC^*}{da_1}$" is the first-order derivative of C^* in a_1.

$-a_2 p/2c \leq A \leq 0$, *C^* may or may not increase in a_2; when* $0 < A < a_2 p/2c$, *C_3^* will decrease in a_2.*

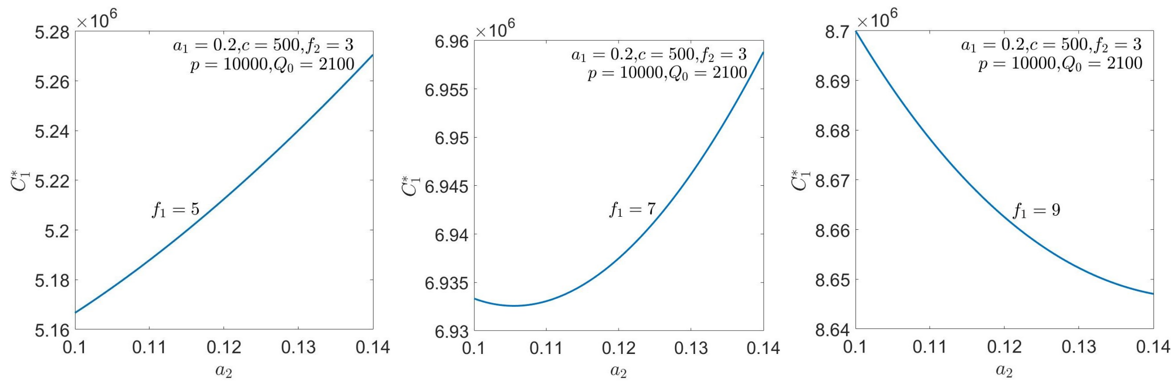
For the first part of Proposition 7, a reasonable explanation is that an increase in a_2 means a unit of program subsidy can attract more new ships, which may contribute to a rise in profit from the new ships that is a major component of the port profit. Although the equilibrium will change with the upturn of a_2 in each of the three intervals, the port profit will finally increase after changes in several terms. In the intervals of $-a_2 p/2c \leq A \leq 0$ and $A < -a_2 p/2c$, we can obtain the second-order derivatives of C_1^* and C_2^* as

$$\frac{d^2 C_1^*}{d{a_2}^2} = \frac{{a_1}^2 p \cdot cf_1}{(a_1 + a_2)^3} > 0 \tag{49}$$

and

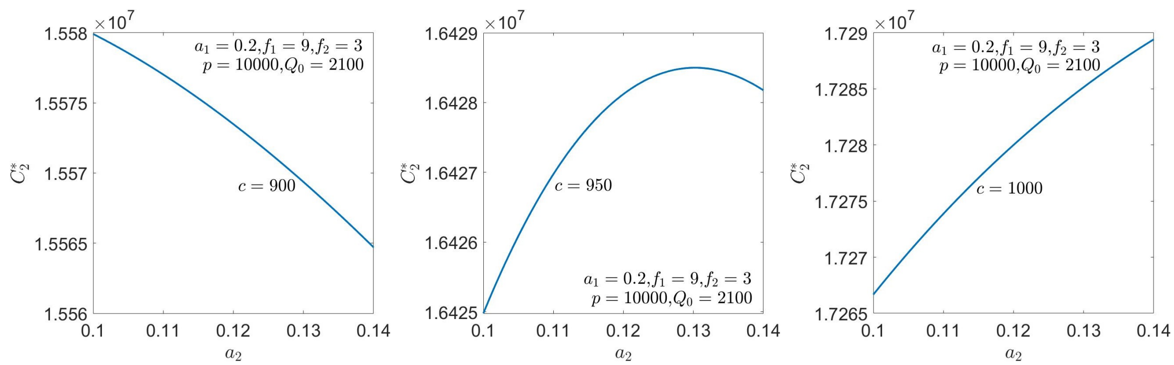
$$\frac{d^2 C_2^*}{d{a_2}^2} = -\frac{{a_1}^2 (p - 2cf_1)^2}{8(a_1 + a_2)^3} < 0. \tag{50}$$

