How should ports share risk of natural disasters? Analytical modelling and implications for adaptation investments

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Abstract

This study theoretically examines disaster adaptation investments under risk of natural disasters. Given two neighboring, competitive ports, the disasters may cause independent damages to either port, or to both ports simultaneously; consequently, some shippers avoid loss by using the unaffected port if an independent disaster occurs in their local port. Since such inter-port risk sharing benefit increases with the share of independent disasters in all disasters, the socially optimal investment decreases with the disaster independence. However, the risk sharing benefit only attributes to the shippers' surplus and does not attribute to profits from the port management, so it does not affect investment of private port authorities that maximize the profits. Such an ignorance of the risk sharing benefit by the private port authorities is likely to lead to underinvestment in disaster adaptation facilities under a lower disaster independence.

Keywords: *independence of disaster, risk sharing, disaster adaptation.*
JEL classification: R42, D81.

1 Introduction

Seaports face risk of various natural disasters that destroy and significantly reduce their function. There are various types of disasters which differ in, among others, frequencies, scales, and measures to mitigate the damages. For example, natural disasters such as floods, hurricanes, and storm surges caused by climate change, have raised worldwide concerns for the past decade, and many countries have taken measures, or made the plans, to deal with the risk (e.g. Verschuur et al. 2020; Xiao et al. 2015). Some countries also face other types of disasters, such as earthquakes, as well as climate change. In Japan, for

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example, earthquake resistance of ports has been promoted after several major earthquakes in recent years.[1]

However, effective measures for those disasters are not limited to capital investments such as breakwaters that directly reduce the damage to individual infrastructures if a disaster occurs. In recent years, much attention was focused also on strengthening resilience of the entire network through functional substitution between ports, or "risk sharing". For example, when ports in the northeast region of Japan mainland were damaged by the Great East Japan Earthquake in March 2011, their facilities were substituted with the ports in Tokyo (Hamano and Varmuelen, 2020). Friedt (2021) reports a similar rerouting pattern of international maritime shipment in the case of Hurricane Katrina in 2005. Furthermore, the Delta Program between the Ports of Rotterdam and Antwerp, designed to ensure resilience to sea level rise and floods in the Netherlands, is a proactive policy measure applying the risk sharing.

Availability of the risk sharing is largely dependent on characteristics of disaster and the geographical characteristics of ports. For example, impact of climate change is more profound in low-lying ports such as those in the Netherlands (Zheng et al., 2021a). The 1995 Great Hanshin Earthquake in Japan was a direct earthquake whose effect stayed local, so although the facilities at Kobe Port were devastated, those at the neighboring Osaka Port were not. In this way, even for nearby ports, possibility of risk sharing may increase when the degree and type of disaster risks they face are different. The possibility of such risk sharing in actual ports is case-by-case, and we need detailed assessments based on various scientific expertise in disaster prediction. It is nevertheless important to carry out economic analysis to actively utilize forecasts obtained through them for disaster countermeasures at individual ports.

In this study, we theoretically investigate socially desirable port investment and management by an appropriate combination of disaster adaptation investment in individual ports and risk sharing between ports. Many existing studies have investigated disaster adaptation investments by private and public entities, considering only disasters that have symmetric and simultaneous impacts on two competing ports (Wang and Zhang, 2018; Randrianarisoa and Zhang, 2019; Wang et al., 2020; Xia and Lindsey, 2021; Zheng et al., 2021b). Zheng et al. (2021a) also considered asymmetric disaster scales between ports, and investigated disaster adaptation investments with possible contracts between terminal operators to transfer excess capacity in the case when disasters occur. While we

[1] According to the Ministry of Land, Infrastructure, Transport and Tourism of Japan, the number of ports completing earthquake-resistant reinforced walls increased from 34 in 1997, to 95 in 2020 out of 125 major ports in Japan. For details, see https://report.jbaudit.go.jp/org/h14/2002-h14-0616-0.htm and https://www.mlit.go.jp/policy/shingikai/content/001335715.pdf

extend the two-port model analyzed in several previous studies, this is the first study to consider possibility of independent (so-called “local”) disasters at each port, as well as the wide-spreading (“common”) disasters that affect both ports.[2] As a consequence, we consider that shippers can switch to the other port when their local port is damaged by a local disaster. Furthermore, we introduce a parameter to represent the share of such local disasters to represent the degree of independence of disastrous shocks between the ports, which is simply called “disaster independence”. We find that, when the disaster independence is high and the expected disaster scale is enormous, the socially optimal level of disaster adaptation investment is small because disaster risk can be mitigated rather by the inter-port functional sharing.

The study further examines whether decentralized adaptive investments realized through competition between privatized ports in various forms are excessive compared to the socially optimal investment. Possibility of privatized adaptation investment and necessity of policy intervention have been recent important issues and repeatedly discussed in the former studies mentioned above. All of our results summarized below show that various factors related to disaster independence and applicability of the risk sharing have an important influence on this debate. First, given risk neutral preference of shippers, the benefits of risk sharing that arise through the availability of other ports do not attribute to the profits of the operators of each port. As a result, private investment is likely to achieve a suboptimal investment when there is small risk independence, a situation considered by previous studies. However, for high disaster independence, profit maximizing operators ignore the risk sharing benefit in the shippers' consumer surplus, which may lead to excessive disaster adaptation. Second, when comparing different forms of port terminal operators, the more competitive form induces a higher level of investment, so it is likely to achieve higher social welfare under lower disaster independence.[3] Finally, we examine the effect of geographical distance between two ports. When the distance is large, risk sharing becomes less available and social necessity for adaptive investment increases, while equilibrium investment levels of privatized port management may decline due to reduced port competition.

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[2] Itoh (2018) also investigated substitution of two infrastructures facing independent disaster risks, but he only focused on cost recoverability under socially optimal investment and management. Relatedly, Balliauw et al. (2019) studied capacity investments of two competing ports under uncertainty using a strategic real options approach.

[3] Effects of operation regimes on the decision of (air)port authorities have been investigated by several former studies. Basso and Zhang (2007) focus on the degree of competition among local operators (carriers) in each airport, Mun and Imai (2021) compare the cases with/without a global terminal operator, and Czerny et al. (2014) examine port competition and associated welfare effects under alternative governance regimes (private or public operators) in an international setting.

This paper is organized as follows. Section 2 presents the model, and Section 3 provides the basic analysis. Section 4 investigates the various forms of port investment and management. Section 5 examines several extensions of the basic settings. Finally, Section 6 contains concluding remarks.

2 The model

2.1 Basic settings

Consider a one dimensional linear hinterland $[-\infty, +\infty]$, in which the potential shippers (port users) are uniformly distributed with population density 1. There are also two seaports, port 1 and 2, whose locations are given by 0 and 1, respectively (see Figure 1 below). When a shipper located in $x = [-\infty, +\infty]$ uses a port located in $y \in \{0,1\}$, (s)he pays $t|x-y|$ for access cost, where $t > 0$ stands for per-distance unit transport cost. Each user consumes a fixed, one unit of port service from either port only if surplus from the service is positive; otherwise, (s)he consumes no port services. We assume, for simplicity, that the two ports are symmetric in their conditions. (The symmetric assumption will be relaxed in Section 5.) These basic settings were also employed by the previous papers (e.g., Basso and Zhang, 2007; Wang and Zhang, 2018). Following these previous studies, we also consider a "vertical structure" of port management and investment in Section 4. [4]

2.2 Disaster occurrence and disaster adaptation technology

The economy faces four types of states or events, denoted as $\{S_0, S_1, S_2, S_3\}$, where state S_0 faces no disaster (and so transportation infrastructure is unaffected). In state S_i, a disaster occurs and infrastructure in region $i \in \{1,2\}$ is unavailable (partly or wholly). Finally, a disaster influences both ports in state S_3: that is, the disaster in S_3 is more widely spreading and concurrent than those in S_i which are local and independent. The probability or frequency that each state occurs is denoted by $\Pr(s)$, which is described as follows:

$$\Pr(s) = \begin{cases} \rho^{S12} & \text{for } s = S_1, S_2 \\ \rho^{S3} & \text{for } s = S_3 \\ 1 - 2\rho^{S12} - \rho^{S3} & \text{for } s = S_0 \end{cases}. \quad (1)$$

[4] A vertical relationship between port investment and management is described by a sequential game in which port investment, port concession fee, and user charge are determined in that order by different entities. Please see Section 4 for more details.

That is, we extend the risk of disaster by introducing states S_i and S_3, while former studies like Wang and Zhang (2018) and Zheng et al. (2021a) only consider the case with $\rho^{S12} = 0$.

We assume that the ports are not congestible, and their basic facilities are denoted by V. We further define the "effective facility", V_i^s, which also stands for the value of the transportation service from infrastructure i, as follows:

$$V_i^s = V - \psi_i^s(D - I_i),$$
$$\psi_i^s = \begin{cases} 1 & \text{for } s = S_i, S_3 \\ 0 & \text{for } s = S_j, S_0, \quad i \neq j. \end{cases} \tag{2}$$

where D is the damage of a disaster when it occurs and ψ_i^s is a disaster indicator that takes 1 in S_i or S_3 and zero in the other states. Analogous to Wang and Zhang (2018) and Wang et al. (2020), we assume that the damage of disaster deteriorates ports' facility but the damage will be mitigated by disaster adaptation facility whose quality is denoted by I_i.[5] The investment cost for the facility is described as $cI_i^2/2$, since we consider I_i is such a facility as height of sea walls and so it is likely that there is increasing marginal cost. We assume $0 < I_i < D < V$ holds in the reminder of the paper.

We now define several measures to characterize the risk of disasters. First, we define $\rho \equiv \rho^{S12} + \rho^{S3}$ to indicate the disaster occurrence probability. It is natural to consider that the disasters are unusual events, so we assume $\rho < 1/2$. Second, we define the *expected* effective port facility as $\overline{V_i} \equiv V - \rho(D - I_i)$. Third, our model distinguishes state S_1 and S_2 from S_3 in order to consider independence of disastrous shocks (or merely called disaster independence), and this is a major innovation of this study because the existing literature only considers the concurrent occurrence of disaster, or only state S_3. While the disaster independence is influenced by many factors such as geographical distance between the ports, we simply treat it in an exogeneous manner by using ρ^{S3}; the disaster independence decreases with ρ^{S3}.[6]

However, note that merely changing ρ^{S3} alone also affects the entire occurrence ρ and the expected facility $\overline{V_i}$ (or, expected damage ρD). Therefore, when we focus on the

[5] Note that the disaster does have an impact on port demand indirectly via V_i^s, which is in turn through specification (2) ("states"). We also assume that, as in most former related studies (e.g., Zheng et al. 2021a), a disaster has no direct influence on demand for shipping. This is consistent with our objective in writing this paper: i.e., to investigate disaster adaptation investments to mitigate the shock which deteriorates port facilities. We note that several former studies have investigated the demand shock (e.g. Xiao et al. 2013).
[6] In other words, ``concurrency" of disaster increases with ρ^{S3}.

effect of independence, we simultaneously control ρ^{S12} with ρ^{S3} to maintain ρ constant.[7] By controlling disaster independence in such a way, we can compare the influences of wide-spreading disaster and local disaster given the same level of expected damage between them.

