Emission Control under Private Port Operator Duopoly

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Abstract: Recent trends in regulating maritime vessel emissions have negative effects on the competitiveness of many ports as regulations increase costs for shipping operators calling the ports. This paper develops analytical models to examine the emission standards set by governments for ports in their jurisdictions. Given the emission standards set by governments, which affects fuel cost experienced by shipping operators, ports determine charges for shipping operators. Unilateral, bilateral, and single-country regulation cases are investigated. Specifically, our analysis focuses on how increase in the maximum reservation price of shipping operators, port capacity, and environmental damage costs of ports affect optimal emission standards.

Keywords: Emission standard, Duopoly, Environmental damage cost, Port capacity, Landlord port, Port charge

1 Introduction

Ports are strategic nodes that facilitate intermodal freight transportation, provide value-added services, and create jobs. With developments in global trade and maritime infrastructure, port competition has become increasingly intense, especially between ports with common/overlapping catchment areas. Port competition has been further fueled by grand-scale shipping operator alliances, vessel size increases, and advancements in intermodal shipping networks (Song, 2002; Song, 2003; Cullinane et al., 2005; Yap and Lam, 2006; Chang et al., 2008; Bae et al., 2013). Ship emissions in and around ports have also attracted increasing attention. Such emissions, including SOx, NOx, and particulate matter (PM), lead to detrimental health effects for people in surrounding areas. PM emissions from ships, for example, is estimated to account for 60,000 cardiopulmonary and lung cancer deaths each year globally (Corbett et al., 2007).

To mitigate the negative environmental impacts, many ports have implemented emission controls. These emission control measures may result from local laws and national regulations such as in Singapore and China. At the local level, port-city municipalities pass legislation to regulate ship emissions at and around ports such as in Antwerp and Rotterdam (Lam and Notteboom, 2014), or establish city-wide air pollution mitigation plans with inclusion of the port
sector as in Shanghai and New York (Zheng et al., 2017; Lee et al., 2014). Port authorities, which typically assume public roles, have also been independently adopting emission control measures (Tichavska and Tovar, 2015; Winnes et al., 2015).

While generating environmental benefits, port emission control measures increase costs for shipping operators. Note that the term “port emission” in this paper refers to ship emissions at and around ports. Ongoing shipping costs can increase by 50-160% in switching from fuel containing 4.5% sulfur (the current standard for non-Emission Control Area (ECA) ports) to fuel containing 0.1% sulfur (Notteboom, 2011). Alternatively, ships may install scrubbers to filter out sulfur content, but this remains expensive (Brynolf et al., 2014). To avoid these additional costs, shipping operators may prefer calling ports with lower or no emission controls, which discourages emission control at ports. A news article concerning the designation of the Pearl River Delta in China as an ECA illustrates this point (Wang and Feng, 2014):

“The fuel cost rise may give a disadvantage to ports within the Pearl River Delta and may also damage the competitiveness of corporations using these ports. Industries may be lured to transfer to places outside the ECA and thus damage the local employment.”

A thorough understanding of emission control impacts on port competition is thus needed, but is currently lacking. The existing literature has focused on the interplay among port charges, shipping demand, and capacity expansion (Basso and Zhang, 2007; De Borger and Van Dender; 2006). The implications of emission regulations for ports has attracted attention only recently. A notable study by Homombat et al. (2013) found that if a port levies a higher pollution tax, shipping demand at the port will decrease. The literature, however, has not considered how to determine emission standards and the sensitivity of standards to maximum reservation price, port charges, port capacity, port congestion, and the extent of environmental damage. Neither has the literature investigated the effects of competing ports setting different emission standards. As mentioned prior, this is important for countries and port authorities to consider in regulating ship emissions at and around ports.

This paper develops analytical models to investigate optimal port emission standards in a duopoly port environment. Emission standards regulate the quality of fuel used by shipping operators, in which improved fuel quality (i.e., less noxious gases emitted from fuel consumption) increases fuel cost. While shipping operators can comply with emission regulations through other policy options such as installing scrubbers or using liquefied natural gas (Cullinane and Bergqvist, 2014), we focus on fuel switching in this paper. This is due to the fuel switching option is readily available and the most widely adopted measure by shipping operators.

We consider cases in which ports are located in both the same country and different countries. National governments set emission standards for ports in order to maximize social welfare. Given the emission standards, profit-maximizing private port operators set port charges. However, it should be noted that although we consider national governments being responsible for setting emission standards, the modeling framework is readily applicable to cases in which emission standard setting is established by municipalities or port authorities. Thus, the insights

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1 Throughout this paper, we use “emission control” and “emission regulation” interchangeably.
obtained should be interpreted as more generic than specific to the context of national
governments setting emission standards.

Utilizing the analytical models, we seek to answer the following questions:

a) How will national governments require shipping operators to internalize environmental
damage by setting port emission standards when port operators seek maximizing profits?

b) How will the maximum reservation price of shipping operators, port capacity, and
environmental damage costs affect optimal port emission standards?

c) How will different emission control cases affect establishing emission standards and
interaction between port operators? Specifically, three cases are investigated: 1) unilateral
regulation in which only one country actively regulates port emissions; 2) bilateral regulation
in which two port operators in two countries compete subject to emission standards set by
their respective national governments; 3) a single country in which two ports are located.

In answering the questions above, this paper makes three major contributions to the
literature. First, unlike existing research concerning port competition (e.g., De Borger and Van
Dender, 2006; De Borger et al., 2008; Luo et al., 2012; Chen and Liu, 2016), we consider port
emission standards as decisions made by national governments. Emission standards affect
the quality of fuel used, and consequently, shipping cost. Second, we examine the effects of port
capacity on optimal emission standards. Port capacity is a major determinant in port selection
of shipping operators (Chang et al., 2008). Yet it remains unknown how port capacity increase may
change optimal emission standards of the port and rivals. In fact, capacity consideration is also
lacking in non-maritime emission control research (e.g., Barrett, 1994; Burguet and Sempere,
2003; Greaker and Rosendahl, 2008). Third, we investigate both symmetric and asymmetric
cases, the latter featuring conditions in which not all ports are subject to emission controls (see
Section 4.3).

Furthermore, we consider landlord ports in which private port operators manage terminals
and labor allocation. The role of a port authority is limited to providing basic infrastructure and
mandatory services such as security. Worldwide, the port sector has witnessed a growing
involvement of private operators as a means of improving administration efficiency and
attracting additional capital (Cullinane and Song, 2002). Given that the primary focus of a
private port operator is maximizing profit (De Monie, 1996), the consideration of private port
operators will promote understanding of public-private interaction in the context of port emission
controls; more specifically, how governments should internalize environmental damage by
setting emission standards.

The remainder of this paper is organized as follows: Section 2 reviews the existing literature
regarding port competition and emission regulations. Section 3 develops the theoretical models
of emission regulation for symmetric private port operators and governments. Section 4
examines the case of asymmetric port operators and governments under three emission

2 Empirical evidence points to the growing port capacities in the world. For instance, “based on the
estimated capacity developments up to 2030, it seems there would already be sufficient capacity planned
in most of the regions to accommodate the future traffic growth. Several regions [e.g., Southeast Asia and
China] seem to have quite severe over-planning of capacity increases” (Mooney, 2016). Given this trend,
analyzing the effect of capacity expansion on emission standard seems to be timely.
regulation cases. Numerical analysis is described in Section 4. Conclusions and directions for future research are offered in Section 5.

2 Literature review

Most existing work on port competition assumed that ports compete based on capacity and price. De Borger and Van Dender (2006) proposed a two-stage model in which competing ports initially determine capacities and subsequently prices. The authors compared port congestion under different market structures and found that duopoly facilities led to greater congestion compared with cases of monopoly and welfare maximization due to duopolistic ports deliberately keep capacities low in order to reduce price competition. Their work was extended by Ishii et al. (2013) who introduced stochastic demand and multiple planning periods. They found that higher port charges were imposed with longer planning periods. Anderson et al. (2008) simulated competition between the ports of Shanghai and Busan, and found that different capacity expansion options, such as adding a gantry crane and investing in new ports, can lead to different outcomes. Entry deterrence games were considered in Luo et al. (2012) in which an incumbent port faces a new entrant providing differentiated services. Preemptive pricing and capacity expansion were considered as strategies that the incumbent port can utilize to deter market entry of new port participants. The authors found that the effectiveness of the incumbent strategy depends on the price elasticity of port services and the difference in port market shares. Recently, Chen and Liu (2016) analyzed optimal port capacity, cargo volume, and service price in a duopoly with uncertain demand. The authors found that ports would not invest in conditions featuring high capacity costs, while one or both ports may invest if at least one port has low capacity costs. In addition, less capacity investment will be made when ports are risk-averse compared with risk-neutral.

Port competition has also been investigated in conjunction with hinterland access. De Borger et al. (2008) developed the first port-inland network model in which port competitiveness is determined not only by port charges and capacity, but also by hinterland congestion and road tolls. The authors argued that adding hinterland access capacity would be more desirable than expanding port capacity. Wan and Zhang (2013) assumed Cournot competition between ports based on previous theoretical and empirical evidence with endogenous tolls on access roads, and found that port capacity expansion under quantity competition increases profits as well as reduces rival profits. If tolls are differentiated between commuters and trucks, policy makers should charge trucks lower fees to maintain port competitiveness. Álvarez-SanJaime et al. (2015) studied the effects of port and inland transport service integration on port profits and welfare. Such integration was found advantageous to ports, but with a corresponding potential welfare decrease which negatively affects shippers located closer to ports. An integrated service provider should impose only a fixed charge to attract shippers located in distant regions.

Privatization is an emerging area in which scholars analyze port competition using analytical models. Matsushima and Takauchi (2014) analyzed government incentives to privatize ports for countries involved in international trade. By developing a two-stage model in which ports establish charges and governments determine types of ownership, the authors concluded that a government with a larger domestic market is more likely to nationalize its port in order to protect its domestic market from foreign firms. Czerny et al. (2014) examined strategic welfare gains of privatization when hub ports compete with each other. In their model, ports compete 1) on
transshipment traffic but have their own hinterland demand, and 2) on price. Their results suggest that simultaneous privatization of both ports can increase the social welfare of their respective countries, for privatizing a port signals “commitment to higher prices” to the competing port. In this case, ports can reap significant profits from international transshipping. Wan et al. (2016) analyzed capacity investment for accessibility at two competing ports and one inland region, the latter of which is the destination of cargo traffic. They found that under privatization, capacity expansion in the inland region increases port price, which increases overall welfare in port regions but decreases welfare in the inland region. This leads to an underinvestment problem for both ports and inland regions. To facilitate the coordination among the two ports and the inland region, ports need to compensate the inland region in order to increase its investment.

Limited attention, however, has been paid to addressing emission controls in the context of port competition. As mentioned prior, we are only aware of Homsombat et al. (2013) who examined emission taxation at ports. The authors showed that competing ports would levy a higher emission tax compared with ports that coordinate emission control efforts. Joint welfare maximization between ports drive down emission taxes below the Pigouvian tax rate due to the consideration of promoting maritime business which also benefits society. Wang et al. (2015) benchmarked the economic implications of an open emission trading scheme and a maritime-only emission trading scheme for container shipping and dry bulk sectors. The emission trading schemes will reduce vessel speed, shipping traffic, and ship fuel consumption. Emission permits will be purchased by the container shipping sector from the dry-bulk sector. Sheng et al. (2017) analyzed how unilateral or uniform regulations would affect shipping lines and ports along two different shipping routes. They found that total emissions increase under unilateral regulations, but decrease under uniform regulations. Regarding non-maritime transportation research, Brueckner and Zhang (2010) examined airline responses to emission charges. The authors found that airlines would raise fares and decrease service quality. This analysis was extended by Czerny (2015), who further considered capital costs. He found that in the case that larger aircraft size improved fuel efficiency, emission charges generally increased aircraft size. In the context of competition between high-speed rail (HSR) and aviation, the effect of competition on the environment is inconclusive due to the opposing effects of mode substitution and induced demand (D’Alfonso et al., 2015; Socorro and Viecens, 2013).

In addition to the transportation research, a stream of studies regarding emission regulation in the environmental economics literature is worth noting. Most studies have focused on environmental standards in international trade. Barrett (1994) showed that when firms are involved in Cournot competition, national governments strategically impose weaker emission standards to support domestic firms. However, in the case that firms feature price competition, more stringent emission standards are set. Burguet and Sempere (2003) argued that governments do not necessarily set lower emission standards under reduced tariffs even though they have incentives to support domestic firms. This is because reduced tariffs can significantly deteriorate the local environment. Greker and Rosendahl (2008) examined upstream firms that sell pollution reduction technologies to downstream companies that pollute. They found that governments strengthen emission standards in order to reduce pollution abatement costs by attracting more firms into the upstream market. David and Sinclair-Desgagné (2005) explored the optimal level of policy instruments, such as taxes and emission quotas, with the eco-industry providing abatement technology to polluting firms. The authors concluded that governments
should impose a higher tax than the social cost of emissions to prevent firms from abating “too little” as the eco-industry exercises market power over polluters.