The two second-order derivatives show that C_1^* is a convex function in a_2 and C_2^* is a concave function in a_2. Figs. 3 and 4 illustrate the possible relationships between C_1^* and a_2 and between C_2^* and a_2, respectively. When $A < -a_2 p/2c$, an increase in a_2 will lead



(a) (b) (c)

Figure 3: Three change tendencies of C_1^* with the increase of a_2



(a) (b) (c)

Figure 4: Three change tendencies of C_2^* with the increase of a_2

to a reduction in the government subsidy per ship visit and to a rise in the number of new ships and in the total number of ships participating in the program, but we cannot further derive the change in the damage cost of air emissions. Hence, we cannot explain the change in C_2^* with a_2. When $-a_2p/2c \le A \le 0$, if a_2 grows, the program subsidy per ship visit and the numbers of original and new ships following the rules in the VSRIP will all increase, meaning that the air emissions from the original ships will decrease and the air emissions from the new ships will increase, but whether the change in the amount of air emissions from the original ships will be more than that from the new ships cannot be inferred, and therefore the change in C_1^* with a_2 also cannot be assessed. In addition, when $0 < A < a_2p/2c$, we observe that with the increase of a_2, the tax per ship visit will decrease, the program subsidy per ship visit will grow, and the numbers of the original and new ships attracted by the VSRIP will increase. We also obtain that the added damage cost of air emissions is less than the increased tax, and hence C_3^* is decreasing monotonically in a_2.

Table 8: Impact of a_2 on Π^* and C^*

Intervals of A (Intervals of a_2)	$\frac{d\Pi^*}{da_2}$	$\frac{dC^*}{da_2}$
$A < -\frac{a_2p}{2c}$ $(0 < a_2 < \underline{a}_2)$	$\frac{a_1p(a_2p-2cA)+a_2p(a_1+a_2)(p-2cf_2)}{8(a_1+a_2)^2} > 0$	$\frac{(a_2p-2cA)[2cf_2(a_1+a_2)+2cf_1a_1-2a_1p-a_2p]}{16(a_1+a_2)^2}$
$-\frac{a_2p}{2c} \le A \le 0$ $(\underline{a}_2 \le a_2 \le \overline{a}_2)$	$\frac{2a_1a_2p^2+{a_2}^2p^2}{4(a_1+a_2)^2} > 0$	$\frac{pc[f_2(a_1+a_2)^2-f_1{a_1}^2]}{2(a_1+a_2)^2}$
$0 < A < \frac{a_2p}{2c}$ $(a_2 > \overline{a}_2)$	$\frac{(a_2p-cA)[2a_1p+a_2p-cf_2(a_1+a_2)-cf_1a_1]}{16(a_1+a_2)^2} > 0$	$\frac{(a_2p-cA)[cf_2(a_1+a_2)+cf_1a_1-2a_1p-a_2p]}{8(a_1+a_2)^2} < 0$

Notes: 1) See Table 6 for the definitions of $\underline{a}_2$ and $\overline{a}_2$. 2) "$\frac{d\Pi^*}{da_2}$" is the first-order derivative of Π^* in a_2, and "$\frac{dC^*}{da_2}$" is the first-order derivative of C^* in a_2.

4. Discussion on function of number of ships participating in the VSRIP

We have assumed a linear relationship between the number of original or new ships participating in the VSRIP and the program subsidy per ship visit. Considering the lack of research on the decision process of shipping companies to participate in the subsidy program, we change this assumption in this section and analyze two new assumptions: (i) a linear relationship between the number of original or new ships participating in the program and the *square* of the program subsidy per ship visit (i.e., a convex function $\hat{Q}(x)$ or $\tilde{Q}(x)$ in x), and (ii) a linear relationship between the number of original or new ships participating in the program and the *square root* of the program subsidy per ship visit (i.e., a concave function $\hat{Q}(x)$ or $\tilde{Q}(x)$ in x).

For Assumption (i), we construct the following functions on the numbers of original and new ships that participate in the VSRIP.

$$\hat{Q}(x) = a_1 x^2 \tag{51}$$

and

$$\tilde{Q}(x) = a_2 x^2. \tag{52}$$

Constraints (51) and (52) will replace Constraints (3) and (4) in models [M1], [M2], and [M3], and the objective functions of the three models should also be modified by the two new constraints. Based on the properties of these models, we can derive their optimal solutions as shown in Table 9.