2.3 Port demand

The surplus that a user located in $x \in [-\infty, +\infty]$ takes from port i is as follows:

$$V_i^s - p_i - t|x - y_i|, \tag{3}$$

where p_i is the user fee of the port service charged by the operator and y_i is the location of port i; hence $p_i + t|x - y_i|$ stands for the cost inducing price. The service level or gross benefit of the port service is equivalent to V_i^s. The benefit of not using the port is assumed zero. This paper assumes that the price is fixed for all the states because terminal operators cannot change it in the short-term facing a disaster. In contrast, shippers can change the port (and operator) to use depending on the states they face without switching costs.[8]

We now derive the demand function for the two ports. We call the hinterland in $[0,1]$ the "overlapping hinterland", while $[-\infty, 0]$ and $[1, +\infty]$ are called the "backyard hinterlands" of port 1 and 2, respectively. Suppose that shippers in the overlapping hinterland use either port, and there is a threshold location, denoted by x_{Ms}, at which the two ports are considered by the shipper as indifferent. Therefore, as depicted in Figure 1, the location of the threshold consumer in states is described as follows:

$$x_{Ms} = \frac{(V_1^s - V_2^s) - (p_1 - p_2)}{2t} + \frac{1}{2}. \tag{4}$$

[7] We suppose that increase in ρ^{S3} occurs with decrease in ρ^{S12} so as to hold $2d\rho^{S12} = -d\rho^{S3}$ and $d\rho = 0$.

[8] In the present set-up, the shippers who change a port must bear additional transport costs in order to access to the more distant port, However, rerouting of shipment sometimes may incur "switching costs" (e.g., having additional time and frictions to change shipping contracts) (e.g. Achurra et al. 2019). Although former theoretical works have not considered the issue, Friedt (2021) shows indirect empirical evidence that shippers' port selection has not recovered to the original level even after the restoration of port function.

In the rest of the paper, we assume that there are some users in the overlapping hinterland to prefer each port, and any overlapping user chooses either port to use.[9] Therefore, given the threshold, demands for port 1 and 2 from the overlapping hinterland are x_{Ms} and $1 - x_{Ms}$, respectively. Note that $x_{MS_1} < x_{MS_3} = x_{MS_0} < x_{MS_2}$ holds for the symmetry of the two ports.[10]

Further, location of the threshold user in each backyard hinterland, at which consuming and not consuming the port service by the shipper is indifferent, are as follows:

$$x_{B1s} = -\frac{V_1^s - p_1}{t},$$
$$x_{B2s} = 1 + \frac{V_2^s - p_2}{t}. \quad (5)$$

Hence the demands from the backyard users for port 1 and 2 are $-x_{B1s}$ and $x_{B2s} - 1$, respectively. Note that $x_{B1S_0} < x_{B1S_1} = x_{B1S_3}$ holds; and it is analogously extended to the backyard of port 2. Therefore, the demand for port i is described as follows:

$$q_i^s = \frac{(3V_i^s - V_j^s) - (3p_i - p_j)}{2t} + \frac{1}{2}. \quad (6)$$

Finally, key variables and parameters are listed in Table 1.

[Insert Figure 1 around here]

[Insert Table 1 around here]

[9] That is, we assume $x_{Ms} \in (0,1)$ for the former property. We also assume $V_1^s - p_1 - tx_{Ms} > 0$ and $V_2^s - p_2 - t(1 - x_{Ms}) > 0$ for the latter; that is, no overlapping users choose not to use any port. Under these conditions, demand for each port is strictly positive. So that the equilibrium satisfies those properties, we need to assume that V is sufficiently large and D is sufficiently small.

[10] Since the two ports are assumed symmetric, $p_1 = p_2$ and $I_1 = I_2$ hold in equilibrium, and hence $x_{MS_3} = x_{MS_0} = 1/2$ also holds.

3 Basic analysis

3.1 Effects of disaster independence and the risk sharing benefit

We investigate the basic effect of the disaster independence since it is the key issue of this paper. As mentioned above, an increase in disaster independence is described by a decrease in ρ^{S3} so as to keep ρ constant. Since the disaster independence merely changes probability of each state to occur, it does not affect demand and welfare within each state as long as the user charge does not change.[11] Therefore, assuming $d\rho = 0$ and $dp_i = 0$, the expected demand $\overline{q_i} \equiv E(q_i^s)$ does not change with disaster independence. Hence the following holds:

$$\left.\frac{d\overline{q_i}}{d\rho^{S3}}\right|_{d\rho=0, dp_i=0} = 0. \tag{7}$$

Therefore, independence does not affect the expected revenue from port management, $\overline{q_i}p_i$, when the price is fixed.

Second, we consider consumer surplus (CS) of both ports, which is presented, in each state, as follows:

$$\mathrm{CS}^s = \underbrace{\int_{x_{B1}^s}^{0} (V_1^s - p_1 - t|x|)dx}_{Surplus\ \text{in Backyad of 1}} + \underbrace{\int_{1}^{x_{B2}^s} (V_2^s - p_2 - t|1-x|)dx}_{\text{Backyad of 2}}$$
$$+ \underbrace{\int_{0}^{x_M^s} (V_1^s - p_1 - t|x|)dx + \int_{x_M^s}^{1} (V_2^s - p_2 - t|1-x|)dx}_{\text{overlapping hinterland}}. \tag{8}$$

Now we define social welfare as the sum of consumer surplus and profit of port management and development of the two ports: i.e., $W^s \equiv CS^s + \sum_{i=1}^{2}(p_i q_i^s - cI_i^2/2)$.[12] Suppose the disaster independence does not affect the prices (which actually is the case as we can show later in Section 4), the influence of the decrease in disaster independence

[11] In section 4, it is proved that the price of private operator is independent of the independence of disaster. See Lemma 1 and Appendix for more details.

[12] Note that the second term includes profit of terminal operators and port authorities. Therefore, the concession fees which is paid by terminal operators to port authorities is completely canceled out in it.

(i.e., increase in concurrency ρ^{S3}) on the expected social welfare, defined as $W \equiv \rho^{S3}W^{S3} + \rho^{S12}(W^{S1} + W^{S2}) + (1 - \rho^{S3} - 2\rho^{12})W^{S0}$, as follows:

$$
\begin{aligned}
\frac{dW}{d\rho^{S3}}\Big|_{d\rho=0, dp_i=0} &= W^{S3} + W^{S0} - (W^{S1} + W^{S2}) \\
&= CS^{S3} + CS^{S0} - (CS^{S1} + CS^{S2}) \\
&= -\sum_{i=1,2} \frac{\left(q_i^{S3} - q_i^{Si}\right)(D - I_i)}{2} \\
&= -\sum_{i=1,2} \frac{(D - I_i)^2}{4t}.
\end{aligned} \tag{9}
$$

The disaster independence only influences the expected consumer surplus; that is, it does not influence the expected profit of port management and development since the expected demand is independent of it as in (7). Equation (9) shows that the expected social welfare (and the expected consumer surplus) decreases with disaster concurrency.

To understand the loss from decrease in independence, consider the loss of consumer surplus from disasters, which is obtained from comparing CS^{Si} or CS^{S3} to CS^{S0}. Now we focus on the benefit of users located in the "territory" of port i, which is defined by the location of its users in state S_0, to compare the loss of disaster in states S_1 and S_3. From Figures 2 (a) and (b) (note each of which depicts the loss of states S_1 and S_3, respectively) we first find that the loss of port 1 users in the overlapping hinterland differs between S_1 and S_3. In state S_1, users in $\left(x_{MS_i}, x_{MS_0}\right)$, called "footloose users", shift to port 2 and mitigate half of their damage that they should take in S_3 in which the other port is also damaged. In contrast, we also see that the loss in the backyard territory of port 1 is the same in both states because there is no alternative port to shift for those users. Therefore, as shown in Figure 2, if we just focus on the consumer surplus in the territory of port i, only difference between S_i and S_3 is the consumer surplus of the footloose users: that is called the "risk sharing benefit" and described as $\frac{\left(q_i^{S3} - q_i^{Si}\right)(D - I_i)}{2}$.

Turning to (9), we find that the loss from a decrease in disaster independence is exactly the same as the risk sharing benefit. This is because the availability of risk sharing decreases and the expected risk sharing benefit decreases when a simultaneous disaster is more likely to occur. The following statement is readily obtained.

Proposition 1.

Assume that the user charge of each port is constant regardless of state. The expected social welfare decreases when disaster independence decreases, and the loss is equivalent to the risk sharing benefit. The risk sharing benefit increases with size of disaster (D) and disaster adaptation investment ($I_{i\in\{1,2\}}$).

Equation (9) also shows that the lost benefit from reduction in independence increases with significance of disaster damage D while decreases with disaster adaptation investment I_i. The inter-port risk sharing plays a significant role to mitigate the risk of large and independent disasters.

[Insert Figure 2 around here]

3.2 Socially optimal investment

Here, a social planner chooses user charge and investment to maximize welfare, which is sum of the total consumer surplus of shippers and profits from each port. Because there are no externalities such as congestion, the social marginal cost of providing additional shipping services is zero once any investment level is given. Therefore, the social planner achieves the first-best allocation of shippers to two ports by charging $p_i = 0$ and choosing the optimal investment. [13]

The profit is always zero under the socially optimal pricing, and hence the objective of the social planner is to maximize the consumer surplus.[14] Since we assume the symmetry of the two ports, the optimal investment should be symmetric as well. Therefore, given $I_1 = I_2 = I$ and $dI_1 = dI_2 = dI > 0$, we obtain the following first-order condition:

$$\frac{\partial W}{\partial I} = \frac{\partial W}{\partial I_1} + \frac{\partial W}{\partial I_2}$$

$$= \rho Q^{S3} - 2(\rho - \rho^{S3}) \sum_{i=1,2} \left(q_i^{S3} - q_i^{Si}\right) - 2cI$$

$$= 0 \tag{10}$$

[13] That is, the equivalent outcomes regarding investment and users' port choices are attained under the case that the social planner directly controls the allocation of shippers to each port. Also note that $p_i = 0$ is optimal user charge regardless of state s.