The above review has made clear four gaps in the literature. First, almost no research has been conducted to jointly consider port competition and setting port emission standards. Second, no studies have examined port emission control and congestion simultaneously. Third, asymmetric cases in which not all ports are subject to emission regulations, which can occur in the real world (Sheng et al., 2017), have not been considered. Lastly, no investigation has been performed on the response of emission standards to shipping demand, port capacity, and environmental damage. Our research intends to fill these gaps. It should be noted that congestion in this study is considered negatively associated with port capacity. Worldwide, port capacities have been increasing to handle future cargo traffic (see footnote 2), but often overinvestment in capacity raises concerns for governments. How emission control should be aligned with capacity expansion? Our analysis will provide useful insight for this question.

3 Model: Symmetric case

In this paper, we consider two-stage games. At the first stage, national governments set emission standards for ports within their jurisdiction while anticipating the pricing behavior of ports. The objective of each government is to maximize the social welfare in its jurisdiction, which considers port profit and environmental damage caused by emissions. For the second stage, given the emission standards, each private port operator determines charges to shipping operator in order to maximize profit. In other words, the emission standard is an ‘endogenous variable’ from governments’ perspective, and an ‘exogenous variable’ from ports’ perspective. This section mainly focuses on the situation that two competing ports in different nations are subject to emission control by their respective governments, though other modified cases (i.e., unilateral and single country regulation) are considered for asymmetric ports and governments in Section 4.

The setting of emission standards and determination of port charges depend on the shipping demand at each port, which is a function of the cost per unit cargo incurred to shipping operators calling a port. For simplicity, we consider that a unit cargo is a twenty-foot equivalent unit (TEU) and the unit cost per TEU has three variable components in the context of port emission controls: fuel cost which is directly affected by emission standards, port charges, and port congestion costs.

We use backward induction to model private port operators’ decision first and governments’ decision next. The resulting solutions of emission standards that satisfy private port operators’ profit maximization should be subgame-perfect Nash Equilibrium.

In Section 3.1, we examine the symmetric case with a general fuel cost function. The shipping demand function is specified in Section 3.1.1. We consider two stages of decision-making: emission standard setting (1st stage) in Section 3.1.2 and port charge determination (2nd stage) in Section 3.1.3. In Section 3.2, we analyze the more specific case that the fuel cost function is reciprocal with respect to emission standard. Under the symmetry assumption, the two governments will set the same level of emission standards in equilibrium. We specify the model by assuming the same capacity and environmental damage costs in both countries, in which case the symmetric emission standards lead to symmetric port charges.
3.1 Symmetric case with general fuel cost function

3.1.1 Shipping demand at ports

In this paper, we consider a system consisting of two adjacent ports which provide perfectly substitutable services. This assumption is a simplification of the reality as the two ports can offer differentiated services. For example, some part of a port’s hinterland can be exclusive to the port (Notteboom, 2009; Homsombat et al., 2016, Wan et al., 2016). In addition, complementary services could also exist for cargo moving between the two ports through a feeder line. Considering imperfect substitutability could lead to somewhat different results. However, it is unlikely to change the insights fundamentally, though more analytical complexity would be added as noted in De Borger et al. (2008). In addition, our model can have realistic implications for ports competing over transshipment cargo, as shipping operators would be indifferent to routes featuring the same operating costs. The model developed in this paper can appeal to Asian ports particularly as transshipment competition is most severe among the Asian ports, and the emission control dilemma is more pronounced than ports in Europe and North America. For this reason, the focus of the paper is on transshipment cargo.

Shipping operators select one of the two ports based on the unit cost per TEU. Following De Borger and Van Dender (2006) and De Borger et al. (2008), we assume that total shipping demand at two ports is given by the inverse demand function \( p(Q_1 + Q_2) \). More specifically, \( p(Q_1 + Q_2) \) is the generalized port price that shipping operators charge to ‘shippers’ using a port. Under equilibrium, total demand is distributed at the two ports so that the generalized port prices using the two ports are the same. This leads to:

\[
\begin{align*}
  p(Q_1 + Q_2) &= P_1 + D(Q_1, K) + f(e_1) \\
  p(Q_1 + Q_2) &= P_2 + D(Q_2, K) + f(e_2)
\end{align*}
\]

where \( P_i \) (\( i=1,2 \)) and \( K \) are port charges per TEU at port \( i \) and handling capacity at each port, respectively; \( D(Q_i, K) \) is the port congestion cost which is a function of port demand \( Q_i \) and handling capacity \( K \). Although we assume that the ports considered compete on container cargo, the analysis could be extended to including other types of cargo, and even cruise passengers. Variable \( e_i \) denotes the maximum amount of pollutants per unit cargo (TEU) permitted by the emission standard at port \( i \). \( f(e_1) \) is the resulting additional fuel cost per TEU. A higher \( e_i \) infers a lower emission standard and consequently lower \( f(e_i) \). For the fuel cost function, we only impose its characteristics: \( f'(e_i) < 0 \). For simplicity, we also use more concise notations later \( f_i = f(e_i) \) and \( f'_i = f'(e_i) \).

The fuel cost here should be interpreted as a normalized cost. The original form of fuel cost can be expressed as \( \theta + f(e_i) \), where \( \theta \) is constant and the second term denotes additional cost burden (or compliance cost, or fuel cost premium) resulting from emission regulations. For
example, one can consider $\theta$ as the price of the most noxious marine oil, and $f(e_i)$ as the additional cost of refining fuel to reduce noxious gas content. We normalize $\theta$ to zero for simplicity, and doing so does not affect the main insights obtained in the paper. Thus, in what follows, we mean ‘additional fuel cost burdens due to emission regulation’ by ‘fuel cost.’

In this paper, we consider the following functional forms for $p(Q_i + Q_2)$ and $D(Q_i, K)$:

\[
p(Q_i + Q_2) = b - a(Q_i + Q_2) \quad \text{(3)}
\]

\[
D(Q_i, K) = \alpha \frac{Q_i}{K} \quad \text{for} \quad i=1,2 \quad \text{(4)}
\]

Eq. (3) specifies a linear form of the inverse demand function with parameters $a, b > 0$. Parameter $b$ is the shipping operators’ maximum reservation price, which depends on external forces that influence shipping operators’ willingness to pay. If we assume that ports provide differentiated services (Dixit, 1979), Eq.(3) would be expressed as $p_i(Q_i, Q_2) = b - a_i Q_i - a_j Q_j$, where $i, j = 1, 2$, $i \neq j$, and $a_i > a_j > 0$. Introducing the differentiation parameters would not change the main results of this paper. Thus, we work with the simpler specification in (3).

Eq. (4) defines port congestion cost as a linear function of port demand–capacity ratio, with parameter $\alpha > 0$ being the factor converting the ratio into congestion cost. The specification suggests that congestion cost increases with port demand, but decreases with hourly capacity. This specification was used in previous studies (e.g., Basso and Zhang, 2007; De Borger and Van Dender, 2006) and has the advantage of being simple and amenable to driving analytical insights. On the other hand, as this specification does not restrict demand to be less than port capacity, simulations were performed later with an alternative form of the congestion cost function $\alpha \frac{Q_i}{K(K-Q_i)}$ (Basso, 2008; Zhang and Zhang, 1997). Under this alternative form, congestion cost approaches infinity as $Q_i \to K$, and the restriction that demand not exceeding capacity is automatically satisfied. Results of the simulations are summarized in Appendix N.

Replacing the relevant terms in Eqs. (1) and (2) by their expressions in Eqs. (3) and (4), demand at each port can be derived as follows:

\[
Q_i = (g^2-a^2)^{-1} \{b(g-a)-gP_1+aP_2-gf_1+af_2\} \quad \text{(5)}
\]

\[
Q_2 = (g^2-a^2)^{-1} \{b(g-a)+aP_1-gP_2+af_1-gf_2\} \quad \text{(6)}
\]

where $g = a + \alpha / K > 0$. Holding $e_1$ and $e_2$ constant, we take derivatives of Eq. (5) with respect to $P_1$ and $P_2$, which yields:
Similar expressions can be derived for $Q_2$. Eqs. (7) and (8) are intuitive: shipping demand at a port decreases when its own port charge is increased, and increases when the other port increases its charge.

### 3.1.2 Port charge setting stage

This section analyzes how ports determine charges for maximizing profits in response to established emission standards. In what follows, backward induction is used to investigate the optimality conditions and comparative statics.

Profit maximization for each port can be expressed as:

$$\max_{\pi_i} \pi_i = P_i Q_i, \quad i = 1, 2$$ \hfill (9)

Eq. (9) implicitly assumes that the marginal cost of a port is constant and normalized to zero. In practice, the full cost structure of private port operators can differ considerably by port (Goss, 1990b), so generalizing costs of operators is difficult. Here we consider the most obvious and common cost component for private port operators: the fixed rent paid to the landlord port authorities that is proportional to cargo volumes (Goss, 1990a). This leads to the objective function $\pi_i = (P_i - c)Q_i, \quad i = 1, 2$. The constant marginal cost ‘$c$’ is normalized to zero following Basso and Zhang (2007), as doing so does not affect the main results below.

For Port 1, the first-order condition (FOC) is given by:

$$\frac{\partial \pi_1}{\partial P_1} = Q_1 + P_1 \frac{\partial Q_1}{\partial P_1} = 0$$ \hfill (10)

Substituting Eq. (7) for $\frac{\partial Q_1}{\partial P_1}$ into Eq. (10) results in:

$$\frac{\partial Q_1}{\partial P_1} = -\frac{g}{g^2 - a^2} < 0$$ \hfill (7)

$$\frac{\partial Q_1}{\partial P_2} = \frac{a}{g^2 - a^2} > 0$$ \hfill (8)
\[ P_1 = a \left(1 - \frac{a}{g}\right)Q_1 + D(Q_1, K) \] (11)

The first term on the right-hand side (RHS) indicates that Port 1 accounts for its market power when determining charge. Recalling that \( g = a + \alpha/K > 0 \), this term will be reduced as port capacity increases. The second term on the RHS is the port congestion cost. The response function of ports regarding competitors is upward-sloping. To see this, we use Eqs. (5)-(7), and Eq. (10) and obtain:

\[
P_1 = \frac{b(g - a) + aP_2 - gf_1 + af_2}{2g}
\]

\[
P_2 = \frac{b(g - a) + aP_1 + af_1 - gf_2}{2g}
\]

The above equations imply that \( \frac{\partial P_i}{\partial P_j} = \frac{a}{2g} > 0 \) for \( i \neq j \). Hence, a port will raise its charge in response to an increase in the charge of its competitor. Figure 1 illustrates the best response functions of ports.

Figure 1. Best response functions of ports

where,
\[ \begin{align*}
&1 = \frac{b(g-a) + aP_2 - gf_1 + af_2}{2g}, \\
&2 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) + agf_1 - (2g^2 - a^2)f_2 \right\}, \\
&3 = \frac{b(g-a) + aP_1 + af_1 - gf_2}{2g}, \\
&4 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) - (2g^2 - a^2)f_1 + agf_2 \right\}
\end{align*} \]

We can establish the stability condition at the pricing stage by summing the own- and cross-price effects.

\[ \frac{\partial Q_1}{\partial P_1} + \frac{\partial Q_2}{\partial P_2} = -\frac{1}{g + a} < 0 \]

As the own-price effect dominates the cross-price effect, the solution of Eq. (10) should lead to a unique stable equilibrium (Dixit, 1986; Basso and Zhang, 2007).

Using Eqs. (5)-(7) and solving for Eq. (10), port charges can be expressed as:

\[ \begin{align*}
&P_1 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) - (2g^2 - a^2)f_1 + agf_2 \right\} \\
&P_2 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) + agf_1 - (2g^2 - a^2)f_2 \right\}
\end{align*} \]

\[ \begin{align*}
&P_1 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) - (2g^2 - a^2)f_1 + agf_2 \right\} \\
&P_2 = (4g^2 - a^2)^{-1} \left\{ b(2g^2 - ag - a^2) + agf_1 - (2g^2 - a^2)f_2 \right\}
\end{align*} \]

With Eqs. (12) and (13), we now investigate how port charges will be affected by the emission standards for Port 1. Taking the first-order derivatives of \( P_1 \) and \( P_2 \) with respect to \( e_1 \) results in:

\[ \begin{align*}
&\frac{\partial P_1}{\partial e_1} = -\frac{(2g^2 - a^2)f_1'}{(4g^2 - a^2)} > 0 \\
&\frac{\partial P_2}{\partial e_1} = \frac{agf_1'}{(4g^2 - a^2)} < 0
\end{align*} \]
where \( f'_1 < 0 \) by assumption. Eq. (14) shows that charge at Port 1 will increase if Government 1 lowers its emission standard (larger \( e_1 \)). This can be explained as follows. A lower emission standard contributes to reduced unit cost per TEU, which increases demand at Port 1. Referring back to Eq. (11), Port 1 would levy a higher charge in response to the increased demand. Considering Eq. (15), when Government 1 lowers the emission standard, additional fuel cost and consequently the generalized port price at Port 1 will be reduced, which imposes more competitive pressure on Port 2. To remain competitive, Port 2 will respond by decreasing its charge.