Table 9: Optimal solutions of models [M1], [M2] and [M3] with Assumption (i)

Intervals of A	$A < -\frac{a_2 p}{3c}$	$-\frac{a_2 p}{3c} \le A \le 0$	$0 < A < \frac{a_2 p}{2c}$
Optimal government policy	Sharing subsidy policy	No intervention	Air emission tax policy
Optimal program subsidy per ship visit	$x_2^* = \frac{4a_2p - 6cA}{9(a_1+a_2)}$	$x_1^* = \frac{2a_2p}{3(a_1+a_2)}$	$x_3^* = \frac{4(a_2p - cA)}{9(a_1+a_2)}$
Proportion of program subsidy provided by the government	$t^* = \frac{-a_2p - 3cA}{2a_2p - 3cA}$	N.A.	N.A.
Fixed tax for air emissions from per ton fuel increased after adopting VSRIP	N.A.	N.A.	$s^* = \frac{a_2p + 2cA}{3A}$
Number of original ships participating in the VSRIP	$\hat{Q}_2^* = \frac{4a_1(2a_2p - 3cA)^2}{81(a_1+a_2)^2}$	$\hat{Q}_1^* = \frac{4a_1{a_2}^2p^2}{9(a_1+a_2)^2}$	$\hat{Q}_3^* = \frac{16a_1(a_2p - cA)^2}{81(a_1+a_2)^2}$
Number of new ships participating in the VSRIP	$\tilde{Q}_2^* = \frac{4a_2(2a_2p - 3cA)^2}{81(a_1+a_2)^2}$	$\tilde{Q}_1^* = \frac{4{a_2}^3p^2}{9(a_1+a_2)^2}$	$\tilde{Q}_3^* = \frac{16a_2(a_2p - cA)^2}{81(a_1+a_2)^2}$
Maximum port profit	$\Pi_2^* = pQ_0 + \frac{4a_2p(2a_2p - 3cA)^2}{243(a_1+a_2)^2}$	$\Pi_1^* = pQ_0 + \frac{4{a_2}^3p^3}{27(a_1+a_2)^2}$	$\Pi_3^* = pQ_0 + \frac{32(a_2p - cA)^3}{729(a_1+a_2)^2}$
Minimum government cost	$C_2^* = cf_1Q_0 - \frac{4(2a_2p - 3cA)^3}{729(a_1+a_2)^2}$	$C_1^* = cf_1Q_0 + \frac{4cA \cdot {a_2}^2p^2}{9(a_1+a_2)^2}$	$C_3^* = cf_1Q_0 - \frac{16(a_2p - cA)^3}{243(a_1+a_2)^2}$

Based on Assumption (ii), Constraints (3) and (4) will be substituted by

$$\hat{Q}(x) = a_1 x^{\frac{1}{2}} \tag{53}$$

and

$$\tilde{Q}(x) = a_2 x^{\frac{1}{2}}. \tag{54}$$

Table 10 reports the optimal solutions of the three models.

Table 10: Optimal solutions of models [M1], [M2] and [M3] with Assumption (ii)