[14] The port investment by a profit maximizing port authority and the optimal investment under privatized management (called the second-best port) are investigated in Section 4.

where $Q^{S3} \equiv q_1^{S3} + q_2^{S3}$ shows the total demand for the two ports. Solving (10) yields the following socially optimal investment:

$$I^O = \frac{2\rho V - 3\rho D + \rho^{S3} D + t}{2ct - 3\rho + \rho^{S3}}. \tag{11}$$

Finally, the result is summarized as follows.

Proposition 2.
The socially optimal investment decreases with the disaster independence and D, while increasing with V.

The proof is given in Appendix 1, but just seeing (10) and (11) is almost sufficient to see some results.[15] As Figure 3 shows, the marginal effects of investment depend on how many users are using the port; hence, the effect of investment is smaller in state S_i than in S_3 by $q_i^{S3} - q_i^{Si} > 0$, which stands for the number of footloose users shifting ports in S_i. This is what the second term of (10) shows, and hence the optimal investment decreases with independence. Further, the number of port users increases with V given the same price; consequently, the value of disaster adaptation increases with V. In the exactly same reason, the investment decreases with D. Comparing the results on the concurrency and D tells us an important policy implication: large disaster adaptation is necessary for wide spreading and non-devastating risks while the risk should be resolved by the inter-regional risk sharing when the disaster is likely to be local and devastating.

[Insert Figure 3 around here]

4 Disaster adaptation under privatized port management

This section considers various forms of port management and investment, especially privatized cases. We begin with private ports where each port is owned by a port authority making disaster adaptation investment to maximize profit. The authorities delegate management of the port to operators, which provide port services to the users and collect user charge while paying concession fees to the authorities. Both the operators and

[15] Note that the denominator of equation (11) is necessarily positive if the second-order condition holds. See Appendix 1 for more details

authorities are risk neutral private entities, and hence maximize the expected profits. We will later consider the cases where the disaster adaptation investment is decided by welfare-maximizing social planner while the port management is privatized in various ways. These cases will be referred to as the "second-best cases".

The procedure of the port development and management consists of following three stages. First, given the risk of disaster, the authority (or planner) of each port chooses the adaptation investment, I_i. Given the investment, port management then consists of the next two stages; i) each port authority determines the concession fee of its own port, and ii) given the concession fee, the operator(s) of each port decide on user charges and pay the concession fees to the authority according to the number of usages. Each of the three stages is represented by a simultaneous move game in which each entity chooses its decision given the others' decisions. However, the whole process is a sequential game; that is, each player anticipates all the outcomes achieved in the following stages.

We consider three port operation regimes which are denoted by R and identified by the type of terminal operator: competitive terminal operator (CTO), monopoly terminal operator (MTO), and the global terminal operator (GTO). First, in CTO, a large number of small operators provide homogeneous service in each port and then there is no profit for the operators. Second, in MTO, a single monopolistic operator provides service in each port. Third, in GTO, a single global terminal operator comprehensively manages the two ports. The operators choose their user charge, which is fixed regardless of state. Assumed risk neutral, they maximize their expected profit.

4.1 Management by monopolistic terminal operators (MTO)

4.1.1 User charge

We begin with the monopolistic port management in each port, in which the user charge of port i is determined to maximize the following operation profit:

$$\begin{aligned}\pi_{Oi} &= (p_i - \phi_i)\overline{q_i} \\ &= (p_i - \phi_i)\frac{3\overline{V_i} - \overline{V_j} - 3p_i + p_j + t}{2t},\end{aligned} \tag{12}$$

where $\overline{V_i} = V - \rho(D - I_i)$ is the expected effective facility of port i (see Section 2). Therefore, as long as the total risk is kept constant, independence never matters for the profit and, hence, the price setting. The first-order condition $\partial\pi_{Oi}/\partial p_i = 0$ yields the following best-response function:

$$p_i = \frac{3\overline{V_i} - \overline{V_j} + 3\phi_i + p_j + t}{6}. \tag{13}$$

Therefore, the monopolistic operators are strategic complements because their own demand and then their intensive margin increase with the rival's price. We obtain the equilibrium user charge as:

$$p_i^{MTO}(\phi_i, \phi_j, \overline{V_i}, \overline{V_j}) = \frac{18\phi_i + 3\phi_j + 7t + 17\overline{V_i} - 3\overline{V_j}}{35}. \tag{14}$$

The result of the price competition among operators is summarized as follows:

Lemma 1.

Under the operation by MTO, the equilibrium user charge of port i increases with $\overline{V}_i$ *,* ϕ_i *and* ϕ_j *, while decreasing with* $\overline{V}_j$*. Further, keeping* ρ *constant, the disaster independence does not affect the profit of operators and their prices.*

Monopolistic operators absorb the facility of ports into their prices to exploit the consumer surplus. Therefore, i's demand decreases with facility of j, so i's operator decreases the user charge to sustain the demand. The increase in the concession fee of the rival port has the opposite effect; it increases j's user charge first, and then decreases i's user charge because of the strategic complementarity between the operators. [16][17]

4.1.2 Equilibrium concession fee

The port authorities choose the concession fee to maximize profit, which is represented as:

$$\pi_{Ai} = \phi_i \overline{q_i} - cI_i^2/2$$

[16] Note that $\phi_i < \overline{V_i}$ should always hold because $\overline{V_i}$ is the highest willingness to pay for port i among all the consumers, and the port authority never imposes a higher concession fee than that.

[17] The results in this section stated by Lemmas 1-3 and Proposition 3 also hold for CTO and GTO, as discussed and shown in Appendix 2.

$$= \phi_i \frac{3\overline{V_i} - \overline{V_j} - 3p_i^{MTO} + p_j^{MTO}}{2t} - cI_i^2/2. \quad (15)$$

Recall that $\overline{q_i}$ is the expected demand for port *i* defined in (7). Note that the authorities' profit is also dependent on the expected facility, so the disaster independence does not matter. Therefore, the concession fee is also unaffected by the disaster independence. The following result holds for the equilibrium concession fee:

Lemma 2.

The following results hold under the operation by MTO: i) the equilibrium concession fee of port i, denoted by $\phi_i^{MTO}(\overline{V_i}, \overline{V_j})$, increases with its own expected effective facility $\overline{V_i}$ and access cost t while decreasing with the other port's $\overline{V_j}$; and ii) Keeping ρ constant, the disaster independence does not affect the profit of operators and port authorities and, thus, their decision makings.

All the details of the analysis on private management and investment are presented in Appendix 2. From Lemma 2 i), the concession fee of a port also increases with its own adaptation investment through the expected facility as in the case of the user charge.

4.1.3 Disaster adaptation investment

Next we examine disaster adaptation investment of each port. Given the monopolistic pricing regime, the equilibrium user charge under the given concession fee is described by $p_i^{MTO}(\phi_i, \phi_j, \overline{V_i}, \overline{V_j})$. Further, the equilibrium concession fee is $\phi_i^{MTO}(\overline{V_i}, \overline{V_j})$. We also define $\frac{dp_i^{MTO}}{dV_i} = \frac{\partial p_i^{MTO}}{\partial \overline{V_i}} + \frac{\partial \phi_i^{MTO}}{\partial \overline{V_i}} \frac{\partial p_i^{MTO}}{\partial \phi_i} + \frac{\partial \phi_j^{MTO}}{\partial \overline{V_i}} \frac{\partial p_i^{MTO}}{\partial \phi_j}$. This study assumes that strictly positive disaster adaptation investment, $I_i > 0$, is chosen regardless of the type of port authorities. Hence, the first-order condition is described as follows:

$$\frac{\partial \pi_{Ai}}{\partial I_i} = \underbrace{\rho \frac{\partial \phi_i}{\partial \overline{V_i}} \overline{q_i}}_{\text{Intensive margin}} + \underbrace{\rho \phi_i \left(\frac{\partial \overline{q_i}}{\partial \overline{V_i}} + \frac{dp_i}{d\overline{V_i}} \frac{\partial \overline{q_i}}{\partial p_i} + \frac{dp_j}{d\overline{V_i}} \frac{\partial \overline{q_i}}{\partial p_j} \right)}_{\text{Extensive margin}} - cI_i = 0, \quad (16)$$

where the first term in the right-hand side (RHS) describes the intensive margin of the investment, or the marginal profit through the change of the concession fee. The second term is the extensive margin from the change in demand. Although the first term in the extensive margin representing the direct effect is definitely positive, the investment also affects the user charges and concession fees in various channels and some of them are negative. Before going to the equilibrium, we mention a property of the best-response function as follows:

Lemma 3.
Under the operation by MTO, the best-response disaster adaptation investment of each port decreases with that of the other port.

That is, the disaster adaptation investments of the two ports are strategic substitutes. When port j increases the investment, both the (expected) demand and its concession fee decrease at port i, leading to decreases in both the intensive and extensive margins of investment. By the same reason, the more significant disaster reduces the investment. We can now readily consider the equilibrium investments, which are symmetric between the two ports and obtained as follows:

$$I^{MTO} = \frac{29019\rho(-2D\rho + t + 2V)}{177785ct - 58038\rho^2}. \quad (17)$$

Note that, as mentioned above, for assuming $I^{MTO} > 0$, we set the parameters at appropriate values so that both the numerator and denominator of (17) are positive. [18] Then, the following result holds for the equilibrium disaster adaptation investment:

Proposition 3.
Under the operation by MTO, the equilibrium disaster adaptation investment increases with V and decreases with D, c, and t, and the independence of disaster does not matter when ρ is kept constant.

The effect of the parameters on equilibrium investment is similar to the effect on the socially optimal investment. That is, the private investment basically follows the social necessity represented on the users' demand. The only difference is that the disaster independence does not influence the private investment since the loss of risk sharing

[18] The denominator is guaranteed positive when the decision making on investment by each port authority satisfies the second-order condition, $\frac{\partial^2 \pi_{Ai}}{\partial I_i^2} < 0$.

benefit from increases in independence is never monetarized when the user charge is constant across states.

4.2 Other operation regimes

We also investigate the other operation regimes while maintaining the assumption of each port authority to determine concession fee and investment. We briefly summarize the result of each regime first, and then offer some detailed comparisons between these regimes and the monopolistic operation. See Appendix 2 for all the details of the analysis.