3.1.3 Emission standard setting stage

This section investigates how national governments set emission standards to maximize social welfare in its jurisdiction. We abstract away shipping operators’ welfare, which in line with De Borger et al. (2008) and Wan and Zhang (2013), as in practice, shipping operators and shippers calling at a port are comprised of numerous nationalities. Another simplification made here is the omission of shippers’ welfare for hinterland access. This is because, as mentioned in Section 3.1.1, the focus of the paper is on transshipment cargo. However, adding hinterland demand or capacity would not change the key results of this paper.\(^3\) As a result, the social welfare maximization by each national government can be expressed as maximizing the port profit minus the environmental damage caused by port emissions:

\[
\max_{e_1} W_1 = (P_1 - \gamma e_1)Q_1
\]

where \( \gamma \) is the environmental damage cost per unit pollutant for each country. Eq. (16) assumes that the environmental damage cost is linear for the noxious gas content emitted per TEU. Alternatively, the damage cost may be specified as quadratic (Kopp et al., 2012), in which case Eq. (16) would become \( W_1 = (P_1 - \gamma e_1^2)Q_1 \). While we did not derive analytical property for such a quadratic damage cost function, our numerical analysis suggests that the insights obtained (i.e., the effect of the maximum reservation price, port capacity, and environmental damage cost on the optimal emission standard) remain under a quadratic damage function.

The FOC of Eq. (16) is:

\[
\frac{\partial W_1}{\partial e_1} = Q_1^* \frac{\partial P_1^*}{\partial e_1} + (P_1^* - \gamma e_1^*) \left( \frac{\partial Q_1^*}{\partial P_1} \frac{\partial P_1^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial P_2} \frac{\partial P_2^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial e_1} \right) - \gamma Q_1^* = 0
\]

\(^3\) We thank one reviewer for raising these points.
\[
\Rightarrow P_1^\ast \left( \frac{\partial Q_1^\ast}{\partial P_2} \frac{\partial P_1^\ast}{\partial e_1} + \frac{\partial Q_1^\ast}{\partial e_1} \right) = \gamma e_1^\ast \left( \frac{\partial Q_1^\ast}{\partial P_1} \frac{\partial P_1^\ast}{\partial e_1} + \frac{\partial Q_1^\ast}{\partial P_2} \frac{\partial P_2^\ast}{\partial e_1} + \frac{\partial Q_1^\ast}{\partial e_1} \right) + \gamma Q_1^\ast
\]

(17)

The second equality above is obtained using the envelop theorem (Eq. (10)). The asterisk denotes it is the value at optimum. From the second equality, it can be seen that the FOC equates the marginal profit (the left-hand side (LHS)) to the marginal environmental damage cost (the RHS) resulting from one unit increase in \( e_1 \). The marginal environmental damage cost consists of two terms: the change in environmental damage cost associated with the change in shipping demand, and the change in environment damage cost due to the unit increase in \( e \). To further interpret Eq. (17), we investigate the effect of emission standards on port demand at \( (e_1^\ast) \). Using Eqs. (5), (7), (8), (14), and (15), and imposing symmetry, we can express \( \frac{dQ_1(e_1^\ast)}{de_1} \) as:

\[
\frac{dQ_1(e_1^\ast,e_2^\ast)}{de_1} = \frac{\partial Q_1^\ast}{\partial P_1} \frac{\partial P_1^\ast}{\partial e_1} + \frac{\partial Q_1^\ast}{\partial P_2} \frac{\partial P_2^\ast}{\partial e_1} + \frac{\partial Q_1^\ast}{\partial e_1} = -\frac{g(2g^2-a^2)f'}{(g^2-a^2)(4g^2-a^2)} > 0
\]

(18)

Hence, ports will attract additional demand when the optimal emission standard becomes lower. The positivity of Eq. (18) means that the bracketed term on the RHS of Eq. (17) is positive at \( e^\ast = e_1^\ast = e_2^\ast \), and therefore, the bracketed term on the LHS of Eq. (17) is also positive.

We now use Eq. (18) to examine whether relieving the emission standard decreases own generalized port price. This is important to understand the strategic use of emission standards, which helps to explain key results of this paper very nicely.

Eqs. (1) and (3) imply

\[
b - a(Q_1^\ast + Q_2^\ast) = P_1^\ast + D(Q_1^\ast, K) + f(e_1^\ast)
\]

Totally differentiating both sides with respect to \( e_1^\ast \), we have

\[
-a \left( \frac{dQ_1^\ast}{de_1} + \frac{dQ_2^\ast}{de_1} \right) = \frac{dP_1^\ast}{de_1} + \frac{dD(Q_1^\ast, K)}{de_1} + \frac{df(e_1^\ast)}{de_1}
\]

The RHS is the effect of the emission standard on own generalized port price (without loss of generality, we consider Port 1 here). To see the effect, we investigate the sign of LHS as it is easier to work with. Using Eqs. (6), (7), (8), (14), and (15), we have
Combining the above equation with Eq. (18), we obtain

\[
\frac{dQ_2^*(e_{1*}^*, e_{2*}^*)}{de_1} = \frac{ag^2f'}{(g^2 - a^2)(4g^2 - a^2)}
\]

That is, reducing the emission standard at a port decreases own generalized port price. This is critical to understanding the strategic use of emission standards to soften competition and manipulate equilibrium prices.

By setting the optimal emission standard, a natural question that may arise is: how does the additional fuel cost compare with Pigouvian tax? Under Pigouvian tax, a regulator levies an amount equal to the environmental damage cost from the polluting firm (Pigou, 1932). In our analysis, the additional fuel cost per TEU, which is \( f^* = f_1^* = f_2^* \) (by symmetry), can be viewed as performing a similar role as an emission tax. If the national governments followed Pigou’s rule, then the emission tax would equal the environmental damage cost per TEU, i.e., \( \gamma e^* \).

On the other hand, we show below that under the optimal emission standard the additional fuel cost will exceed the unit environmental damage cost per TEU, i.e., \( f^* > \gamma e^* \). That is, the emission standard will impose a greater cost burden than a Pigouvian tax. This is formalized in Proposition 1.

**Proposition 1.** When governments and ports are symmetric, the additional fuel cost (due to regulation) incurred per TEU will be greater than the unit environmental damage cost at ports, i.e., \( f^* > \gamma e^* \).

**Proof:** See Appendix A. ■

---

\( ^4 \) The general definition of Pigouvian tax covers taxation on any negative externalities, including the corrective tax for congestion as well as emission. In this manuscript, we focus our attention on tax levied on ‘emission’.
Why is the result different from the desirable regulation that Pigou suggested? This may be because governments do not directly interact with shipping operators (which produce emissions), but with ports which do not correct negative externalities. Since ports compensate shipping operators’ fuel cost through lowering port charge (Eq. (14)) without correcting for their negative social impacts, governments have greater incentives to tighten regulations.

More interesting insight can be drawn if we connect Proposition 1 with the generalized port price: governments raise the emission standards at a sufficiently high level to soften the competition between ports on generalized port price. As shown just above, a higher emission standard increases its own generalized port price, which can counteract the effect of port charge reduction on competition (see Eq. (14)). Softening generalized port price competition is rational from governments’ perspective. Fierce price competition between ports make their nations worse-off because ports collect lower revenue and port traffic increases. Both effects decrease the average social welfare per TEU. As governments cannot manipulate port charge directly, they decrease environmental damage cost instead by increasing emission standards. This argument echoes previous studies (e.g., Basso and Zhang, 2007; De Borger and Van Dender, 2006; Czerny et al., 2017), which showed that port capacity should be set at a low level to soften port charge competition. The difference here is that we consider raising emission standards instead of lowering the capacity to soften the competition on generalized port price.

Proposition 1 provides an interesting implication for practice. Chang et al. (2018) found that increased fuel cost from emission controls reduces port traffic in Europe substantially. While this concerns policy makers in Europe for losing competitiveness of their ports (also concerns policy makers in Asia), our results suggest that more stringent emission controls are ‘desirable’ for society. After all, social welfare is the combination of port profits and environmental costs of port operations. However, it remains to be seen whether this result is generalizable to regulating public port operators, which we leave for future studies.

### 3.2 Symmetric case with a reciprocal fuel cost function

This subsection analyzes the symmetric case in which the fuel cost function form is known. Specifically, the following reciprocal fuel cost function form is considered:

$$f(e_i) = \frac{\beta}{e_i}, \quad i=1,2$$

Eq. (19) assumes that the additional fuel cost increases with higher emission standards, and the rate of cost increases with the emission standard. This reciprocal functional form has a solid empirical grounding that removing pollutants becomes increasingly costly with cleaner fuels. For instance, marine diesel oil costs increase by 20-30% if the sulfur content in fuel decreases from 1.5% to 0.5%, but increases by 50-60% if the sulfur content in fuel decreases from 0.5% to 0.1% (Notteboom, 2011). With this explicit functional form for fuel cost, one can obtain definitive effects of the maximum reservation price, port capacity, and environmental damage on emissions standards.
One can obtain port demand and the optimal pricing of ports by substituting \( f(e) = \beta/e \) into Eqs. (5), (6), (12), and (13). For brevity, we do not detail them here. In addition, new information about the equilibrium conditions can be derived. Differentiating Eq. (16) with respect to \( e_1 \) twice and imposing symmetry results in:

\[
\frac{\partial^2 W_1}{\partial e_1^2} = \frac{2g\beta(2g^2 - a^2)}{e^3(g^2 - a^2)(4g^2 - a^2)} \left( \frac{\beta(2g^2 - a^2)}{e^*(4g^2 - a^2)} - 2P^* \right)
\]

The above second-order condition (SOC) requires that

\[
P^* > \frac{\beta(2g^2 - a^2)}{2e^*(4g^2 - a^2)}
\]

(20)

In the special case that \( a^2 << g^2 \), i.e., \( \alpha(2aK + \alpha)/K^2 >> 0 \), inequality (20) can be approximated by \( P^* > \frac{\beta}{4e^*} = \frac{f^*}{4} \), i.e., port charge should be set higher than a quarter of the additional fuel cost per TEU. In the subsequent analysis, the SOC is assumed to hold.

In the following propositions, the effects of a few key exogenous variables are examined.

**Proposition 2.** If ports and governments are symmetric and the fuel cost has a reciprocal function form, then governments will lower port emission standards when shipping operators’ maximum reservation price increases, i.e., \( \partial e^* / \partial b > 0 \).

**Proof:** See Appendix B. ■

An increase in the maximum reservation price drives up the overall demand, which increases congestion in equilibrium given the capacity. This softens the competition on generalized port price, which reduces governments’ need to further soften the competition by tightening the emission standards. Instead, governments decrease emission standards to encourage port business that has become more lucrative (due to greater demand) than before.

**Proposition 3.** If ports and governments are symmetric and the fuel cost function is reciprocal, then governments will raise emission standards when ports expand capacity, i.e., \( \partial e^* / \partial K < 0 \).

**Proof:** See Appendix C. ■
One may interpret Proposition 3 again through generalized port price competition. An increase in port capacity reduces congestion when the demand function is given. This strengthens the generalized port price competition if emission standards remain unchanged. Thus, a need arises for governments to soften the competition by strengthening emission standards.

Heavy capacity expansion is frequently observed in the real world, particularly in northeast Asia where ports compete for hub status. Proposition 3 indicates that national governments seeking social welfare maximization should consider stricter emission controls.

**Proposition 4.** If ports and governments are symmetric and the fuel cost function is reciprocal, then governments will raise emission standards at ports in which the environmental damage cost per unit pollutant at ports increases, i.e., $\frac{\partial e^*}{\partial \gamma} < 0$.

**Proof:** See Appendix D. ■

This proposition can be intuitively understood. When $\gamma$ becomes larger, negative externalities from port emissions will increase. To reduce the environmental damage, governments will naturally respond by raising emission standards.

Proposition 4 may be used to explain why port emission controls have become more stringent lately around the world. Record high port traffic has deteriorated atmospheric conditions in many port areas, causing significant public health problems. The growing public awareness of this issue has increased perception and valuation of environmental damage, resulting in governments adopting more stringent emission controls, especially in Europe and North America.

4 Model: Asymmetric case

This section relaxes the symmetry assumption. Section 4.1 specifies demand at ports. Section 4.2 presents the profit-maximization problem of private port operators. We then analyze how governments set emission standards in cases where regulation is unilateral and bilateral in Sections 4.3 and 4.4, respectively. Lastly, in Section 4.5, we derive emission standards in which the government has both ports in its jurisdiction.