Intervals of A	$A < -\frac{2a_2p}{3c}$	$-\frac{2a_2p}{3c} \leq A \leq 0$	$0 < A < \frac{a_2p}{2c}$
Optimal government policy	Sharing subsidy policy	No intervention	Air emission tax policy
Optimal program subsidy per ship visit	$x_2^* = \frac{a_2p-3cA}{9(a_1+a_2)}$	$x_1^* = \frac{a_2p}{3(a_1+a_2)}$	$x_3^* = \frac{a_2p-cA}{9(a_1+a_2)}$
Proportion of program subsidy provided by the government	$t^* = \frac{-2a_2p-3cA}{a_2p-3cA}$	N.A.	N.A.
Fixed tax for air emissions from per ton fuel increased after adopting VSRIP	N.A.	N.A.	$s^* = \frac{2a_2p+cA}{3A}$
Number of original ships participating in the VSRIP	$\hat{Q}_2^* = a_1\left[\frac{a_2p-3cA}{9(a_1+a_2)}\right]^{\frac{1}{2}}$	$\hat{Q}_1^* = a_1\left[\frac{a_2p}{3(a_1+a_2)}\right]^{\frac{1}{2}}$	$\hat{Q}_3^* = a_1\left[\frac{a_2p-cA}{9(a_1+a_2)}\right]^{\frac{1}{2}}$
Number of new ships participating in the VSRIP	$\tilde{Q}_2^* = a_2\left[\frac{a_2p-3cA}{9(a_1+a_2)}\right]^{\frac{1}{2}}$	$\tilde{Q}_1^* = a_2\left[\frac{a_2p}{3(a_1+a_2)}\right]^{\frac{1}{2}}$	$\tilde{Q}_3^* = a_2\left[\frac{a_2p-cA}{9(a_1+a_2)}\right]^{\frac{1}{2}}$
Maximum port profit	$\Pi_2^* = pQ_0 + \frac{2a_2p(a_2p-3cA)^{\frac{1}{2}}}{9(a_1+a_2)^{\frac{1}{2}}}$	$\Pi_1^* = pQ_0 + \frac{2(a_2p)^{\frac{3}{2}}}{3\sqrt{3}(a_1+a_2)^{\frac{1}{2}}}$	$\Pi_3^* = pQ_0 + \frac{2(a_2p-cA)^{\frac{3}{2}}}{27(a_1+a_2)^{\frac{1}{2}}}$
Minimum government cost	$C_2^* = cf_1Q_0 - \frac{2(a_2p-3cA)^{\frac{3}{2}}}{27(a_1+a_2)^{\frac{1}{2}}}$	$C_1^* = cf_1Q_0 + \frac{cA(a_2p)^{\frac{1}{2}}}{\sqrt{3}(a_1+a_2)^{\frac{1}{2}}}$	$C_3^* = cf_1Q_0 - \frac{2(a_2p-cA)^{\frac{3}{2}}}{9(a_1+a_2)^{\frac{1}{2}}}$

Tables 9 and 10 indicate that the optimal solutions of models [M1], [M2], and [M3] as well as the negative threshold of A vary according to the assumption made regarding the number of ships participating in the program. For Assumption (i) or (ii), there still exist three intervals of A (i.e., less than the negative threshold, between the two thresholds, and greater than zero) where the sharing subsidy policy, no government intervention, and the air emission tax policy will be implemented, and the results of the comparison of the numbers of original and new ships participating in the VSRIP, the port profit, and the government cost under different policies are unchanged (see Table 3).

5. Conclusions

We have analyzed a subsidy design problem based on a Stackelberg game, taking into account new ships attracted by the VSRIP and government policies. For each assumption made regarding the number of ships participating in the program, we found that the total change in fuel consumption caused by the unit subsidy provided for each ship visit has two important thresholds: a negative threshold related to parameter values, and zero. When the total change in fuel consumption per unit subsidy provided for each ship visit is less than the negative threshold, the government should enforce the sharing subsidy policy; when it is between the negative threshold and zero, the government should not intervene in the VSRIP; and when it is greater than zero, the optimal decision for the government is the air emission tax policy. For each government policy, the port will adopt the VSRIP and design a different program subsidy per ship visit. An interesting finding is that the port subsidy per ship visit is the same when the sharing subsidy policy is implemented or when the government does not intervene in the VSRIP. Shipping companies will determine their participation rate in the program based on the subsidy provided. The two important indexes (the total change in fuel consumption per unit subsidy for each ship visit and the negative threshold) are determined by several practical factors, such as the damage cost of air emissions per ton of fuel and the subsidy sensitivities of original and new ships. The government should estimate the two indexes in the decision-making process for intervention policies using the values of these factors, and the port can obtain some managerial implications from a sensitivity analysis of several factors. For example, we observe that the port profit increases with the increased subsidy sensitivity of new ships when the total change in fuel consumption per unit subsidy for each ship visit is greater than zero, and hence, a port with more adjacent ports that could lead to a higher subsidy sensitivity of new ships may be better suited to adopt the VSRIP; we also observe that the higher subsidy sensitivity of original ships may lead to fewer new ships, meaning that a port with a higher subsidy sensitivity of original ships may have difficulty improving its profit through the program.