4.2.1 Global terminal operator (GTO)

The global terminal operator provides homogeneous service in the two ports, so it simultaneously controls p_1 and p_2 to maximize the total profit $\pi_{O1} + \pi_{O2}$, while the concession fee and the investment of each port are determined by each authority. First, the FOC for p_i yields the following condition for the operator's profit maximizing behavior:

$$p_i = \frac{3\overline{V_i} - \overline{V_j} + 3\phi_i - \phi_j + 2p_j + t}{6}. \quad (18)$$

According to the comparison of (18) with (13), the GTO always chooses a higher user charge than the MTO given the same conditions.[19]

The mega operator also considers the profit of the other port when choosing the price of a port; this is why it is more reluctant to reduce the price. This incentive also leads to higher price complementarity between ports; that is, the user charges of two ports are more correlated to each other. As a result, the profit-maximizing user charge is solved as:

$$p_i^{GTO}(\phi_i, \phi_j, \overline{V_i}, \overline{V_j}) = \frac{2\phi_i + t + 2\overline{V_i}}{4}. \quad (19)$$

The user charge of each port is more sensitive to the facility but is less sensitive to the concession fee. That is, because of the greater market power, the GTO chooses its user

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[19] Note that user charge of the GTO is higher by $(p_j - \phi_j)/6$, where $p_j - \phi_j$ is per user profit that is positive in equilibrium.

charge by the users' willingness to pay to a greater extent. It is also less sensitive to the facility of the other port because of the high price complementarity, and its effect completely diminishes just coincidentally. Further, as in the case of monopoly, the GTO also ignores the effect of concurrency of disaster.

Next, the properties of the port authorities' behavior are the same as those in the MTO case. However, the authorities have different incentives because of the different outcomes in the operation stages. Skipping any details here, we just show the equilibrium investment as:

$$I^{GTO} = \frac{51\rho(-2D\rho + t + 2V)}{350ct - 102\rho^2}. \tag{20}$$

Although the detailed comparison with the different regimes is noted in Section 4.2.3, Proposition 3 is straightforwardly extended to the GTO case in Appendix 2; that is, the investment increases with V and ρ, decreases with D and c, and is independent of the concurrency (or independence).

4.2.2 Competitive terminal operators (CTO)

In the case of small competitive operators, these CTOs set price as $p_i^{CTO} = \phi_i$; that is, unlike the former two cases, only the concession fee or the marginal cost determines the price. Since the competitive user charge has no markup, it is lower than the prices in the other cases. This operators' behavior leads to the following equilibrium investment, by which all the statements in Proposition 3 can be extended to the CTO case:

$$I^{CTO} = \frac{51\rho(-2D\rho + t + 2V)}{175ct - 102\rho^2}. \tag{21}$$

4.2.3 Comparison of operation regimes

This part gives some detailed comparisons of the three operation regimes, namely, MTO, GTO, and CTO, focusing particularly on the authorities' investments. We begin with the effects of investment on user charges given that the concession fee is also endogenized to maximize the authorities' profit. The result is summarized as follows:

Lemma 4.

Under the equilibrium concession fee given a symmetric investment, the user charges in each regime, denoted by $p_i^R = p_i^R\left(\phi_i^R(\cdot), \phi_j^R(\cdot), \overline{V_i}, \overline{V_j}\right)$ *, satisfy* $0 < dp_i^{CTO}/dI_i < dp_i^{MTO}/dI_i < dp_i^{GTO}/dI_i$*; furthermore,* $p_i^{CTO} < p_i^{MTO} < p_i^{GTO}$ *holds.*

Even after considering the endogenous concession fee, our basic intuition from (14) and (19) remains: that is, less competitive operators set a higher user charge and exploit more benefit of investment from users. These two properties on equilibrium pricing are useful to understand the following results regarding the comparison of equilibrium investment.

Proposition 4.
i) The levels of disaster adaptation investment of the three regimes hold as: $I^{GTO} < I^{MTO} < I^{CTO}$*;*
ii) the marginal loss of social welfare from decreases in independence of disaster is larger under the operation by GTO, MTO, and CTO in that order.

The first statement can be explained as follows. According to the first property of Lemma 4, there is less port demand under a less competitive regime given the same investment level. Further, from the second property, a less competitive operator leads to less demand expansion by investment. These two facts lead to less intensive and extensive margins of investment, respectively, reducing incentives for investment by less competitive operators.

The second statement is fairly straightforward based on the first statement and Proposition 1 or equation (9). That is, when disaster independence decreases, the loss of social welfare is smaller given the large investment. This is why a more competitive regime is likely to have relatively superior social welfare under small independence because of its larger investment.

4.3 Port investment by public entities

4.3.1 Landlord ports

The former analysis on private planners reveals that they ignore the disaster independence in their investment. In contrast, this subsection considers the case of landlord ports, in which two ports are developed as an integrated port area by a public entity and their investment is controlled so as to maximize social welfare while the management is committed to private entities sustaining the profit maximizing user charges and concession fees.[20] Analysis of this case provides a welfare-inducing "second-best" investment, which reveals how government should intervene in privatized disaster adaptation investments.

The first-order condition for the second-best investment is:

$$\frac{\partial W}{\partial I} = \frac{\partial W}{\partial I_1} + \frac{\partial W}{\partial I_2}$$

$$= \underbrace{\rho Q^{S3}|_{p=0} - 2(\rho - \rho^{S3}) \sum_{i=1,2} \left(q_i^{S3} - q_i^{Si}\right)}_{\text{Direct effect}} - \underbrace{\frac{dp^R}{dI}\frac{p^R}{t}}_{\text{Indirect effect}} - 2cI$$

$$= 0, \quad (22)$$

where $\rho Q^{S3}|_{p=0}$ shows the total expected demand for the two ports when $p = 0$ is given, which describes the total *direct effect* of investment in state S_3.[21]

Although only the direct effect appears in the first-best case in which the price is fixed, investment also affects welfare through the endogenous user charge, which is called the *indirect effect*. Because the indirect effect stands for the change in the dead-weight loss from the distorted user charge as shown in Figure 4(b), it is usually negative since the investment increases the user charge from Lemma 4. That is, investment increases the distortion to decrease the benefit of investment, and then the second-best investment is generally smaller than the first-best one because of that negative effect.

We then compare the second-best outcomes among the different operation regimes. First, since the direct effect depends on the total demand, it is larger for more competitive regimes to set lower user charge. That is why the second-best investment is the largest under CTO among the private pricing regimes. This is because the indirect effect is smaller under less competitive regimes since they achieve lower dp^R/dI as well as lower p^R as Lemma 4 stated. That is, investment causes larger additional dead weight loss under less-competitive regime because of the higher price and higher sensitivity of price to investment. These two reasons make the planner more reluctant to increase investment. We can readily show that the second-best investment is even larger under socially optimal pricing, which is equivalent to the first-best. However, note that it does

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[20] However, as in the case of risk-sharing between Belgium and the Netherland, it is also possible that two ports are developed by different governments. Such decentralized decision making may cause externalities between them, an issue that remains for future research.

[21] Note that this term also includes the increase in the total profit of the authorities and the operators from the direct (i.e., ignoring the change in price) demand expansion by the investment. See Figure 4(a).

not mean the second-best investment is too small because merely achieving the first-best level investment under private pricing regime reduces social welfare.

Finally, the effects of each parameter are basically the same as those in the former cases. Those results are summarized as follows:

Proposition 5.
i) Investment of landlord ports is the largest under CTO, followed by MTO and GTO in this order, and all of them are smaller than the first-best investment;
ii)In any pricing regimes, the investment of landlord ports increases with V*, while decreasing with* D *and the disaster independence.*

Next, we compare the investment by the landlord with the private investments, to consider if the private investment is too large or too small comparing to the welfare inducing second-best investment.

Proposition 6.
If comparing the private investment to the second-best investment by landlord under the same pricing regime, the private investment is likely to be too large (too small, respectively) when the disaster independence is low (high, respectively).

This is readily obtained from the fact that the welfare maximizing investment decreases with the independence while the private investment does not. When the independence increases, the private investment is likely to be suboptimal because it ignores a large necessity for disaster adaptation. Hence, for port areas facing a large risk of wide-spreading disasters, public intervention to support private entities may be necessary for reinforcing their investment. In contrast, the overinvestment might instead occur in the result of excess competition under the large risk of independent disasters.

This result is also supported by the numerical result shown in Figure 5, which presents two additional findings. First, comparing the three different operation regimes, excess investment is more likely to occur in a less competitive regime such as GTO. Under such regimes, price is kept high, and then operators and port authorities are likely to secure higher profits. This is why private authorities are likely to choose large investment. Second, in any regime, excess investment is more likely to occur under the risk of more devastating disaster or larger D. Under such a significant disaster, there is large benefit from risk sharing, but that is included in consumer surplus. This is why the risk-sharing benefit is ignored by private entities; hence they have an excessively large incentive to mitigate the decrease in demand by conducting disaster adaptation.

[Insert Figure 4 around here]

4.3.2 Cost-recovering port management by public entities

Although collecting no user charge is the best pricing rule in principle, the financial deficit of such management is unacceptable even for many public entities in reality which are required to keep self-financing port management. Now, we consider a (semi) public entity which pursues welfare maximization but has to cover all those costs by the revenue from user charge. Therefore, we consider the welfare maximizing investment under a cost-recovering user charge which is set to cover the investment cost exactly. This is as an alternative form of second-best investment, and this kind of operation is actually conducted in some ports such as the New York-New Jersey port.

Given the cost-recovery pricing, the first-order condition (22) is also available as it is, and the results are summarized as follows:

Proposition 7.

The cost-recovering public investment is smaller than the first-best one, and increases with V while decreasing with D and the disaster independence.

Under any public port operation, the disaster adaptation investment is greater than that under private operation because lower user charge is set and then the demand for each port is larger, which means a greater number of users are affected by investment. In the same reason, the first-best investment is greater because it keeps the user charge to zero, while the cost-recovering user charge increases with the investment, increasing the dead weight loss.

5 Extensions

We have so far considered a simplified model just for convenience. In this section we extend the model to consider more generalized situations.

5.1 Effect of distance

We first consider distance between the two ports by assuming the distance between the ports as X, although it was fixed to be 1 in the former sections. We control the distance while the total number of users in the medium hinterland is kept constant, hence the density of consumer is given $1/X$ there. The demand function is now given as:

$$q_i^s = \frac{(2 + 1/X)(V_i^s - p_i) - (1/X)\left(V_j^s - p_j\right)}{2t}. \tag{23}$$

We investigate the model given this new (extended) demand function. Although the cases of private operation regimes are hardly tractable, we can show the following result regarding the public operation regimes:

Proposition 8.
The first-best investment and the cost-recovering public investment increase with the inter-port distance X.