4.1 Shipping demand at ports

When the two competing ports differ in their characteristics, port demand equilibrium in Eqs. (1) and (2) is modified as:

\[
p(Q_1 + Q_2) = P_1 + D(Q_1, K_1) + f(e_1)
\]

\[
p(Q_1 + Q_2) = P_2 + D(Q_2, K_2) + f(e_2)
\]
where all notations directly follow Eqs. (1) and (2) except that \( K_i \) \((i=1,2)\), the handling capacity at port \(i\), is now different for ports. The functional forms for \( p(Q_i + Q_2) \), \( D(Q_i, K_i) \), and \( f(e_i) \) are assumed to be the same as Eqs. (3), (4) and (19), respectively.\(^5\) Similar to the symmetric case, we can derive the expressions for the two ports:

\[
Q_1 = (g_1 g_2 - a^2)^{-1} \left\{ b(g_2 - a) - g_2 P_1 + aP_2 - g_2 \beta /e_1 + a\beta /e_2 \right\} \quad (23)
\]
\[
Q_2 = (g_1 g_2 - a^2)^{-1} \left\{ b(g_1 - a) + aP_1 - g_1 P_2 + a\beta /e_1 - g_1 \beta /e_2 \right\} \quad (24)
\]

where \( g_i = a + \alpha /K_i \) \((i=1,2)\). Note that \( g_i g_2 - a^2 > 0 \). Holding \( e_1 \) and \( e_2 \) constant, we take the derivative of Eq. (23) with respect to \( P_1 \) and \( P_2 \), which leads to:

\[
\frac{\partial Q_1}{\partial P_1} = \frac{g_2}{g_1 g_2 - a^2} < 0 \quad (25)
\]
\[
\frac{\partial Q_1}{\partial P_2} = \frac{a}{g_1 g_2 - a^2} > 0 \quad (26)
\]

which can be similarly interpreted as Eqs. (7) and (8).

### 4.2 Port charge setting stage

Profit maximization of each port can be expressed as:

\[
\max_{P_i} \pi_i = P_i Q_i, \quad i=1,2
\]

The FOC is given by:

\[\text{FOC} = \text{Profit Maximization}\]

\(^5\) Alternatively, one could generalize the congestion function as \( D_i(Q_i, K_i) = \alpha_i \frac{Q_i}{K_i} \) \((i=1,2)\), where each country has different time costs. This, however, does not change the main results that would follow, as \( \alpha_i \) is contained in the expression \( g_i = a + \alpha_i /K_i \) \((i=1,2)\). We thank a reviewer for pointing this out.
\[
\frac{\partial \pi_1}{\partial P_1} = Q_1 + P_1 \frac{\partial Q_1}{\partial P_1} = 0
\]  

(28)

Substituting Eq. (25) for \( \frac{\partial Q_1}{\partial P_1} \) in Eq. (28) results in the following pricing rule:

\[
P_1 = a \left( 1 - \frac{a}{g_2} \right) Q_1 + D(Q_1, K_1)
\]

(29)

This is analogous to the pricing rule in the symmetric case (Eq. (11)). However, now the capacities at the two ports are not equal. A higher capacity at Port 2, which is associated with a lower \( g_2 \), will decrease the relative market power of Port 1 (the first term on the RHS of Eq. (29)), leading to decreased port charge.

Using Eqs. (23)-(24) and solving Eq. (29) for both ports, port charges can be expressed as:

\[
P_1 = (4g_1g_2 - a^2)^{-1} \left\{ b(2g_1g_2 - ag_1 - a^2) - (2g_1g_2 - a^2)\beta/e_1 + ag_1\beta/e_2 \right\}
\]

(30)

\[
P_2 = (4g_1g_2 - a^2)^{-1} \left\{ b(2g_1g_2 - ag_2 - a^2) + ag_2\beta/e_1 - (2g_1g_2 - a^2)\beta/e_2 \right\}
\]

(31)

Taking the first-order derivatives with respect to \( e_1 \), we obtain:

\[
\frac{\partial P_1}{\partial e_1} = \frac{\beta(2g_1g_2 - a^2)}{e_1^2(4g_1g_2 - a^2)} > 0
\]

(32)

\[
\frac{\partial P_2}{\partial e_1} = -\frac{ag_2\beta}{e_1^2(4g_1g_2 - a^2)} < 0
\]

(33)

which can be similarly interpreted as Eqs. (14) and (15).

4.3 Unilateral regulation case

This section analyzes the case in which only one of two countries regulates port emissions. For the other country, its government only considers port revenue maximization. We use subscripts 1 and 2 to denote the country/port with and without emission regulation. We further assume that Country 2 should still comply with a minimum emission standard which is associated with the ‘dirtiest’ fuel used in maritime shipping. For example, the International
Maritime Organization stipulates that sulfur content in fuel should not exceed 3.5% for all ships as of 2015.

We again consider a leader-follower game structure. The stage of setting port charges is the same as in Section 3.2 and thus not repeated here. At the stage of setting the emission standards, the two governments face the following problems:

\[
\begin{align*}
\max_{e_1} & \quad W_1^u = (P_1 - \gamma_1 e_1)Q_1 \\
\max_{e_2} & \quad w_2^u = P_2 Q_2 \\
\text{s.t.} & \quad e_2 \leq \bar{e}
\end{align*}
\]

where superscript \( u \) in \( W_1^u \) and \( w_2^u \) denotes “unilateral”; \( e_1 \) and \( e_2 \) are the emission standards at ports 1 and 2 respectively; and \( \bar{e} \) denotes the minimum emission standard for Country 2.

For Port 1, the FOC is:

\[
\frac{\partial W_1^u}{\partial e_1} = Q_1^* \frac{\partial P_1^*}{\partial e_1} + (P_1^* - \gamma_1 e_1^*) \left( \frac{\partial Q_1^*}{\partial P_1} \frac{\partial P_1^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial P_2} \frac{\partial P_2^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial e_1} \right) - \gamma_1 Q_1^* = 0
\]

\[
\Rightarrow P_1^* \left( \frac{\partial Q_1^*}{\partial P_1} \frac{\partial P_1^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial P_2} \frac{\partial P_2^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial e_1} \right) = \gamma_1 e_1^* \left( \frac{\partial Q_1^*}{\partial P_1} \frac{\partial P_1^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial P_2} \frac{\partial P_2^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial e_1} \right) + \gamma_1 Q_1^* + \gamma_1 Q_1^* = 0
\]

The second equality is obtained using Eq. (28). The asterisk denotes values at optimum. Eq. (35) is almost similar to Eq. (17), except that the environmental damage cost per unit pollutant has subscript 1 (\( \gamma_1 \)).

Next, we consider the effects of the emission standards on port demand at \((e_1^*, \bar{e})\). Using Eqs. (23), (25), (26), (32), and (33), we can express \( \frac{dQ_1(e_1^*, \bar{e})}{de_1} \) as:

\[
\frac{dQ_1(e_1^*, \bar{e})}{de_1} = \frac{\partial Q_1^*}{\partial P_1} \frac{\partial P_1^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial P_2} \frac{\partial P_2^*}{\partial e_1} + \frac{\partial Q_1^*}{\partial e_1} = \frac{g_2 \beta (2g_1g_2 - a^2)}{e_1^* + (g_1g_2 - a^2)(4g_1g_2 - a^2)} > 0
\]

which has a similar form as Eq. (18).

Eq. (35) cannot be solved explicitly, but can be rearranged to gain insights. After some algebra (see Appendix E), Eq. (35) leads to the following implicit form for the optimal emission standard:
\[
e_{1}^{e2} = \frac{2\beta(2g_{1}g_{2} - a^2)}{\gamma_{1}(1 + e_{1})(4g_{1}g_{2} - a^2)}
\]

where \( e_{1} = (dQ_{1}^{*}/de_{1})(e_{1}^{*}/Q_{1}^{*}) \). Eq. (32) implies that holding \( e_{1} \) constant, a government will lower its emission standard if \( \beta \) increases. One possible cause for a larger \( \beta \) is higher crude oil price. On the contrary, holding \( e_{1} \) constant, the emission standard will be set higher when the unit environmental damage cost per pollutant (\( \gamma_{1} \)) increases. These interpretations, however, are only tentative because \( e_{1} \) depends on \( \beta \) and \( \gamma_{1} \).

For Port 2, it is conceptually valid that \( e_{2} \) will be set at \( \bar{e} \) to minimize fuel cost. In fact, it can be shown that \( w_{2}^{e} \) decreases with \( e_{2} \):

\[
\frac{\partial w_{2}^{e}}{\partial e_{2}} = Q_{2}^{*} \frac{\partial P_{2}^{e}}{\partial e_{2}} + P_{2}^{e} \left( \frac{\partial Q_{2}^{e}}{\partial P_{1}} \frac{\partial P_{2}^{e}}{\partial e_{2}} + \frac{\partial Q_{2}^{e}}{\partial P_{2}} \frac{\partial P_{2}^{e}}{\partial e_{2}} + \frac{\partial Q_{2}^{e}}{\partial e_{2}} \right) = P_{2}^{e} \left( \frac{\partial Q_{2}^{e}}{\partial P_{1}} \frac{\partial P_{2}^{e}}{\partial e_{2}} + \frac{\partial Q_{2}^{e}}{\partial e_{2}} \right) > 0
\]

where the inequality holds due to Eqs. (24), (26), (31) and (33). Thus the choice of \( e_{2}^{e} = \bar{e} \) by Country 2 is independent of the emission standard of Country 1.

We also examine the second-order condition (SOC) of Eq. (34) for Port 1. Differentiating \( \partial W_{i}^{b}/\partial e_{1} \) with respect to \( e_{1} \) results in:

\[
\frac{\partial^{2} W_{i}^{e}}{\partial e_{1}^{2}} = \frac{2g_{2}\beta(2g_{1}g_{2} - a^2)}{e_{1}^{*}(g_{1}g_{2} - a^2)(4g_{1}g_{2} - a^2)} \left( \frac{\beta(2g_{1}g_{2} - a^2)}{e_{1}^{*}(4g_{1}g_{2} - a^2)} - 2P_{1}^{*} \right)
\]

The SOC requires \( \partial^{2} W_{i}^{e}/\partial e_{1}^{2} < 0 \), which yields:

\[
2P_{1}^{*} > \frac{\beta(2g_{1}g_{2} - a^2)}{e_{1}^{*}(4g_{1}g_{2} - a^2)}
\]

If \( a^2 \ll g_{1}g_{2} \), i.e., \( \alpha(a(K_{1} + K_{2}) + \alpha)/K_{1}K_{2} >> 0 \), inequality (38) suggests that \( P_{1}^{e} > \frac{\beta}{4e_{1}^{*}} = \frac{f(e_{1}^{*})}{4} \); i.e., port charge should be set higher than a quarter of the additional fuel
cost per TEU, which is the same as the symmetric case (see discussions below inequality (20)). In our analysis, we assume that the SOC holds.

Also similar to the symmetric case is that the emission standard at Port 1 will impose a greater cost burden to shipping operators than a Pigouvian tax. We formalize this as Proposition 5 below.

**Proposition 5.** Under unilateral regulation, the additional fuel cost per TEU due to the imposition of emission control will be greater than the unit environmental damage cost at Port 1, i.e., \( \beta/e_1^* > \gamma_1 e_1^* \).

**Proof:** See Appendix F. ■

Proposition 5 can be interpreted in a similar way as Proposition 1: Government 1 imposes stricter emission regulations than would be under Pigouvian taxation, expecting that Port 1 will compensate shipping operators’ fuel cost by reducing port charges (Eq. (32)). Moreover, tightening of the emission standards will relieve the competition on generalized port price competition.

We further examine the effects of shipping operators’ maximum reservation price \( b \), port capacities \( K_1 \) and \( K_2 \), and the environmental damage cost per unit pollutant \( \gamma_1 \) on the optimal emission standard at Port 1 \( e_1^* \). The findings are formalized in Propositions 6-8.

**Proposition 6.** Government 1 will lower the emission standard at Port 1 when the maximum reservation price of shipping operators increases, i.e., \( \partial e_1^*/\partial b > 0 \).

**Proof:** See Appendix G. ■

Proposition 6 can be interpreted in a similar way as Proposition 2. Because a higher maximum reservation price relieves the competition on generalized port price, Government 1 does not need to further soften competition. Instead, Government 1 will support port business by weakening its emission standard.

**Proposition 7.** Government 1 will raise the emission standard at Port 1 when either port expands capacity, i.e., \( \partial e_1^*/\partial K_1 < 0 \) and \( \partial e_1^*/\partial K_2 < 0 \).

**Proof:** See Appendix H. ■

Capacity expansion at either port results in more intense competition on generalized port price, as congestion is reduced and both ports will respond by lowering port charges. To relieve competition, Government 1 will impose a more stringent emission standard.
For the effects of the environmental damage cost per unit pollutant, only $\gamma_1$ is considered. $\gamma_2$ does not appear in (34) and thus has no effects on the optimal emission standards at Port 1.

**Proposition 8.** Government 1 will raise the emission standard at Port 1 when the environmental damage cost per unit pollutant at Port 1 increases, i.e., $\partial e_i^b/\partial \gamma_1 < 0$.

**Proof:** See Appendix I. ■

This proposition can be intuitively understood as in the symmetric case (Proposition 4). Government 1 raises the emission standard at Port 1 in order to mitigate the increased negative externalities from emissions from Port 1.

### 4.4 Bilateral regulation case

This section investigates the case in which the two national governments both consider the environmental costs of their respective port operations. The problem faced by each government is:

$$\max_{e_i} W_i^b = (P_i - \gamma_i e_i)Q_i, \quad i=1,2$$  \hspace{1cm} (39)

The FOC of Eq. (39) has the same expressions as Eq. (35). The optimal emission standards for both governments follow a similar form as Eq. (37):

$$e_i^{b*} = \frac{2\beta(2g_1 g_2 - a^2)}{\gamma_i (1 + \varepsilon_i)(4g_1 g_2 - a^2)}, \quad i = 1,2$$

As the structure of the FOC is the same for both governments, it can be easily seen that Proposition 5 now applies to both countries.