We summarize the performance of the subsidy program as follows. When the VSRIP is adopted, some original and new ships will participate in the program, the port profit will always increase, and the government cost will decrease when the total change in fuel consumption per unit subsidy for each ship visit is negative, and will increase when it is positive. The numbers of original and new ships complying with the rules of the VSRIP (port profit, government cost) can be further increased (increased, decreased) under the sharing subsidy policy. In contrast, the air emission tax policy can lead to a reduction in the numbers of original and new ships participating in the program and can contribute to decreasing government cost and port profit, so the government cost in this case is lower than that without the VSRIP, while the port profit will still be higher than that without the program.

Future research could examine the following two aspects. First, the amount of fuel consumption per ship visit within the VSRZ for ships not participating in the program is assumed to be identical in this study. We can further analyze the subsidy design problem with various types of ships with different sailing speeds and fuel consumption functions. Second, this paper considers only two subsidy providers. Studies involving new subsidy sources, such as a fund from an environmental non-governmental organization, should be of interest.

Appendix A. List of notations

Notations

- a_1 — Subsidy sensitivity of original ships, where subsidy sensitivity is the degree to which the number of ships participating in the VSRIP is affected by the program subsidy per ship visit.
- a_2 — Subsidy sensitivity of new ships, $a_1 > a_2$.
- A — Total change in fuel consumption caused by the per-unit program subsidy provided for each ship visit.
- c — Damage cost of air emissions from consuming one ton of fuel.
- f_1 — Fuel consumption per ship visit within the VSRZ for the ships not participating in the VSRIP.
- f_2 — Fuel consumption per ship visit within the VSRZ for the ships participating in the VSRIP, $f_1 > f_2$.
- p — Profit obtained from each ship visit.
- s — Fixed tax for the air emissions from one ton of fuel that are increased after the adoption of the VSRIP in Case 3.
- s^* — Optimal fixed tax for the air emissions from one ton of fuel that are increased after the adoption of the VSRIP in Case 3.

S	Total fixed tax for the air emissions increased after the adoption of the VSRIP in Case 3.
t	Proportion of program subsidy per ship visit provided by the government in Case 2.
t^*	Optimal proportion of program subsidy per ship visit provided by the government in Case 2.
x	Program subsidy per ship visit.
x_1^*	Optimal program subsidy per ship visit in Case 1.
x_2^*	Optimal program subsidy per ship visit in Case 2.
x_3^*	Optimal program subsidy per ship visit in Case 3.
C_0	Government cost in Case 0.
C_1^*	Government cost in Case 1.
$C_2(t)$	Government cost function in Case 2.
C_2^*	Minimum government cost in Case 2.
$C_3(s)$	Government cost function in Case 3.
C_3^*	Minimum government cost in Case 3.
Π_0	Port profit in Case 0.
$\Pi_1(x)$	Port profit function in Case 1.
Π_1^*	Maximum port profit in Case 1.
$\Pi_2(t,x)$	Port profit function in Case 2.
Π_2^*	Maximum port profit in Case 2.
$\Pi_3(s,x)$	Port profit function in Case 3.
Π_3^*	Maximum port profit in Case 3.
Q_0	Number of original ships visiting the port without the VSRIP.
$\hat{Q}(x)$	Function of the number of original ships participating in the VSRIP.
$\tilde{Q}(x)$	Function of the number of new ships participating in the VSRIP.
$\hat{Q}_1^*$	Optimal number of original ships participating in the VSRIP in Case 1.
$\tilde{Q}_1^*$	Optimal number of new ships participating in the VSRIP in Case 1.
$\hat{Q}_2^*$	Optimal number of original ships participating in the VSRIP in Case 2.
$\tilde{Q}_2^*$	Optimal number of new ships participating in the VSRIP in Case 2.
$\hat{Q}_3^*$	Optimal number of original ships participating in the VSRIP in Case 3.
$\tilde{Q}_3^*$	Optimal number of new ships participating in the VSRIP in Case 3.