This statement can be explained by the fact that the number of footloose users to use the other port in case of a disaster, described by $(D - I)/(2tX)$, decreases with the distance. Therefore, the inter-port risk sharing is less available when the alternative port is less accessible and the necessity of disaster adaptation increases from the viewpoint of social welfare.

Effects of the distance in other cases are ambiguous and we can provide no analytical statement. However, although only the numerical results can be provided, the opposite result is obtained under private operation regimes regardless of whether the investment is private or public, as presented in Figure 6. From the demand function (23), the two ports become less substitutable and the demand becomes less sensitive to the facility of the other port when the distance increases, which may make private port authorities and operator less competitive, and the investment falls. Furthermore, the less competition also increases price and reduces demand, and then the optimal investment also decreases because of the less direct effect on welfare.

These results show that the problem of under-investment intensifies when the two ports are distant and, consequently, the disaster adaptation must be subsidized or supported by the central government. In contrast, when the two ports are close to each other, their competition makes them to keep a high degree of disaster adaptation.

[Insert Figure 5 around here]

5.2 Asymmetric ports

We have considered asymmetry of the two ports, focusing first on the damage of disaster, basic facility of the ports, and the probability of disaster to occur in each port, which are given by D_i, V_i , and ρ_i , respectively. We change those parameters while keeping D_j, V_j, and ρ_j constant to examine asymmetric changes. First, we consider changes in those parameters only around the symmetric equilibrium. The result is summarized as follows:

Proposition 9.

Around the symmetric equilibrium of private port authorities, investment I_i decreases with D_i and increases with V_i, while I_j changes in the opposite direction.

When D_i increases, it decreases both the prices (i.e., user fee and concession fee) and the expected demand for port i. Therefore, port i has less incentive for disaster adaptation. In contrast, it increases the prices and the demand for port j to exert the investment. This is also the case for V_i although the direction is opposite. However, the effect of ρ_i is ambiguous for both ports.

Furthermore, departing from the neighbor of the symmetric equilibrium, we consider more general asymmetry of parameters, whose results are presented in Figure 7. This figure shows Proposition 9 can be extended under significant asymmetry, and ρ_i decreases the investment of the other port only slightly. This is mainly caused by the fact that the investment is a strategic substitute between the two ports.

[Insert Figure 6 around here]

5.3 Endogenous port facilities and number of ports

The analysis so far has focused only on disaster adaptation, assuming that basic facilities of port are exogenously given. However, since the efficiency and capacity of ports are important factors to determine how much backup facilities can be provided in case that other ports are damaged, investment in these facilities also needs to be discussed in an integrated manner with disaster adaptation. Note that the discussion of future research in the final section is based on the analysis so far.

Now we consider investment that enhances the basic functions of ports V_i^s, and it may be reasonable to consider that such investments particularly increase the facilities in the normal times of the port (i.e. states S_0 and S_j for port i).[22] Just for simplicity of

[22] Although one may consider that such investments would raise V and increase basic facilities regardless of state, if we consider that a certain share of functions is lost and unavailable due to disasters, the

discussion, we assume that such an investment would only increase V_i^s in those normal states. Then the marginal social welfare of such an investment is described as $\rho^{S0} + \rho^{Sj}$. Therefore, the marginal value of the investment will increase with disaster independence.

This conjecture implies that it is intuitively expected that socially optimal investment in basic facilities will increase with disaster independence, which is contrastive to disaster adaptation investment.[23] However, the intuition behind this conjecture is almost identical to that of Propositions 1 and 2, meaning that the supply of mutual backup functions is more important than individual disaster response investments, as risk-sharing functions work more heavily when disaster independence is high.

Furthermore, by extending the inference on port facilities, we can obtain some implications for the socially optimal number of ports. In other words, if disaster risk is local and independent, the establishment of new ports and diversification of investment to various port are effective risk avoidance policy measures, but for disasters with a wide-spreading impact, investment in disaster prevention at each individual port is more effective. Further examination on concentration or diversification of port investment is another important topic for future research.

6 Concluding remarks

This study has theoretically analyzed disaster adaptation investments under the risk of independent, local disasters that damage only one port, as well the risk of common disasters. Although former studies have focused only on the risk of common (concurrent) disasters that affect all ports simultaneously, this study parameterizes disaster independence (that is, the share of independent disasters in all disasters). In the two-port model adopted in this study, some shippers avoid the loss of disaster by using the unaffected port if an independent disaster occurs in their local port. Since such inter-port risk-sharing benefit increases with disaster independence, the socially optimal investment decreases with the disaster independence. However, since the risk-sharing benefit only attributes to the shipper's consumer surplus and does not to the profits obtained from the port, it does not affect the investment of private port authorities that maximize profits. Such an ignorance of the risk-sharing benefits by the private entities is likely to lead to more serious underinvestment when the independence of disasters is low, so there is a large necessity for public investment promotion through subsidies. In contrast, if the disaster independence is high, it may be possible to leave investment to the market while

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damage of disasters, D, will increase with the investment for efficiency.

[23] However, since we are ignoring the interdependence of two types of investments when they are decided simultaneously, more rigorous mathematical examination will be needed for a further discussion.

caring about overinvestment through the excess competition between ports. Furthermore, comparing various forms of privatized operators, we showed that the more competitive forms that induce higher investment levels are more likely to be superior in terms of social welfare when the independence of disasters is lower.

This paper has examined the importance of disaster independence for the first time in the discussion of the combination of disaster adaptation investment and inter-port risk sharing. Although the simplification of the model has been useful in grasping the essence of the problem, some of the practically important elements may have been discarded, so further examination is necessary in future research. First, we ignored the risk-aversion incentives of shippers and terminal operators, and the contractual actions to avoid the risk. Since attribution of risk and the sharing benefit between them may differ depending on the form of contracts, they may also influence the investment and policy intervention. Further, investigating the role of the functional transfer agreement between operators examined by Zheng et al. (2021a) in our framework can be important. Second, ports in some countries such as Japan are operated by local governments, and it is an important policy issue how investment by such entities is affected and distorted by the disaster independence.

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Appendices

Appendix 1. The first-best investment

Proof of Proposition 2

The first-order condition for the social optimum under the symmetry ports, described by (10), is:

$$\frac{\partial W}{\partial I}=\frac{\partial W}{\partial I_1}+\frac{\partial W}{\partial I_2}$$

$$= \rho Q^{S3} - 2(\rho - \rho^{S3}) \sum_{i=1,2} \left(q_i^{S3} - q_i^{Si}\right) - 2cI$$

$$= \rho \left[2 \frac{V - D + I}{t} + 1\right] - (\rho - \rho^{S3}) \frac{D - I}{t} - 2cI$$

$$= 0, \tag{24}$$

where Q^s shows the total demand for two ports. Since the effect of an exogenous variable, denoted by $\#$, is described as $\frac{dI}{d\#} = -\frac{\partial^2 W/\partial I^2}{\partial^2 W/\partial I\,\partial \#}$. Therefore, given the second-order condition, $\frac{\partial^2 W}{\partial I^2} = -\frac{1}{t}(2ct - 3\rho + \rho^{S3}) < 0$, holds, the sign of $\frac{dI}{d\#}$ is identical to that of $\frac{\partial^2 W}{\partial I\,\partial \#}$. The more details for each variable are shown as follows:

$$\frac{\partial^2 W}{\partial I\,\partial \rho^{S3}}|_{d\rho=0} = 2\left(q_i^{S3} - q_i^{Si}\right) > 0,$$

$$\frac{\partial^2 W}{\partial I\,\partial \rho} = 2q_i^{Si} > 0,$$

$$\frac{\partial^2 W}{\partial I\,\partial V} = \frac{2\rho}{t} > 0,$$

$$\frac{\partial^2 W}{\partial I\,\partial D} = -\frac{\rho + \rho^{S3}}{t} < 0.$$

From the sign of these cross derivatives, we can readily show $\frac{dI}{d\rho^{S3}} > 0$, $\frac{dI}{d\rho} > 0$, $\frac{dI}{dV} > 0$, and $\frac{dI}{dD} < 0$, which are mentioned in Proposition 2.

Further, solving (24) yields the following social optimal investment.

$$I^O = \frac{2\rho V - 3\rho D + \rho^{S3} D + t}{2ct - 3\rho + \rho^{S3}}$$

Appendix 2. Private investment

We prove all the statements in this Appendix 2 not only for the monopolistic case but also for arbitrary operation regime $R = \{MTO, GTO, CTO\}$.

Proof of Lemma 2

From the FOC for profit maximization of port authorities, the equilibrium concession fee is solved as follows.

$$\phi_i^R(\overline{V_i},\overline{V_j})$$

$$= \frac{\Delta'_{p,\phi|R}\left[5(t-2\overline{\Delta_{p|R}}) + \left(3-7\Delta'_{p,v|R}-3\Delta_{p,v|R}\right)\overline{V_i} + \left(7-3\Delta'_{p,v|R}-7\Delta_{p,v|R}\right)\overline{V_j}\right]}{5\Delta'^{2}_{p,\phi|R}+18\Delta'_{p,\phi|R}-35\Delta^{2}_{p,\phi|R}}$$

$$+ \frac{\Delta_{p,\phi|R}\left[-7(t-2\overline{\Delta_{p|R}}) + \left(-17-3\Delta'_{p,v|R}+17\Delta_{p,v|R}\right)\overline{V_i} + \left(3+17\Delta'_{p,v|R}-3\Delta_{p,v|R}\right)\overline{V_j}\right]}{5\Delta'^{2}_{p,\phi|R}+18\Delta'_{p,\phi|R}\Delta_{p,\phi|R}-35\Delta^{2}_{p,\phi|R}}$$

$$= \underbrace{\frac{\left[\Delta'_{p,\phi|R}\left(3-7\Delta'_{p,v|R}-3\Delta_{p,v|R}\right)+\Delta_{p,\phi|R}\left(-17-3\Delta'_{p,v|R}+17\Delta_{p,v|R}\right)\right]\overline{V_i}}{5\Delta'^{2}_{p,\phi|R}+18\Delta'_{p,\phi|R}-35\Delta^{2}_{p,\phi|R}}}_{=\frac{\partial\phi_i^R}{\partial\overline{V_i}}\overline{V_i}=\Delta_{\phi,v|R}\overline{V_i}}$$