In the remainder of this section, we investigate the effects of shipping operators’ maximum reservation price ($b$), port capacities ($K_1$ and $K_2$), and the environmental damage cost per unit of noxious content ($\gamma_1$ and $\gamma_2$) on the optimal emission standards $e_i^{b*}$ and $e_2^{b*}$. For the effect of $b$, a conclusion cannot be drawn analytically by taking the derivative of $e_i^{b*}$ ($i = 1,2$) with respect to $b$. However, if port charges are held constant at the equilibrium values ($P_1^{b*}$ and $P_2^{b*}$), the following proposition can be obtained:
**Proposition 9.** Under the bilateral regulation, if port charges are fixed at \( P_1^{b*} \) and \( P_2^{b*} \), then each government will set a higher emission standard as the maximum reservation price increases, i.e., \( \frac{\partial e_i^{b*}}{\partial b} \bigg|_{b_1^{r*}, b_2^{r*}} < 0 \) (i = 1,2).

**Proof:** See Appendix J. ■

At first sight, Proposition 9 seems to contradict Propositions 2 and 6. However, the result is conditional on fixing port charges at \( P_1^{b*} \) and \( P_2^{b*} \), which dampens the change in the generalized price competition. In this case, the governments would focus more on the environmental damage. Because an increase in the maximum reservation price attracts more demand resulting in greater environmental damage, the governments set higher emission standards to mitigate the damage.

The effect of port capacities on \( e_i^{b*} \) can only be analytically derived when port charges are held constant at \( P_1^{b*} \) and \( P_2^{b*} \), as described in Proposition 10.

**Proposition 10.** Under the bilateral regulation, if port charges are fixed at the equilibrium values \( (P_1^{b*} \text{ and } P_2^{b*}) \), then each government will set a higher emission standard as the capacity of its port is expanded, but will lower its emission standard if the capacity of the other port is expanded, i.e., \( \frac{\partial e_i^{b*}}{\partial K_i} \bigg|_{K_1^{r*}, K_2^{r*}} < 0 \) and \( \frac{\partial e_i^{b*}}{\partial K_j} \bigg|_{K_1^{r*}, K_2^{r*}} > 0 \) (i, j = 1,2, j ≠ i).

**Proof:** See Appendix K. ■

Similar to the reasoning for Proposition 9, fixing port charges at \( P_1^{b*} \) and \( P_2^{b*} \) and increasing capacity at Port 1, Government 1 will mainly focus on mitigating the environmental damage due to increased demand. The emission standard will be strengthened at Port 1. On the other hand, if Port 2 increases capacity, the competition on generalized port price will favor Port 2. To stay competitive, Government 1 will respond by lowering its emission standard.

In reality, port charges will also respond to port capacity change. To see this, we differentiate \( P_1 \) (Eq. (30)) with respect to \( K_1 \) and \( K_2 \) while holding emission standards constant:

\[
\frac{\partial P_1}{\partial K_{1_i,1_2}} = \frac{a^2}{(4g_1g_2-a^2)^2} \frac{\partial g_1}{\partial K_1} \left( 2g_2(b-\frac{\beta}{e_1}) + a(b-\frac{\beta}{e_2}) \right) \]
\[
= \frac{a^2}{(4g_1g_2-a^2)^2} \frac{\partial g_1}{\partial K_1} \left( a(2g_2+a)(Q_1+Q_2) + 2g_2(P_1+D(Q_1,K_1)) + a(P_2+D(Q_2,K_2)) \right) \]
\[
< 0 \quad (40)
\]
\[
\frac{\partial P_1}{\partial K_2}\bigg|_{e_1,e_2} = \frac{2ag_1}{(4g_1g_2-a^2)} \frac{\partial g_2}{\partial K_2} \left( a(b-\frac{\beta}{e_1}) + 2g_1(b-\frac{\beta}{e_2}) \right)
\]
\[
= \frac{2ag_1}{(4g_1g_2-a^2)} \frac{\partial g_2}{\partial K_2} \left( a(2g_2+a)(Q_1+Q_2) + a(P_1+D(Q_1,K_1)) + 2g_1(P_2+D(Q_2,K_2)) \right)
\]
\[
< 0
\]

The second equality in (40) is obtained using Eqs. (1)-(4) and (19). The last inequality in (40) derives from the fact that \(4g_1g_2-a^2 > 0\), \(\partial g_1/\partial K_1 < 0\), and \(a(2g_2+a)(Q_1+Q_2) + 2g_2(P_1+D(Q_1,K_1)) + a(P_2+D(Q_2,K_2)) > 0\). Similarly, for expression (41), the full effects of port capacity on emission standards without fixing port charges will be investigated in the numerical analysis (Section 4).

Finally, we can draw analytical conclusions on the effects of \(\gamma_1\) and \(\gamma_2\) when port charge is sufficiently large. This does not require fixing port charges.

**Proposition 11.** If port charge \(P_i^{Kr}\) is sufficiently large such that
\[
\Gamma_i^{*} \Gamma_2 > \frac{a^2g_1g_2(2g_1g_2-a^2)}{(4g_1g_2-a^2)^2},
\]
where \(\Gamma_i^{*} = \left( \frac{2P_i^{Kr}e_i^{Kr}}{\beta} - \frac{2g_1g_2-a^2}{4g_1g_2-a^2} \right) \left( \frac{P_i^{Kr}e_i^{Kr} + 2g_1g_2-a^2}{\beta} \right) (i = 1,2),\)

each government will raise its emission standard facing a higher environmental damage cost per unit pollutant in the country, but will lower its emission standard when the environmental damage cost per unit pollutant in the other country increases, i.e., \(\partial e_i^{Kr}/\partial \gamma_j < 0\) and \(\partial e_j^{Kr}/\partial \gamma_j > 0\) \((i = 1,2, j \neq i)\).

**Proof:** See Appendix L. ■

Note that \(\Gamma_i^{*} > 0 \ (i = 1,2)\) always holds because the first bracketed term on the RHS of the expression is positive as we assume the SOC (Eq. (38)) holds.

The sensitivity of \(e_i^{Kr}\) and \(e_j^{Kr}\) to \(\gamma_1\) and \(\gamma_2\) is straightforward. When \(\gamma_1\) increases, the environmental damage cost at Port 1 will increase. To mitigate this, Government 1 will respond by raising its emission standard. When \(\gamma_2\) increases, the unit cost per TEU at Port 2 will increase, which negatively affects the competitiveness of Port 2. In response, Government 1 will lower its emission standard to gain further competitive advantage.

### 4.5 Single country case

This section examines the case that two competing ports are located in the same country. The government sets emission standards at both ports to maximize overall social welfare:
\[
\max_{e_1, e_2} W = \sum_{i=1}^2 (P_i - \gamma_i e_i)Q_i \quad (42)
\]

Taking the first-order derivative with respect to \(e_1\) and let it be zero, the optimal emission standard at Port 1 must satisfy (details in Appendix M):

\[
e_1^{*s} = \frac{2(2g_1g_2 - a^2)\beta}{\gamma_1(1 + e_1)(4g_1g_2 - a^2)} - \frac{ag_1g_2\beta(P_2^{**} - \gamma_2 e_2^{**})}{\gamma_1 Q_1^{**} (1 + e_1)(g_1g_2 - a^2)(4g_1g_2 - a^2)} \quad (43)
\]

where \(e_i = (dQ_i^*/de_i)(e_i^*/Q_i^*)\) and superscript \(s\) denotes the single country case. The first term on the RHS is the same as for unilateral and bilateral regulation (see Eq. (37)). The second term suggests that the emission standard at Port 1 will be stricter as \(P_2^{**} - \gamma_2 e_2^{**}\) becomes higher. Here we assume that \(P_2^{**} - \gamma_2 e_2^{**}\) is positive. Otherwise, the government would be better off by choosing an emission standard such that \(Q_2^* = 0\). (then the model would deal with only one port, which is less interesting) Note that \(P_2^{**} - \gamma_2 e_2^{**}\) is the welfare per TEU at Port 2. Thus, if the government believes that additional social welfare will be gained by handling a TEU at Port 2 compared to Port 1, the government would divert traffic from Port 1 to Port 2 by raising the emission standard at Port 1.

From Eq. (43), the following comparison can be made between unilateral/bilateral emission standards and the single country emission standard.

**Proposition 12.** Emission standards under single country regulation are stricter than under unilateral and bilateral regulations, i.e., \(e_1^{**} < e_1^{*s}, e_1^{bs}\).

In the case of unilateral and bilateral schemes, governments' competition-softening behavior is limited: both governments should consider how the other governments would respond to their own emission standard setting. Specifically, increasing its own emission standard may decrease emission standard in the other country, in which case its own port industry can lose competition. When a single government has full discretion to control emission at both ports, however, it can soften generalized port price competition more freely than another government is present. In effect, more stringent emission standard is set than unilateral and bilateral regulations.

In practice, emission control within a country is rarely different by ports. For example, the ECA in Europe/North America and the emission tax in Norway do not differentiate regulatory intensity for each port. However, our analysis may suggest that to maximize social welfare, a government can strategically set different emission standards at individual ports. One way to achieve this is to mix global emission controls (e.g., ECA) and local emission controls (e.g., emission tax) that are port specific.
We are also interested in the effects of the maximum reservation price \((b)\), port capacities \((K_1, K_2)\), and the environmental damage cost per unit pollutant \((\gamma_1, \gamma_2)\) on the optimal emission standards \(e_t^*\) and \(e_t^*\). Similar to the bilateral regulation case, the first two effects can be derived only when port charges are fixed at \(P_1^*\) and \(P_2^*\). Because port charges in the single country case will be determined in the same way as in the bilateral regulation case, the same insight will be generated for the single country case as in the bilateral regulation case. The effects of \(\gamma_1\) and \(\gamma_2\) cannot be obtained analytically due to its complex form. Further investigation will be performed numerically in Section 5.

### 4.6 Summary

Table 1 summarizes the effects of the maximum reservation price, port capacities, and the environmental damage cost per unit pollutant on the optimal emission standards at port \(i\) for the three regulation cases. The most complete findings are from the unilateral regulation case. For the other two cases, some effects are either conditional on fixed port charges at equilibrium or indeterminate.

Table 1. Effects of the maximum reservation price, port capacities, and the environmental damage cost per unit pollutant on the optimal emission standard at port \(i (i = 1, 2; i \neq j)\) from the analytical modeling

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum reservation price ((b))</th>
<th>Port capacities ((K_i, K_j))</th>
<th>Environmental damage cost per unit pollutant ((\gamma_1, \gamma_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Symmetric</td>
<td>(\downarrow)</td>
<td>(\uparrow)</td>
<td>(\uparrow)</td>
</tr>
<tr>
<td>Unilateral regulation</td>
<td>(\downarrow)</td>
<td>(K_i: \uparrow, K_j: \uparrow)</td>
<td>(\gamma_i: \uparrow, \gamma_j: \text{no effect})</td>
</tr>
<tr>
<td>Bilateral regulation</td>
<td>(\uparrow) (fixing (P_1^<em>, P_2^</em>))</td>
<td>(K_i: \uparrow, K_j: \downarrow) (fixing (P_1^<em>, P_2^</em>))</td>
<td>(\gamma_i: \uparrow, \gamma_j: \downarrow)  (plausibly)</td>
</tr>
<tr>
<td>Single country</td>
<td>(\uparrow) (fixing (P_1^<em>, P_2^</em>))</td>
<td>(K_i: \text{no effect})</td>
<td>(K_j: \text{no effect})</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>(\text{Indeterminate})</td>
</tr>
</tbody>
</table>

Note: An upward arrow indicates a change towards a higher emission standard.

### 5 Numerical analysis

This section performs numerical analysis to investigate three emission regulation cases. The focus is to further explore the propositions in Section 4.4, as those propositions are subject to certain conditions. For other propositions, the numerical analysis is to validate the theoretical findings. The purpose of the numerical analysis is not to perfectly reflect reality. Rather, it is to
provide economic and managerial insights about how port emission standards should be set and the sensitivity of these standards to key model parameters.

5.1 Model parameter values

We confine our analysis to sulfur dioxide (SO$_2$) emissions, given that it is the main target of port emission controls worldwide. Parameter values are determined, based on empirical evidence whenever possible. The value for $\alpha$ draws from Chang et al. (2012) and is assumed $2.279$/TEU. The value for $\beta$ follows Wang and Corbett (2007) who found that 1) 57,932 tons of SO$_2$ emissions are associated with $140,209,151$ of 1.5% sulfur-content fuel; and 2) 19,311 tons of SO$_2$ emissions are associated with a fuel cost totaling $180,268,908$ using 0.5% sulfur-content fuel. Dividing these numbers by the total TEUs handled at the U.S. west coast ports (the scope of their study), we obtain two sets of values for ($f_1, e_1$): (1.771, 0.731) and (2.277, 0.244), the fuel cost and sulfur emissions per TEU. Each set gives a $\beta$ value. The $\beta$ used in the numerical analysis is the average value, equal to 0.925.