Appendix B. Proof of Proposition 1

Proof. When $A < -a_2p/2c$, the optimal proportion of program subsidy per ship visit offered by the government t^* is between 0 and 1, and the optimal program subsidy per ship visit x_2^* is between 0 and p. Hence, the government and the port will provide $t^*x_2^* = (-a_2p - 2cA)/[4(a_1 + a_2)]$ and $(1 - t^*)x_2^* = a_2p/[2(a_1 + a_2)] = x_1^*$ for each ship visit, respectively. When $-a_2p/2c \leq A < a_2p/2c$, the optimal shared proportion of program subsidy t^* will be no greater than 0, and therefore the government can minimize its cost by setting $t = 0$, meaning the government will not intervene in the program. The port will design the optimal program subsidy per ship visit as x_1^* (see Section 2.2). □

Appendix C. Proof on the relationship between the first-order derivative of port profit function in Case 1 and that in Case 2

Proof. In Case 1, we have analyzed in section 2.2 that the first-order derivative of $\Pi_1(x)$ is $a_2p - 2(a_1 + a_2)x$. In Case 2, t is in its domain only when $A < -a_2p/2c$. We rearrange $\Pi_2(t, x)$ by introducing a new variable $\tilde{x} = (1 - t)x$ that is the port subsidy per ship visit, and we have

$$\Pi_2(t, \tilde{x}) = pQ_0 + a_2p \cdot \frac{1}{1-t}\tilde{x} - (a_1 + a_2) \cdot \frac{1}{1-t}\tilde{x}^2 \tag{C.1}$$

with the first-order derivative

$$\frac{d\Pi_2(t, \tilde{x})}{d\tilde{x}} = a_2p \cdot \frac{1}{1-t} - 2(a_1 + a_2) \cdot \frac{1}{1-t}\tilde{x}. \tag{C.2}$$

Therefore, the first-order derivative of $\Pi_2(t, \tilde{x})$ with the port subsidy per ship visit is $1/(1 - t)$ times that of $\Pi_1(x)$. Recall that both x in $\Pi_1(x)$ and $\tilde{x}$ in $\Pi_2(t, \tilde{x})$ are port subsidies per ship visit. □

Appendix D. Proof of Proposition 2

Proof. When $A < -a_2p/2c$, the difference between C_2^* and C_1^* is $C_2^* - C_1^* = -(a_2p + 2cA)^2/[16(a_1+a_2)] < 0$, and the difference between Π_2^* and Π_1^* is $\Pi_2^* - \Pi_1^* = -a_2p(a_2p + 2cA)/[8(a_1+a_2)] > 0$. We have $C_1^* < C_0$ when $A < -a_2p/2c$ based on the analysis in Section 2.2, and the inequality $\Pi_1^* > \Pi_0$ is straightforward. Therefore, this proposition can be obtained by reorganizing the mentioned inequalities. □

Appendix E. Proof of Proposition 3

Proof. These inequalities can be proved easily by referring to the proof of Proposition 2. □

Appendix F. Derivation of the values of $\frac{dC_2^*}{dc}$ and $\frac{dC_1^*}{dc}$

When $A < -a_2p/2c$, as $Q_0 > a_1p$, we derive the first-order derivative of the minimum government cost C_2^* below:

$$\begin{aligned}
\frac{dC_2^*}{dc} &= f_1Q_0 + \frac{(a_2p - 2cA)A}{4(a_1+a_2)} \\
&> f_1 \cdot a_1p + \frac{\{a_2p - 2c[f_2(a_1+a_2) - f_1a_1]\}\,[f_2(a_1+a_2) - f_1a_1]}{4(a_1+a_2)} \\
&= \frac{1}{4(a_1+a_2)}\{2cf_2(a_1+a_2)[2f_1a_1 - f_2(a_1+a_2)]\} \\
&\quad + \frac{1}{4(a_1+a_2)}\left[2f_1{a_1}^2(2p - cf_1) + 3a_2p \cdot f_1a_1 + a_2p \cdot f_2(a_1+a_2)\right] > 0. \quad \text{(F.1)}
\end{aligned}$$

When $-a_2p/2c \le A \le 0$, it follows that

$$\begin{aligned}
\frac{dC_1^*}{dc} &= f_1Q_0 + \frac{a_2pA}{2(a_1+a_2)} > f_1 \cdot a_1p + \frac{a_2p \cdot f_2}{2} - \frac{a_2p \cdot f_1a_1}{2(a_1+a_2)} \\
&= \frac{2a_1p \cdot f_1a_1 + a_2p \cdot f_1a_1}{2(a_1+a_2)} + \frac{a_2p \cdot f_2}{2} > 0. \quad \text{(F.2)}
\end{aligned}$$

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