$$+ \underbrace{\frac{\left[\Delta'_{p,\phi|R}\left(7-3\Delta'_{p,v|R}-7\Delta_{p,v|R}\right)+\Delta_{p,\phi|R}\left(3+17\Delta'_{p,v|R}-3\Delta_{p,v|R}\right)\right]\overline{V_j}}{5\Delta'^{2}_{p,\phi|R}+18\Delta'_{p,\phi|R}\Delta_{p,\phi|R}-35\Delta^{2}_{p,\phi|R}}}_{=\frac{\partial\phi_i^R}{\partial\overline{V_j}}\overline{V_j}=\Delta'_{\phi,v|R}\overline{V_j}}$$

$$+ \underbrace{\frac{5(t-2\overline{\Delta_{p|R}})\Delta'_{p,\phi|R}-7(t-\overline{\Delta_{p|R}})\Delta_{p,\phi|R}}{5\Delta'^{2}_{p,\phi|R}+18\Delta'_{p,\phi|R}\Delta_{p,\phi|R}-35\Delta^{2}_{p,\phi|R}}}_{=\overline{\phi^R}}$$

$$\equiv \Delta_{\phi,v|R}\overline{V_i}+\Delta'_{\phi,v|R}\overline{V_j}+\overline{\phi^R},$$

where $\Delta_{p,\phi|R} = \partial p_i/\partial\phi_i|_R = \partial p_j/\partial\phi_j|_R$ and $\Delta'_{p,\phi|R} = \partial p_i/\partial\phi_j|_R = \partial p_j/\partial\phi_i|_R$ under a regime R, which is obtained from equation (14) (Note that $\partial p_i/\partial\phi_i|_R = \partial p_j/\partial\phi_j|_R$ and $\partial p_i/\partial\phi_j|_R = \partial p_j/\partial\phi_i|_R$ hold even if we do not assume the symmetry or $\overline{V_i} = \overline{V_j}$). Further, $\Delta_{p,v|R} = \partial p_i/\partial\overline{V_i}|_R$ and $\Delta'_{p,v|R} = \partial p_i/\partial\overline{V_j}|_R$ are defined. Finally, $\overline{\Delta_{p|R}}$ is the fixed term of p_i under regime R, which is independent of user port facilities and concession fees. Therefore, equilibrium concession fee under each regime is as follows.

$$\phi_i(\bar{V}_i, \bar{V}_j; R) = \begin{cases} \dfrac{569\bar{V}_i - 51\bar{V}_j + 259t}{1147} & if \quad MTO \\ \dfrac{17\bar{V}_i - 3\bar{V}_j + 7t}{35} & if \quad GTO \\ \dfrac{17\bar{V}_i - 3\bar{V}_j + 7t}{35} & if \quad CTO \end{cases} \tag{26}$$

Lemma 2 is readily proved from (26). ■

Proof of Lemma 4

We obtain the following by substituting (26) in pricing equations (14) and (19):

$$p_i^R = \begin{cases} \dfrac{52(569\bar{V}_i - 51\bar{V}_j + 259t)}{40145} & \text{if MTO} \\ \dfrac{104\bar{V}_i - 6\bar{V}_j + 49t}{140} & \text{if GTO} \\ \dfrac{17\bar{V}_i - 3\bar{V}_j + 7t}{35} & \text{if CTO} \end{cases} . \tag{27}$$

Then, given the symmetry of parameters and investment (i.e., $\bar{V}_i = \bar{V}_j = \bar{V}$), the following holds.

$$p_i^R = \begin{cases} 0.67.\bar{V} + 0.33.t & \text{if MTO} \\ 0.7\bar{V} + 0.35t & \text{if GTO} \\ 0.4\bar{V} + 0.2t & \text{if CTO} \end{cases} \tag{28}$$

Therefore, the Lemma 4 is readily proved from (28). ■

Proof of Lemma 3, proposition 3, and proposition 4. We define $\frac{dp_i}{d\bar{V}_i} = \frac{\partial p_i}{\partial \bar{V}_i} + \frac{\partial \phi_i}{\partial \bar{V}_i}\frac{\partial p_i}{\partial \phi_i} + \frac{\partial \phi_j}{\partial \bar{V}_i}\frac{\partial p_i}{\partial \phi_j}$. So, the first order condition is described as follows.

$$\frac{d\pi_{Ai}}{dI_i} = \underbrace{\frac{\partial \overline{V_i}}{\partial I_i}\frac{\partial \overline{q_i}}{\partial \overline{V_i}}\phi_i}_{\text{direct effect}} + \underbrace{\frac{\partial \overline{V_i}}{\partial I_i}\frac{dp_i^R}{d\overline{V_i}}\frac{\partial \overline{q_i}}{\partial p_i}\phi_i + \frac{\partial \overline{V_i}}{\partial I_i}\frac{dp_j^R}{d\overline{V_i}}\frac{\partial \overline{q_i}}{\partial p_j^R}\phi_i + \frac{\partial \overline{V_i}}{\partial I_i}\frac{\partial \phi_i}{\partial \overline{V_i}}\overline{q_i}}_{\text{indirect effect}} - cI_i$$

$$= \frac{\rho\phi_i}{2t}\left[3 - 3\frac{dp_i^R}{d\overline{V_i}} + \frac{dp_j^R}{d\overline{V_i}}\right] + \rho\frac{\partial \phi_i}{\partial \overline{V_i}}\overline{q_i} - cI_i$$

$$= \frac{\rho\phi_i}{2t}\left[3 - 3\left(\frac{\partial p_i^R}{\partial \overline{V_i}} + \frac{\partial \phi_j}{\partial \overline{V_i}}\frac{\partial p_i^R}{\partial \phi_j}\right) + \left(\frac{\partial p_j^R}{\partial \overline{V_i}} + \frac{\partial \phi_j}{\partial \overline{V_i}}\frac{\partial p_j^R}{\partial \phi_j}\right)\right] - cI_i$$

$$= \frac{\rho\phi_i}{2t}\left[3 - 3\left(\Delta_{p,v|R} + \Delta'_{\phi,v|R}\Delta'_{p,\phi|R}\right) + \left(\Delta'_{p,v|R} + \Delta'_{\phi,v|R}\Delta_{p,\phi|R}\right)\right] - cI_i = 0, \tag{29}$$

where the effect of investment through the change of ϕ_i is omitted by the envelop theorem because φ_i is chosen to maximize the profit. In the RHS of the first line, the first term describes the direct effect of the investment to mitigate the damage of the disaster and extend the demand in state S_i and S_3. The others, except for cI_i, are indirect effects which appear through the concession fee of the other port or pricing of the operators. We first prove Lemma 3 for any operation regime and then proposition 3 and 4.

Proof of Lemma 3.

The total differentiation of (29) yields:

$$\frac{dI_i}{dI_j} = -\frac{\partial^2\pi_{Ai}/\,\partial I_i\,\partial I_j}{\partial^2\pi_{Ai}/\,\partial I_i^2}. \tag{30}$$

Because the second order condition for profit maximization, $\partial^2\pi_{Ai}/\,\partial I_i^2 < 0$, holds. Further, the following holds.

$$\frac{\partial^2\pi_{Ai}}{\partial I_i\,\partial I_j} = \frac{\partial \overline{V_j}}{\partial I_j}\frac{\partial \phi_i}{\partial \overline{V_j}}\frac{\rho_i}{2t}\Omega < 0,$$

where $\Omega \equiv 3 - 3\left(\Delta_{p,v|R} + \Delta'_{\phi,v|R}\Delta'_{p,\phi|R}\right) + \left(\Delta'_{p,v|R} + \Delta'_{\phi,v|R}\Delta_{p,\phi|R}\right)$ is independent of all those parameters, and the value must be strictly positive when the first order condition (29) holds for positive investment and prices. This is why $\frac{dI_i}{dI_j} < 0$ holds.

■

Proof of Proposition 3 and 4.

Condition (29) can be rewritten as follows:

$$\rho\left(\Delta_{\phi,v|R}\overline{V_i} + \Delta'_{\phi,v|R}\overline{V_j} + \overline{\phi}\right)\Omega - 2ctI_i = 0.$$

Given the symmetry, we obtain the following symmetric equilibrium.

$$I_1 = I_2 = I^R = \frac{\rho\Omega\left[(V - \rho D)\left(\Delta_{\phi,v|R} + \Delta'_{\phi,v|R}\right) + \overline{\phi}\right]}{\rho^2\left(\Delta_{\phi,v|R} + \Delta'_{\phi,v|R}\right)\Omega - 2ct} \tag{31}$$

The equilibrium in each regime is as follows.

$$I^R = \begin{cases} \dfrac{\rho(V - D\rho + t/2)}{\dfrac{177785}{58038}ct - \rho^2} & \text{if MTO} \\ \dfrac{\rho(V - D\rho + t/2)}{\dfrac{175}{51}ct - \rho^2} & \text{if GTO} \\ \dfrac{\rho(V - D\rho + t/2)}{\dfrac{175}{102}ct - \rho^2} & \text{if CTO} \end{cases} \tag{32}$$

We then prove proposition 3 and 4 using (32).

For proposition 4- i), first note that $\frac{175}{51} > \frac{177785}{58038} > \frac{175}{102}$ holds. Therefore, $I^{GTO} < I^{MTO} < I^{CTO}$ is proved. Further, $\partial I^R/\partial\rho|_{\rho=0} > 0$ is readily seen from (32). Further, proposition 4-ii) is readily proved from $I^{GTO} < I^{MTO} < I^{CTO}$ and proposition 1.

Next, we prove proposition 3 for all the regimes. Effects of the parameters except for ρ are readily seen from (32) because the denominator is positive from the second order condition $\frac{d^2\pi_{Ai}}{dI_i^2} < 0$ obtained from (29). For ρ, we begin with best response investment of each port authority. Since the total differentiation of (29) yields $dI_i/d\rho =$

$-\frac{\partial^2\pi_{Ai}}{\partial I_i \partial \rho} / \frac{\partial^2\pi_{Ai}}{\partial I_i^2}$, and $\frac{\partial^2\pi_{Ai}}{\partial I_i^2} < 0$ must hold for the second order condition, the sign of the effect of ρ depends on $\frac{\partial \pi_{Ai}}{\partial I_i \partial \rho} = \frac{\Omega}{2t}\left(\phi_i + \frac{\partial \phi_i}{\partial \rho}\rho\right)$.