The values for $\gamma_1$ and $\gamma_2$ also follows Wang and Corbett (2007), who suggested that each kilogram of sulfur dioxide increases social cost by $12.197$. Hence, $\gamma_1 = \gamma_2 = 12.197$. The values for $a$ and $b$ cannot be drawn from the literature. We set $a = 1$ and $b = 20000000$. The base port capacity is assumed to be $K_1 = K_2 = 10000000$.

5.2 Unilateral regulation case

Table 2 summarizes the results for the unilateral regulation case. Six scenarios are tested. Column ① is the base scenario. Each of the other scenarios differs by one or two parameter values (in bold) from the base scenario. As in Section 4.3, subscripts 1 and 2 denote countries with and without emission controls. Scenarios 1-5 are similarly specified as in Section 5.2 (scenario 6 does not apply to unilateral regulation). Country 1 determines its emission standard with Country 2 implementing a minimum emission standard at $e_2 = 2$. Intuitively, the loosely regulated Port 2 will attract more demand than the actively regulated Port 1 due to lower additional fuel costs. Port 2 will leverage this cost advantage by levying a higher port charge than Port 1. Consistent with Propositions 5-7, the emission standard at Port 1 will be lowered when the maximum reservation price increases, but raised when either port expands capacity or the environmental damage cost per unit pollutant increases.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>①</th>
<th>②</th>
<th>③</th>
<th>④</th>
<th>⑤</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>2.00.E+07</td>
<td>3.00.E+07</td>
<td>2.00.E+07</td>
<td>2.00.E+07</td>
<td>2.00.E+07</td>
</tr>
<tr>
<td>$a$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

6 We note that a similar approach was used in previous airport studies (e.g., Basso, 2008; Pels and Verhoef, 2004).
\[ \begin{array}{cccccc}
\alpha & 2.279 & 2.279 & 2.279 & 2.279 & 2.279 \\
\beta & 0.925 & 0.925 & 0.925 & 0.925 & 0.925 \\
K_1 & 1.00.E+07 & 1.00.E+07 & 1.50.E+07 & 1.50.E+07 & 1.00.E+07 \\
K_2 & 1.00.E+07 & 1.00.E+07 & 1.00.E+07 & 1.50.E+07 & 1.00.E+07 \\
\gamma_1 & 12.197 & 12.197 & 12.197 & 12.197 & 18.296 \\
\gamma_2 & 12.197 & 12.197 & 12.197 & 12.197 & 12.197 \\
\end{array} \]

**Endogenous**

\[ \begin{array}{cccccc}
Q_2^* & 1.34.E+07 & 1.81.E+07 & 1.37.E+07 & 1.57.E+07 & 1.49.E+07 \\
P_1^* & 2.991 & 5.436 & 2.385 & 1.639 & 2.317 \\
P_2^* & 6.125 & 8.238 & 5.212 & 5.957 & 6.799 \\
e_1^* & 0.179 & 0.198 & 0.169 & 0.1497 & 0.1287 \\
e_2^* & 2.000 & 2.000 & 2.000 & 2.000 & 2.000 \\
\beta/e_1^* & 5.164 & 4.665 & 5.463 & 6.179 & 7.185 \\
\beta/e_2^* & 0.463 & 0.463 & 0.463 & 0.463 & 0.463 \\
\gamma_1e_1^* & 2.185 & 2.418 & 2.065 & 1.826 & 2.355 \\
\end{array} \]

**Port profit**

\[ \begin{array}{cccccc}
\text{Port profit1} & 1.96.E+07 & 6.48.E+07 & 1.50.E+07 & 7.08.E+06 & 1.18.E+07 \\
\text{Port profit2} & 8.23.E+07 & 1.49.E+08 & 7.15.E+07 & 9.34.E+07 & 1.01.E+08 \\
\text{Social welfare1} & 5.29.E+06 & 3.60.E+07 & 2.01.E+06 & -8.04.E+05 & -1.94.E+05 \\
\text{Social welfare2} & -2.45.E+08 & -2.92.E+08 & -2.63.E+08 & -2.89.E+08 & -2.62.E+08 \\
\end{array} \]

**Diagnostic numbers**

\[ \begin{array}{cccccc}
\frac{\partial^2 W_1}{\partial e_1^*} & -1.41.E+09 & -1.89.E+09 & -1.60.E+09 & -1.59.E+09 & -2.94.E+09 \\
\end{array} \]

Similar to Section 5.3, we examine the government reactions functions (Figures 2a-2c). The reaction function for Country 2 is a straight line, as its emission standard is always set at the minimum level. On the other hand, when the maximum reservation price \((b)\) increases the reaction function of Country 1 moves upward from \(o\) to \(o\,'\), meaning a lowered emission standard.
Figure 2a. Effects of the maximum reservation price on the unilateral regulation equilibrium

The equilibrium shift when port capacity is expanded is depicted in Figure 2b. If capacity expands first at Port 1 and then at Port 2, the initial equilibrium $o$ shifts to $o'$ and then to $o''$. Country 1 will set a higher emission standard when its port increases capacity, and even stronger when both ports expand capacities.
In Figure 2c, an increase in the environmental damage cost per unit pollutant at Country 1 will prompt Country 1 to raise its emission standard, changing the equilibrium from $o$ to $o'$. The result is the same when the environmental damage costs per unit pollutant are increased in both countries, because Port 2 maintains a minimum emission standard $e_2 = e''_2$ regardless of the damage level ($e_2(e_1) = e''_2(e_1)$).
5.3 Bilateral regulation case

Table 3 presents the results of bilateral regulation. We find that when shipping operators’ maximum reservation price increases by 50% (in scenario 2 where b increases from 2.00.E+07 to 3.00.E+07), emission standards will be set slightly lower, which differs from the earlier theoretical finding assuming fixed port charges (Proposition 9). This can be explained by the fact that a higher maximum reservation price increases port charges and relieves competition on generalized port price (in our case substantially, as port charges increase from $4.558 to $6.837). As a result, additional softening of generalized port price competition is not necessary. In fact, the governments respond by lowering the emission standards to counteract the port charge increase.

In scenario 3, the capacity of Port 1 is increased by 50%. The emission standards at both ports are set higher. The changing direction of emission standards for Port 1 is in line with the theoretical finding. Expanded capacity leads to reduced congestion, which in turn reduces port charges (Eq. (11)). Both reduced congestion and port charges suggest more intense competition on generalized port price. To soften competition, a higher emission standard is enforced at Port 1. The changing direction of emission standards for Port 2 is different from the theoretical finding. This is because the added competition from capacity expansion at Port 1 results in Port 2 reducing its charge from 4.558 to 3.493, which also intensifies competition. To soften competition, Government 2 raises its emissions standard to drive up generalized port price.

In scenario 4, capacities of both ports are increased by 50%. Emission standards will be set at a higher level than in scenario 3. This is because capacity expansion at both ports leads to even
greater congestion reduction and consequently further reduced port charges (at $3.039), which suggest more intense competition on generalized port price than scenario 3. To soften the competition, both governments set higher emission standards.

Table 3. Scenario analysis for the bilateral regulation case

<table>
<thead>
<tr>
<th>Parameters</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>$b$</td>
<td>2.00E07</td>
<td>3.00E07</td>
<td>2.00E07</td>
<td>2.00E07</td>
<td>2.00E07</td>
<td>2.00E07</td>
</tr>
<tr>
<td>$a$</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$\alpha$</td>
<td>2.279</td>
<td>2.279</td>
<td>2.279</td>
<td>2.279</td>
<td>2.279</td>
<td>2.279</td>
</tr>
<tr>
<td>$\beta$</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
<td>0.925</td>
</tr>
<tr>
<td>$K_1$ (TEU)</td>
<td>1.00E07</td>
<td>1.00E07</td>
<td>1.50E07</td>
<td>1.50E07</td>
<td>1.00E07</td>
<td>1.00E07</td>
</tr>
<tr>
<td>$K_2$ (TEU)</td>
<td>1.00E07</td>
<td>1.00E07</td>
<td>1.00E07</td>
<td>1.50E07</td>
<td>1.00E07</td>
<td>1.00E07</td>
</tr>
<tr>
<td>$\gamma_1$ ($)</td>
<td>12.197</td>
<td>12.197</td>
<td>12.197</td>
<td>12.197</td>
<td>18.296</td>
<td>18.296</td>
</tr>
<tr>
<td>$\gamma_2$ ($)</td>
<td>12.197</td>
<td>12.197</td>
<td>12.197</td>
<td>12.197</td>
<td>18.296</td>
<td>18.296</td>
</tr>
</tbody>
</table>

Endogenous

| $Q_1^*$ (TEU)    | 1.00E07 | 1.50E07 | 1.08E07 | 1.00E07 | 8.88E06 | 1.00E07 |
| $Q_2^*$ (TEU)    | 1.00E07 | 1.50E07 | 9.20E06 | 1.00E07 | 1.11E07 | 1.00E07 |
| $P_1^*$ ($)      | 4.558 | 6.837 | 4.104 | 3.039 | 4.048 | 4.558 |
| $P_2^*$ ($)      | 4.558 | 6.837 | 3.493 | 3.039 | 5.068 | 4.558 |
| $e_1^*$ (kg)    | 0.194 | 0.204 | 0.191 | 0.180 | 0.148 | 0.153 |
| $e_2^*$ (kg)    | 0.194 | 0.204 | 0.185 | 0.180 | 0.196 | 0.153 |
| $\beta/e_1^*$ ($) | 4.768 | 4.534 | 4.843 | 5.139 | 6.250 | 6.046 |
| $\beta/e_2^*$ ($) | 4.768 | 4.534 | 5.000 | 5.139 | 4.719 | 6.046 |
| $\gamma_e_1^*$ ($) | 2.366 | 2.488 | 2.330 | 2.195 | 1.805 | 2.799 |
| $\gamma_e_2^*$ ($) | 2.366 | 2.488 | 2.256 | 2.195 | 3.586 | 2.799 |
| Port profit1 ($) | 4.56E07 | 1.03E08 | 4.43E07 | 3.04E07 | 3.59E07 | 4.56E07 |
| Port profit2 ($) | 4.56E07 | 1.03E08 | 3.21E07 | 3.04E07 | 5.64E07 | 4.56E07 |
| Social welfare1 ($) | 2.19E07 | 6.52E07 | 1.92E07 | 8.43E06 | 1.99E07 | 1.76E07 |
| Social welfare2 ($) | 2.19E07 | 6.52E07 | 1.14E07 | 8.43E06 | 1.65E07 | 1.76E07 |

Diagnostic numbers

| $\delta^2W_1 / \delta e_1^2$ | -1.69E09 | -2.18E09 | -1.91E09 | -2.11E09 | -3.38E09 | -3.44E09 |
| $\delta^2W_2 / \delta e_2^2$ | -1.69E09 | -2.18E09 | -1.79E09 | -2.11E09 | -1.82E09 | -3.44E09 |
In scenario 5, the environmental damage cost per unit pollutant at Port 1 \( (\gamma_1) \) is increased by 50%. In scenario 6, both \( \gamma_1 \) and \( \gamma_2 \) are increased by 50%. In scenario 5, Government 1 raises the emission standard at Port 1 to mitigate the increased environmental impacts. This provides Port 2 with a competitive advantage. To further leverage this advantage, Government 2 lowers its emission standard. In scenario 6, higher emission standards will be set by both governments.

Figures 3a-3c plot the government reaction functions. \( e_1(e_2) \) denotes the optimal emission standard for Country 1 which is a function of Country 2’s emission standard. \( e_1'(e_2) \) denotes a new reaction function of \( e_1 \) after change in one model parameter. In Figures 3b and 3c, \( e_1''(e_2) \) denotes a new reaction function after simultaneous increase in either capacities or environmental damage costs per unit pollutant at both ports. \( e_2(e_1), \ e_2'(e_1), \) and \( e_2''(e_1) \) are similarly defined. The intersecting red dots of the reaction functions give the equilibrium points.

For all reaction functions, the slopes are downward. This means that if one country increases its emission standard, the other will respond by lowering its emission standard. Clearly, doing so will give the port in the first country a competitive disadvantage. Thus this may explain why governments tend to delay stricter emission controls under port competition.

In terms of the sensitivity of the reaction functions to model parameters, Figure 2a shows that when the maximum reservation price \( (b) \) increases, the equilibrium will shift from \( o \) to \( o' \) with weaker emission standards in both countries.

![Figure 3a. Effects of the maximum reservation price on the bilateral regulation equilibrium](image-url)
In Figure 3b, the initial equilibrium $o$ changes to $o'$ with enhanced capacity of Port 1. More stringent regulations in both countries result. If both ports expand capacities, the equilibrium will shift to $o''$, which suggests even more stringent emission standards than at $o'$. Figure 3b indicates that capacity expansion at one port results in stricter emission controls at both ports. Compared to Proposition 3, this is a new insight as there we consider capacity increase at both ports simultaneously. Note that the changing direction of emission control at one port in response to capacity increases at another port is also different from the result in Proposition 10, where port charges are fixed at the initial equilibrium values. In fact, from scenario 3 in Table 5 we see that after the capacity at Port 1 increases, the charge at Port 2 will decrease quite substantially. The government of Country 2 will then raise the emission standard to relieve generalized port price competition towards maximizing social welfare (although social welfare will still be reduced compared to prior to capacity expansion).