Recall that Ω is positive under the first order condition and independent of ρ, as mentioned in the proof of Lemma 3. Therefore, we only focus on whether $\phi_i + \frac{\partial \phi_i}{\partial \rho}$ is positive or not around the symmetric equilibrium, and obtain the following:

$$\phi_i + \frac{\partial \phi_i}{\partial \rho} = (\Delta_{\phi,v|R} + \Delta'_{\phi,v|R}(V - \rho(D - I^R)) + \bar{\phi}^R - (\Delta_{\phi,v|R} + \Delta'_{\phi,v|R}\rho(D - I^R)$$
$$= (\Delta_{\phi,v|R} + \Delta'_{\phi,v|R}(V - 2\rho(D - I^R)) + \bar{\phi}^R$$
$$> 0,$$

where recall the assumption $\rho < 1/2$. Also, $V - (D - I^R) > 0$ must hold; otherwise, there is no demand for the port during the disaster and such situation is ruled out by assumption. Finally, $\overline{\phi^R}$ is positive in any regime from (26). This is why $\frac{\partial \pi_{Ai}}{\partial I_i \partial \rho} > 0$ holds, and hence $dI_i/d\rho > 0$ holds. Furthermore, increase in independence means ρ^{S3} changes keeping ρ_i constant. Therefore, it does not affect I^R from (32). ■

Appendix 3. Second-best investment

Proof of Proposition 5. Investment under private management

We consider the socially optimal investment to maximize the aggregated social welfare under private management, whose first order condition is as follow.

$$\frac{dW}{dI_i} = \frac{dW}{dI_i}|_{dp_i = dp_j = 0} + \frac{dp_i}{dI_i}\frac{dW}{dp_i}|_{dI_i = 0}$$
$$= \underbrace{\left(\rho^{S12}q_i^{Si} + \rho^{S3}q_i^{S3}\right) + \frac{\partial \overline{V}_i}{\partial I_i}\left(\frac{\partial \overline{q}_i}{\partial \overline{V}_i}p_i + p_j\frac{\partial \overline{q}_j}{\partial \overline{V}_i}\right)}_{direct\ effect}$$
$$\underbrace{+\frac{dp_i}{dI_i}\left(p_i\frac{\partial \overline{q}_i}{\partial p_i} + p_j\frac{\partial \overline{q}_j}{\partial p_i}\right) + \frac{dp_j}{dI_i}\left(p_i\frac{\partial \overline{q}_i}{\partial p_j} + p_j\frac{\partial \overline{q}_j}{\partial p_j}\right)}_{indirect\ effect} - cI_i$$

$$= 0 \tag{33}$$

Since we assume the symmetric conditions of the two ports, the optimal investment should be also the symmetric. Therefore, rewriting the first order condition (33) under the symmetry, or $dI_1 = dI_2 = dI > 0$ and $I_1 = I_2 = I$, yields the following.

$$\frac{\partial W}{\partial I} = \frac{\partial W}{\partial I_1} + \frac{\partial W}{\partial I_2}$$
$$= \underbrace{\rho Q^{S3|}_{p=0} - 2(\rho - \rho^{S3}) \sum_{i=1,2} \left(q_i^{S3} - q_i^{Si}\right)}_{direct\ effect} - \underbrace{\frac{dp^R}{dI}\frac{p^R}{t}}_{indirect\ effect} - 2cI$$
$$= 0, \tag{34}$$

where $Q^{S3}|_{p=0}$ shows the total demand when $p = 0$ is given. Since both $Q^{S3}|_{p=0}$ and $q_i^{S3} - q_i^{Si}$ are independent of the price level if the ports are symmetric, the direct effect is independent of the user charge. This is why the direct effect is independent of the regime. In the indirect effect, p^R and $\frac{dp^R}{dI}$ are given from (28) under symmetry. Note that $p^{CTO} < p^{MTO} < p^{GTO}$ from Lemma 4 and $0 < \frac{dp^{CTO}}{dI} < \frac{dp^{MTO}}{dI} < \frac{dp^{GTO}}{dI}$ hold given the same investment level. Therefore, when the same investment level is given, marginal social welfare is the largest under CTO, and followed by MTO and GTO. Therefore, socially optimal investment is also in that order. For the same reason, the first best investment is larger than any second-best investment because $p = 0$ holds and then the indirect effect is zero in the first-best case while those are negative in the second-best cases.

We also examine the effects of parameters on investment. Substituting (28) into (34) and solve it yields the following socially optimal investment.

$$I^{O,R} = \begin{cases} \dfrac{D(-72075\rho + 21632\rho^2 + 24025\rho^{S3}) + 13209\rho(t + 2V)}{-72075\rho + 21632\rho^2 + 24025(\rho^{S3} + 2ct)} & \text{if MTO} \\ \dfrac{D(-300\rho + 98\rho^2 + 100\rho^{S3}) + 51\rho(t + 2V)}{-300\rho + 98\rho^2 + 100(\rho^{S3} + 2ct)} & \text{if GTO} \\ \dfrac{D(-75\rho + 8\rho^2 + 25\rho^{S3}) + 21\rho(t + 2V))}{-75\rho + 8\rho^2 + 25(\rho^{S3} + 2ct)} & \text{if CTO} \end{cases}$$

where deflator of each equation is negatively proportional to $\frac{\partial^2 W}{\partial I^2}$; hence it is positive when the second order condition holds. Therefore, the socially optimal disaster adaptation increases with ρ^{S3} (keeping ρ constant) and V. Effect of ρ is generally ambiguous, but it has positive effect when ρ is small enough and change in ρ^2 is negligible.

Proof of Proposition 7. Cost recovering user charge

i) Under the cost recovering user charge, there is no operational profit or $p\bar{Q} = cI^2$ holds, hence the social welfare is equal to the consumer surplus. Therefore, the first order condition for investment under the symmetricity is as follows.

$$\frac{dW}{dI} = \left(\rho Q_1^{S1} + \rho Q_1^{S2} + \rho^{S3} Q^{S3}\right) + \frac{dp}{dI}\left(p\frac{\partial \bar{Q}}{\partial p}\right)$$
$$= 0 \qquad (35)$$

Because the first term is always positive, the second term, showing the indirect effect, is always negative; it means that cost recovering price must be increasing with investment around the equilibrium. Here, we show the first order condition again following equation (10).

$$\frac{dW}{dI} = \underbrace{\rho Q^{S3|}_{p=0} - 2(\rho - \rho^{S3}) \sum_{i=1,2} \left(q_i^{S3} - q_i^{Si}\right)}_{\text{direct effect}} - \underbrace{\frac{dp}{dI}\frac{p}{t}}_{\text{indirect effect}} - 2cI = 0 \qquad (36)$$

Recall that the direct effect is independent of the user charge, and only dependent on investment level. Therefore, difference in pricing regime only appears at the indirect effect. When the optimal price, $p = 0$, is charged, price is constant and the second term is always zero. However, for any other schemes including cost-recovery, price increases with investment and hence the indirect effect is negative. Therefore, the first-best investment under $p = 0$ is larger than investment under any other pricing regimes.

ii) The effect of parameter # is dependent on the sign of $\frac{dW^2}{dId\#}$. Remember that the cost recovery price decreases with V because the demand increases with them. Therefore, when V increases, Q^{S3} definitely increase both in direct and indirect (i.e., through price change) channels. Also, $q_i^{S3} - q_i^{Si} = \frac{D-I_i}{2t}$, or the number of the footloose users does not change with V. Therefore, the direct effect increases with V. Further, the indirect effect increases with V because p decreases while $dp/dI = 3/(2t)$ is constant. Therefore, investment increases with V. Since the effect of D is opposite to that of V, the investment decreases when D increases (Note that the second term also decreases with D). Finally, the independence does not matter for the cost-recovery price because it only depends on $\bar{Q}$. Therefore, it does not matter Q^{S3} and Q^{S1} does not change with the independence as in other private regimes. Therefore, when the independence increases, the direct effect decreases by the decreases in ρ^{S3}, and then the investment decreases. ■

Appendix 4. Proofs in section 5.

Proof of proposition 8

Both types of public pricing are not affected by X. Therefore, indirect effect does not change with X. Hence only the direct effect on consumer surplus matters. When X increases keeping investment constant, port i's demand from the backyard hinterland does not change in every state, while demand from overlapping hinterland in state S_i increases. This is why the direct effect in marginal social benefit of investment always increases with X. Therefore, the public investment increases with X. ■

Proof of proposition 9

We show (29), the first order condition of each port authority under asymmetry, again:

$$\frac{d\pi_{Ai}}{dI_i} = \frac{\rho_i \Phi_i}{2t}\Omega - cI_i$$
$$= 0. \qquad (37)$$

Note that what inside the square bracket is independent of D_i and V_i. Here, note that φ_i increases with $\overline{V_i}$, while decreases with $\overline{V_j}$. Therefore, proposition 9 definitely holds. This argument is valid regardless of type of operators. ■

Table 1. List of variables and parameters

S_0, S_i, S_3	States: S_0 means no disaster, S_i means local disaster occurring in port i, S_3 means simultaneous disaster occurring in both ports
ρ^{S3}, ρ^{S12}	Probability of state S_3, and S_1 or S_2 , respectively
ρ	Probability of each port to have disaster (=$\rho^{S12} + \rho^{S3}$)
D	Significance of a disaster; decrease of port facility when a disaster occurs
V	Basic facility of each port
I_i	Disaster adaptation investment
V_i^s	Effective facility of each port or the service level
$\overline{V_i}$	Expected port facility $E(V_i^s) \equiv V - \rho(D - I_i)$
p_i	User fee of port i
c	Cost parameter of disaster adaptation investment (total investment cost is $cI_i^2/2$)
ϕ_i	Port concession fee of port i paid by operators to the port authority
q_i^s	demand for port i in state s; $q_i^s > 0$ for any i and s.
$\overline{q_i}$	expected port demand $E(q_i^s) \equiv \sum Pr(s) q_i^s$
t	per distance access cost
R	There are three types of operation regime R: competitive operator (CTO), monopolistic operator (MTO), and global operator (GTO).
W	Expected social welfare defined by consumers' surplus plus profits of user charges and concession fees. Social welfare in each state is denoted by W^s.