Figure 3b. Effects of port capacity on the bilateral regulation equilibrium

In Figure 3c, $e_1'(e_2) = e_2'(e_1)$ and $e_1'(e_1) = e_2'(e_2)$ because one country reacts to the emission standard of the other country, but not directly to the other country’s environmental damage cost per unit pollutant. If the environmental damage cost per unit pollutant only increase in Country 1, Country 1 will raise its emission standard. Country 2 will lower its emission standards. When the cost increase in both countries, more stringent emission standards will be imposed at both ports, as reflected by the equilibrium shift from $o$ to $o''$. 
Figure 3c. Effects of the environmental damage cost per unit pollutant on the bilateral regulation equilibrium

5.4 Single country case

Results for the single country case are reported in Table 4. Compared to unilateral and bilateral regulations, we find that the single country case leads to more stringent emission standards than the unilateral and bilateral regulation cases (for Port 1), which is predicted by Proposition 12.

<table>
<thead>
<tr>
<th>Table 4. Scenario analysis for the single country case</th>
</tr>
</thead>
<tbody>
<tr>
<td>PARAMETERS</td>
</tr>
<tr>
<td>---</td>
</tr>
<tr>
<td>$b$</td>
</tr>
<tr>
<td>$a$</td>
</tr>
<tr>
<td>$\alpha$</td>
</tr>
<tr>
<td>$\beta$</td>
</tr>
<tr>
<td>$K_1$ (TEU)</td>
</tr>
<tr>
<td>$K_2$ (TEU)</td>
</tr>
<tr>
<td>$\gamma_1$ ($)</td>
</tr>
<tr>
<td>$\gamma_2$ ($)</td>
</tr>
</tbody>
</table>
Table 4 shows that an increase in the maximum reservation price (scenario 2) leads to less stringent emission standards as the government seek to encourage port businesses to maximize social welfare. When either Port 1 or both ports expand capacity (scenarios 3 and 4), the emission standards at both ports will become slightly more stringent. When the environmental damage cost per unit pollutant at Port 1 \( (\gamma_1) \) increases (scenario 5), Government 1 will raise emission control at Port 2, which may be the net result of two opposing effects. On the one hand, by lowering emissions standard at Port 2, demand will shift from Port 1 to Port 2, helping reduce the environmental damage costs at Port 1 as a result of increased \( \gamma_1 \). On the other hand, the demand shift causes more environmental damage at Port 2, which leads the government to raise the emission standard at Port 2. It seems that the former effect dominates the latter. If the environmental damage costs per unit pollutant at both ports increase, (scenario 6) higher emission standards will be set at both ports.
5.5 Summary

Table 5 summarizes the numerical results of the effects of the maximum reservation price, port capacities, and the environmental damage cost per unit pollutant on optimal emission standards at port i. Asterisks denote places where restrictions as required in the analytical results (Table 1) are no longer required.

Table 5. The effects of maximum reservation price, port capacities, and the environmental damage cost per unit pollutant on the optimal emission standard at port i (i=1,2; i ≠ j) from the numerical analysis

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum reservation price (b)</th>
<th>Capacity (K_i, K_j)</th>
<th>Environmental damage cost per unit pollutant (γ_i, γ_j)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilateral regulation</td>
<td>↓*</td>
<td>K_i: ↑<em>, K_j: ↑</em></td>
<td>γ_i: ↑<em>, γ_j: ↓</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_i, K_j: ↑*</td>
<td>γ_i, γ_j: ↑*</td>
</tr>
<tr>
<td>Unilateral regulation</td>
<td>↓</td>
<td>K_i: ↑, K_j: ↑</td>
<td>γ_i: ↑, γ_j: no effect</td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_i, K_j: ↑</td>
<td>γ_i, γ_j: ↑</td>
</tr>
<tr>
<td>Single country</td>
<td>↓*</td>
<td>K_i: ↑<em>, K_j: ↑</em></td>
<td>γ_i: ↑<em>, γ_j: ↓</em></td>
</tr>
<tr>
<td></td>
<td></td>
<td>K_i, K_j: ↑*</td>
<td>γ_i, γ_j: ↑*</td>
</tr>
</tbody>
</table>

Note: An upward arrow indicates a change towards a higher emission standard.

6 Conclusion

This paper develops analytical models to investigate port emission controls in a duopoly port environment, where government(s) determine optimal emission standards for ports in their jurisdiction(s). Private port operators aim to maximize profits subject to emission regulations and congestion effects. Three cases were analyzed: (1) two ports in two countries but only one subject to emission controls (unilateral regulation), (2) two ports in two countries and both subject to emission controls (bilateral regulation), and (3) two ports in the same country and subject to emission controls. Under each case, attempts were made to derive optimal emission standards. We analyzed the effects of the maximum reservation price, port capacity, and the unit environmental damage cost on the optimal emission standards. The analytical findings were further complemented by numerical analysis. We find that, as the maximum reservation price of shipping operators increases, a government will lower its emission standard. Capacity expansion at a port will prompt more stringent emission regulation at both ports. If the unit environmental damage cost at a port increases, a higher emission standard will be imposed at the port.

The insights from the analysis can help inform future policy-making, not just for individual countries but also at the international level towards reducing the environmental impacts of maritime shipping at and around ports. In particular, our analysis shows that the emission standards will be set such that the additional fuel cost to shipping operators will be higher than a Pigouvian tax. In other words, the emission regulation should be sufficiently ‘tough’ to have shipping operators’ internalize their negative externalities. Moreover, the tough regulation can
relieve generalized port price competition between ports. Another critical insight is that heavy capacity expansion and increased environmental damage costs should result in stricter emission control at a port. In the real world, ports are often involved in intense competition through capacity expansion, especially in Asian countries such as China, Singapore, and South Korea. Major ports in these countries are often located within the boundary of metropolitan cities, where health impacts from emissions could be severe. While designating ECA in Asia has been under policy discussions, joint emission regulations may be better than individual efforts to increase their respective and overall social welfare.

We suggest a few directions for future research. First, the environmental damage cost in the paper was assumed linear to the maximum amount of pollutant allowed per TEU. It is possible that some environmental damage such as health impacts is convex increasing with respect to $e_i$. Thus, it would be interesting to examine if a nonlinear specification provides additional insights. Second, in the present analysis we assumed that the environmental damage at one port does not cause damage at the other port. However, if two ports are sufficiently close, the environmental damage may have transboundary effects. In this case, emission standard setting would likely involve cooperation between governments. Third, as an alternative to using cleaner fuel, environmental damage at and around ports can be reduced by slowing ship speed, which increases shipping time. It would be interesting to examine which of the two options would be preferred. Fourth, as a special case for setting emission standards, one could consider a binary decision of whether to join ECA, a situation that many countries are currently contemplating in compliance with MARPOL protocols. Lastly, one may analyze how ‘distance to ports’ would affect emission standards, as longer distances would decrease shipping operators’ maximum reservation price. By Proposition 6 and the numerical results, governments would impose higher emission standards. This should be further investigated through formal model development.

Acknowledgement

We appreciate Anming Zhang and Xiaowen Fu for their helpful suggestions. We also thank participants of the 2017 Aviation and Maritime Operations Management Workshop, held at Sun Yat-sen University, Guangzhou, China, for various comments received. This work was supported by the Ministry of Education of the Republic of Korea and the National Research Foundation of Korea (NRF-53956-01).

References


Appendix A. Proof of Proposition 1

Manipulating (17) and imposing symmetry leads to:

\[
P^* \left( \frac{\partial Q^*_i}{\partial e_i} + \frac{\partial Q^*_j}{\partial e_i} \right) - \gamma e^* \frac{dQ_i(e^*)}{de_i} - \gamma Q^* = 0
\]

\[
\rightarrow 2P^* \frac{dQ_i(e^*)}{de_i} - \gamma e^* \frac{dQ_i(e^*)}{de_i} - \gamma Q^* = 0
\]

\[
\rightarrow P^* \left( 2f' + \frac{\gamma g^2 - a^2}{2g^2 - a^2} \right) = \gamma e^* f'
\]

(A.1)

Because the RHS of (A.1) should be negative by \( f' < 0 \), the LHS should also be negative. The negative LHS implies \( f'e^* + \gamma e^* < 0 \) because:

\[
f'e^* + \gamma e^* < e^* \left( 2f' + \frac{\gamma g^2 - a^2}{2g^2 - a^2} \right) < 0
\]

To find expressions for \( f'e^* \), we use Taylor expansion to have \( f(2e^*) \approx f^* + f'e^* \). This, together with \( f'e^* + \gamma e^* < 0 \), leads to:

\[-f^* + \gamma e^* < f(2e^*) - f^* + \gamma e^* < 0 \]

The leftmost inequality indicates that \( f^* > \gamma e^* \).

Appendix B. Proof of Proposition 2

Repeating similar procedures as Appendix A, we obtained the following equation:

\[
P^* \left( \frac{2 - e^*(g^2 - a^2)}{\gamma (2g^2 - a^2)} \right) = e^*
\]

(B.1)

Rearrange (B.1) and define \( \phi = P^* \left( \frac{2 - e^*(g^2 - a^2)}{\gamma (2g^2 - a^2)} \right) - e^* \). By the implicit function theorem, \( \frac{\partial e^*}{\partial b} = -\frac{\phi}{\partial e^*} \), where:
\[
\phi_y = \frac{2g^2 - ag - a^2}{4g^2 - a^2} \left( \frac{2 - e^2(4g^2 - a^2)}{\gamma \beta(2g^2 - a^2)} \right) \\
= \frac{e^2(2g^2 - ag - a^2)}{P^* (4g^2 - a^2)} > 0 \quad (\because \text{Eq.}(B.1))
\]

\[
\phi_e = -\left( 1 + \frac{2P^* e^* (4g^2 - a^2)}{\beta (2g^2 - a^2)} - \frac{\beta (2g^2 - a^2)}{e^2 (4g^2 - a^2)} \left( \frac{2 - e^2 (4g^2 - a^2)}{\gamma \beta (2g^2 - a^2)} \right) \right)
\]

\[
= -\left( 1 + \frac{2P^* e^* (4g^2 - a^2)}{\beta (2g^2 - a^2)} - \frac{\beta (2g^2 - a^2)}{P^* e^* (4g^2 - a^2)} \right)
\]

\[
= -\left( 1 + \frac{2P^* e^* (4g^2 - a^2)}{\beta (2g^2 - a^2)} - \frac{\beta (2g^2 - a^2)}{P^* e^* (4g^2 - a^2)} \right) - \frac{ag \beta}{P^* e^* (4g^2 - a^2)} < 0
\]

(\because \text{Eq.(20)})

Combining (B.2) and (B.3), we obtain \( \partial e^* / \partial b > 0 \). ■

**Appendix C. Proof of Proposition 3**

Similar to Proposition 6, applying the implicit function theorem leads to \( \partial e^* / \partial g = -\phi_e / \phi_g \), where \( \phi_e \) is defined in (B.3), and \( \phi_g = \frac{ae^* (4g^2 + 4ag + a^2)}{(4g^2 - a^2)(2g^2 - ag - a^2)} + \frac{P^* e^* (4g^2 - 3a^2)}{\beta (4g^2 - a^2)(2g^2 - a^2)^2} > 0 \).

By the definition of \( g \) and the chain rule, \( \partial e^* / \partial g > 0 \Leftrightarrow \partial e^* / \partial K < 0 \). ■

**Appendix D. Proof of Proposition 4**

By the implicit function theorem, \( \partial e^* / \partial \gamma = -\phi_e / \phi_\gamma \), where \( \phi_\gamma = -2P^* / \gamma^2 < 0 \). By (B.3), \( \partial e^* / \partial \gamma < 0 \). ■

**Appendix E. Derivation of emission standard rule under the unilateral and bilateral regulation case**

Eq. (35) leads to:

\[
\]
Appendix F. Proof of Proposition 5

Manipulating (30) leads to:

\[
Q_i \left( \frac{\partial P^*}{\partial e_i} - \gamma_i \right) + \frac{dQ_i(e_i^*, e_2^*)}{de_i} (P_i - \gamma_i e_i^*) = 0
\]

\[
\Rightarrow Q_i \frac{\partial P^*}{\partial e_i} - Q_i \gamma_i + \frac{dQ_i(e_i^*, e_2^*)}{de_i} \frac{Q_i^*(g_1 g_2 - a^2)}{g_2} - \frac{dQ_i(e_i^*, e_2^*)}{de_i} \gamma_i e_i^* = 0
\]

\[
\Rightarrow 2 \beta (2 g_1 g_2 - a^2) e_i^* \left( 4 g_1 g_2 - a^2 \right) - \gamma_i e_i^* = 0
\]

\[
\Rightarrow e_i^* = \frac{2 \beta (2 g_1 g_2 - a^2)}{\gamma_i (1 + e_i^*) (4 g_1 g_2 - a^2)}
\]

In equilibrium, the bracketed term in (B.1) should be positive. This implies that:

\[
\gamma_i e_i^* < \frac{2 \beta (2 g_1 g_2 - a^2)}{e_i^* (4 g_1 g_2 - a^2)} < \frac{\beta}{e_i^*}.
\]

Appendix G. Proof of Proposition 6

Manipulate (F.1) and define \( \phi = P_i^* \left( \frac{2}{\gamma_i} - \frac{e_i^* (4 g_1 g_2 - a^2)}{\beta (2 g_1 g_2 - a^2)} \right) - e_i^* \). By the implicit function theorem, \( \partial e_i^*/\partial b = -\phi_i/\phi_e \), where:
\[
\phi_b = \frac{2g_1g_2-a_1-a^2}{4g_1g_2-a^2} \left( \frac{2}{\gamma_1} - \frac{e^2_1(4g_1g_2-a^2)}{\beta(2g_1g_2-a^2)} \right)
\]
\[
= \frac{e^*_1(2g_1g_2-a_1-a^2)}{P^*_1(4g_1g_2-a^2)} > 0 \quad (\because \text{Eq.}(F.1))
\]

\[
\phi_{\alpha_1} = -\left(1 + \frac{2P^*_1 e^*_1(4g_1g_2-a^2)}{\beta(2g_1g_2-a^2)} - \frac{e^*_1(4g_1g_2-a^2)}{\beta(2g_1g_2-a^2)} \left( \frac{2}{\gamma_1} - \frac{e^2_1(4g_1g_2-a^2)}{\beta(2g_1g_2-a^2)} \right) \right)
\]
\[
= -\left(1 + \frac{2P^*_1 e^*_1(4g_1g_2-a^2)}{\beta(2g_1g_2-a^2)} - \frac{\beta(2g_1g_2-a^2)}{e^*_1(4g_1g_2-a^2)} \right) \left( P^*_1 + \frac{\beta(2g_1g_2-a^2)}{e^*_1(4g_1g_2-a^2)} \right) < 0 \quad (\because \text{Eq.}(F.1))
\]

\[
\phi_{\alpha_2} = \frac{-e^*_1(4g_1g_2-a^2)}{P^*_1 \beta(2g_1g_2-a^2)} \left( 2P^*_1 - \frac{\beta(2g_1g_2-a^2)}{e^*_1(4g_1g_2-a^2)} \right) \left( P^*_1 + \frac{\beta(2g_1g_2-a^2)}{e^*_1(4g_1g_2-a^2)} \right) < 0 \quad (\because \text{Eq.}(38))
\]

Combining (G.1) and (G.2), we obtain $\partial e^*_1 / \partial b > 0$. ■

**Appendix H. Proof of Proposition 7**

Similar to Proposition 6, applying the implicit function theorem leads to $\partial e^*_1 / \partial g_1 = -\phi_{g_1} / \phi_{e_1}$, where $\phi_{e_1}$ is defined in (G.2), and $\phi_{g_1} = \left( \frac{P^*_1 M}{e^*_1} + \frac{2a^2 g_2 P^*_1 e^2_1}{\beta(2g_1g_2-a^2)} \right) > 0$. Note that

\[
M = \frac{a^2 \left[ 2g_2(b - \beta / e^*_1) + a(b - \beta / e^*_2) \right]}{(4g_1g_2-a^2)^2} > 0.
\]

By the definition of $g_1$ and the chain rule,

$\partial e^*_1 / \partial g_1 > 0 \iff \partial e^*_1 / \partial K_1 < 0$.  Likewise, $\partial e^*_1 / \partial g_2 = -\phi_{g_2} / \phi_{e_1}$, where

\[
\phi_{g_2} = \left( \frac{2g_2 P^*_1 M}{a e^*_1} + \frac{2a^2 g_1 P^*_1 e^*_2}{\beta(2g_1g_2-a^2)} \right) > 0.
\]

Combining this with $\phi_{e_1} < 0$ gives $\partial e^*_1 / \partial g_2 > 0 \iff \partial e^*_1 / \partial K_2 < 0$. ■

**Appendix H. Proof of Proposition 8**

By the implicit function theorem, $\partial e^*_1 / \partial \gamma_1 = -\phi_{\gamma_1} / \phi_{e_1}$, where $\phi_{\gamma_1} = -2P^*_1 / \gamma_1^2 < 0$. By (G.2),

$\partial e^*_1 / \partial \gamma_1 < 0$. ■

**Appendix J. Proof of Proposition 9**

Implicitly differentiating (30) and (31) with respect to $b$ results in:
\[
\frac{\partial P_1'}{\partial b} = \frac{2g_1g_2 - ag_1 - a^2}{4g_1g_2 - a^2} + \frac{\beta(2g_1g_2 - a^2)}{e_1^2(4g_1g_2 - a^2)} \frac{\partial e_1^*}{\partial b} - \frac{ag_1\beta}{e_2^2(4g_1g_2 - a^2)} \frac{\partial e_2^*}{\partial b} \\
\frac{\partial P_2'}{\partial b} = \frac{2g_1g_2 - ag_1 - a^2}{4g_1g_2 - a^2} - \frac{ag_2\beta}{e_1^2(4g_1g_2 - a^2)} \frac{\partial e_1^*}{\partial b} + \frac{\beta(2g_1g_2 - a^2)}{e_2^2(4g_1g_2 - a^2)} \frac{\partial e_2^*}{\partial b} 
\] (J.1)

Setting \( \frac{\partial P_1'}{\partial b} = \frac{\partial P_2'}{\partial b} = 0 \) and applying Cramer’s rule gives:

\[
\begin{bmatrix}
\frac{\partial e_1^*}{\partial b} \\
\frac{\partial e_2^*}{\partial b}
\end{bmatrix}
_{|r_1^*, r_2^*} = \frac{-e_1^* e_2^*}{\beta(g_1g_2 - a^2)(4g_1g_2 - a^2)} \begin{bmatrix}
\frac{(2g_1g_2 + a_1 - a^2)}{e_1^*} \\
\frac{(2g_1g_2 + a_2 - a^2)}{e_2^*}
\end{bmatrix}
\] (J.3)

Hence, \( \frac{\partial e_1^*}{\partial b} \bigg|_{|r_1^*, r_2^*} < 0 \) and \( \frac{\partial e_2^*}{\partial b} \bigg|_{|r_1^*, r_2^*} < 0 \).

**Appendix K. Proof of Proposition 10**

Implicitly differentiating (30) and (31) with respect to \( g_1 \), and repeating the similar procedure as the proof of Proposition 9, we obtain:

\[
\begin{bmatrix}
\frac{\partial e_1^*}{\partial g_1} \\
\frac{\partial e_2^*}{\partial g_1}
\end{bmatrix}
_{|r_1^*, r_2^*} = \begin{bmatrix}
\frac{a^2M e_1^*}{\beta(g_1g_2 - a^2)} \\
\frac{g_2M e_2^*(4g_1g_2 - 3a^2)}{a\beta^3(g_1g_2 - a^2)}
\end{bmatrix}
\] (K.1)

where \( M = \frac{a^2 \{2g_2(b - \beta/e_1^*) + a(b - \beta/e_2^*)\}}{(4g_1g_2 - a^2)^2} \). Eq.(K.1) suggests that \( \frac{\partial e_1^*}{\partial g_1} \bigg|_{|r_1^*, r_2^*} > 0 \) and \( \frac{\partial e_2^*}{\partial g_1} \bigg|_{|r_1^*, r_2^*} < 0 \). Because \( \frac{\partial g_1}{\partial K_1} < 0 \) and \( \frac{\partial g_2}{\partial K_2} < 0 \), so \( \frac{\partial e_1^*}{\partial K_1} \bigg|_{|r_1^*, r_2^*} < 0 \) and \( \frac{\partial e_2^*}{\partial K_2} \bigg|_{|r_1^*, r_2^*} > 0 \).

**Appendix L. Proof of Proposition 11**
Implicitly differentiating (F.1) with respect to \( \gamma_1 \) results in:

\[
\Gamma_1^* \beta (4g_1g_2 - a^2) \frac{\partial e_1^*}{\partial \gamma_1} + \frac{a g_1 \beta e_1^*}{e_1^2} \frac{\partial e_2^*}{\partial \gamma_1} = -\frac{2P_1^{* 2}}{y_1^*}
\]  

(L.1)

where \( \Gamma_1^* = \left( \frac{2P_1^* e_1^*}{\beta} - \frac{2g_1g_2 - a^2}{4g_1g_2 - a^2} \left( \frac{P_1^* e_1^*}{\beta} + \frac{2g_1g_2 - a^2}{4g_1g_2 - a^2} \right) \right) \). Similarly, implicitly differentiating (F.1) of Port 2 with respect to \( \gamma_1 \) leads to:

\[
\frac{a g_2 e_2^*}{e_2^2} \frac{\partial e_1^*}{\partial \gamma_1} + \frac{\Gamma_1^* \beta (4g_1g_2 - a^2) \frac{\partial e_2^*}{\partial \gamma_1}}{e_2^2 (4g_1g_2 - a^2)} = 0
\]  

(L.2)

Solving (L.1) and (L.2) by Cramer’s rule gives:

\[
\begin{pmatrix}
\frac{\partial e_1^*}{\partial \gamma_1} \\
\frac{\partial e_1^*}{\partial \gamma_1} \\
\frac{\partial e_2^*}{\partial \gamma_1}
\end{pmatrix}
= \frac{1}{T}
\begin{pmatrix}
-\frac{\Gamma_1^* P_1^{* 2} \beta (4g_1g_2 - a^2)}{e_2^* \gamma_1^2 (2g_1g_2 - a^2)} \\
\frac{2 a g_2 e_2^*}{e_2^* (4g_1g_2 - a^2)} \\
\frac{\Gamma_1^* \beta (4g_1g_2 - a^2)}{e_2^* (4g_1g_2 - a^2)}
\end{pmatrix}
\]  

(L.3)

where \( T = \frac{\Gamma_1^* \Gamma_2^* (4g_1g_2 - a^2)^2}{e_1^* e_2^* (2g_1g_2 - a^2)^2} - \frac{a^2 g_1 g_2 \beta^2}{e_1^* e_2^* (4g_1g_2 - a^2)^2} \). It is evident that \( \frac{\partial e_1^*}{\partial \gamma_1} < 0 \) and \( \frac{\partial e_1^*}{\partial \gamma_2} > 0 \) if \( \frac{\Gamma_1^* \Gamma_2^*}{\Gamma_1^*} > \frac{a^2 g_1 g_2 (2g_1g_2 - a^2)^2}{(4g_1g_2 - a^2)^4} \). Moreover, the signs of \( \frac{\partial e_1^*}{\partial \gamma_1} \) and \( \frac{\partial e_1^*}{\partial \gamma_2} \) are opposite. ■

Appendix M. Derivation of the optimal emission standard under the single country case

The first-order condition of (42) leads to:

\[
\left( \frac{\partial P_1^*}{\partial e_1} - \gamma_1 \right) Q_1^* + \left( P_1^* - \gamma_1 e_1^* \right) \frac{dQ_1^* (e_1^*)}{de_1} + \left( P_2^* - \gamma_2 e_2^* \right) \frac{dQ_2^* (e_1^*)}{de_1} = 0
\]
\[
\frac{2(g_1g_2 - a^2)}{g_2} \frac{dQ_1(e_1^*)}{de_1} - \gamma_1 - \gamma_1 e_1 + \frac{ag_1g_2\beta(P_2^* - \gamma_1 e_1^*)}{Q_1^2 e_1^2 (g_1g_2 - a^2)(4g_1g_2 - a^2)} = 0
\]

\[
\therefore P_2^* = \frac{Q_1^2 (g_1g_2 - a^2)}{g_2}
\]

\[
\rightarrow e_1^{**} = \frac{2(2g_1g_2 - a^2)\beta}{\gamma_1(1+\epsilon_1)(4g_1g_2 - a^2)} - \frac{ag_1g_2\beta(P_2^{**} - \gamma_2 e_1^{**})}{\gamma_1 Q_1^2 (1+\epsilon_1)(g_1g_2 - a^2)(4g_1g_2 - a^2)}
\]

### Appendix N. Summary of numerical experiment for convex congestion function

Table N1. Effects of maximum reservation price, port capacities, and the environmental damage cost per unit pollutant on the optimal emission standard (numerical - convex congestion function)

<table>
<thead>
<tr>
<th>Case</th>
<th>Maximum reservation price ((b))</th>
<th>Capacity ((K_1, K_2))</th>
<th>Environmental damage cost per unit pollutant ((\gamma_1, \gamma_2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bilateral regulation</td>
<td>↓</td>
<td>(K_1: \uparrow, K_2: \downarrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \downarrow)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(K_1, K_2: \uparrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \uparrow)</td>
</tr>
<tr>
<td>Unilateral regulation</td>
<td>↓</td>
<td>(K_1: \uparrow, K_2: \uparrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \text{no effect})</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(K_1, K_2: \uparrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \uparrow)</td>
</tr>
<tr>
<td>Single country</td>
<td>↓</td>
<td>(K_1: \downarrow, K_2: \uparrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \downarrow)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(K_1, K_2: \uparrow)</td>
<td>(\gamma_1: \uparrow, \gamma_2: \uparrow)</td>
</tr>
</tbody>
</table>

Note: Upward arrow indicates more stringent emission regulation.

*: The effects that are different from those from numerical analysis involving linear congestion function.