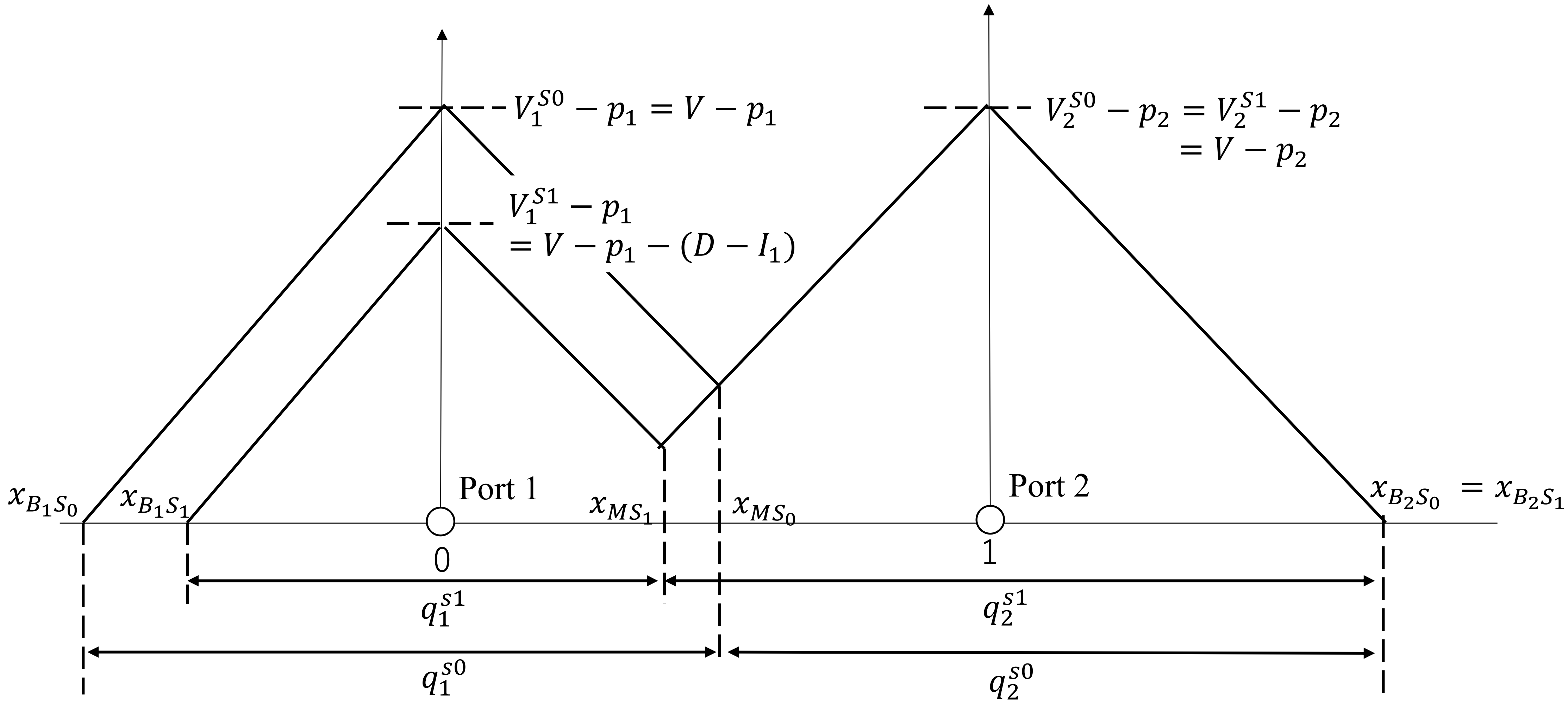

Figure 1. User distribution and port demand

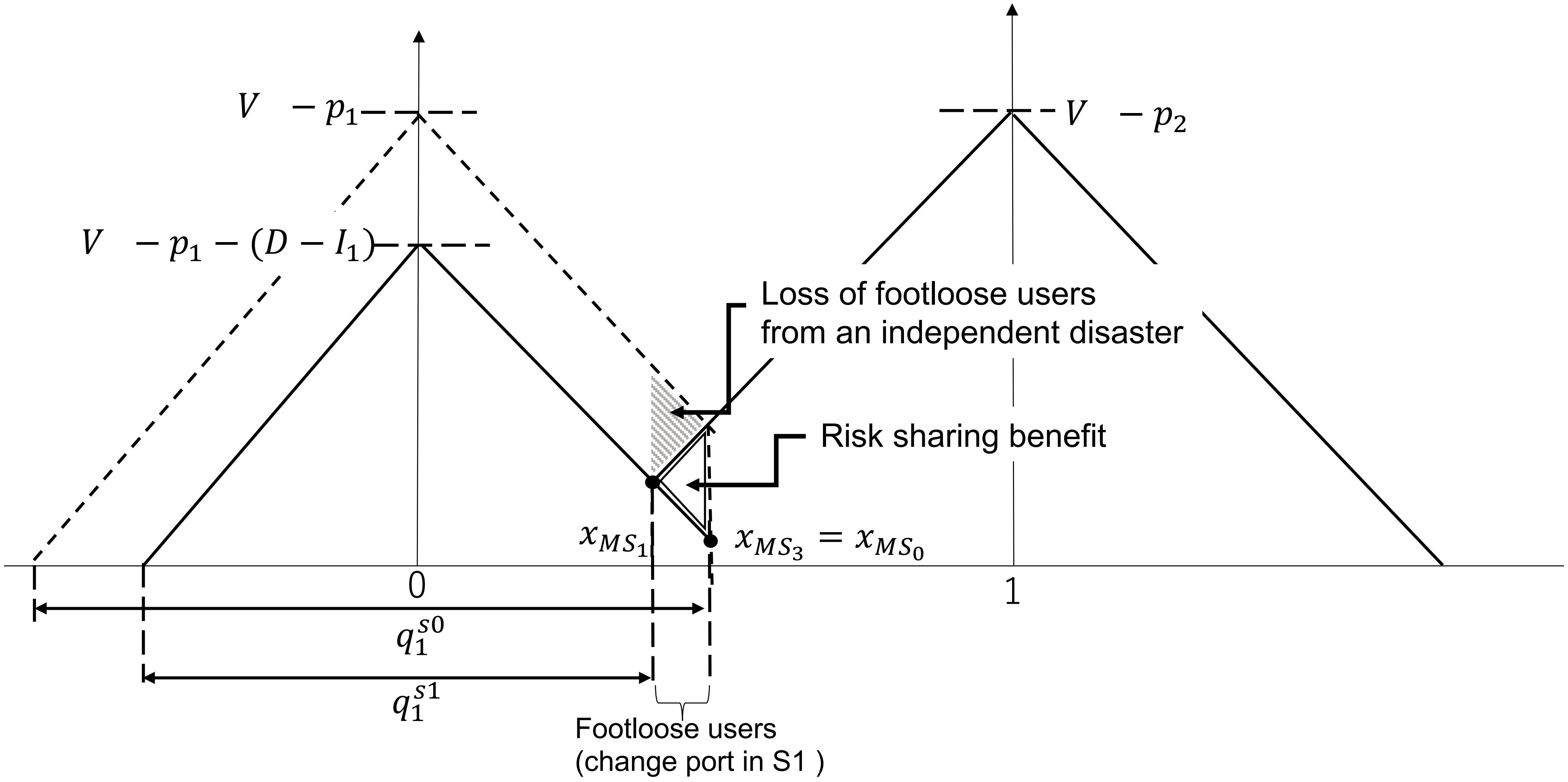

Figure 2(a). Loss from disaster in state S1

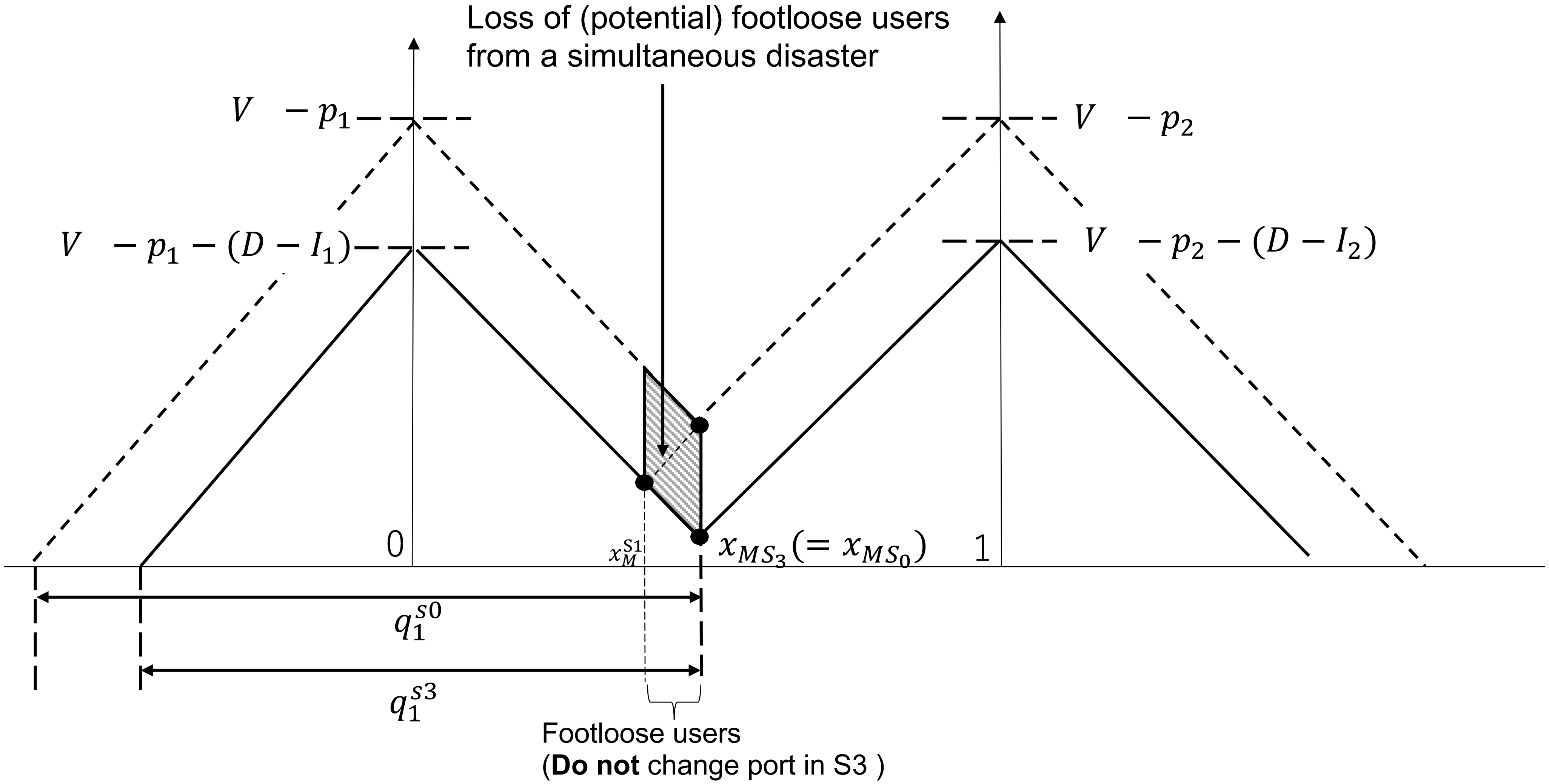

Figure 2(b). Loss from disaster in state S3

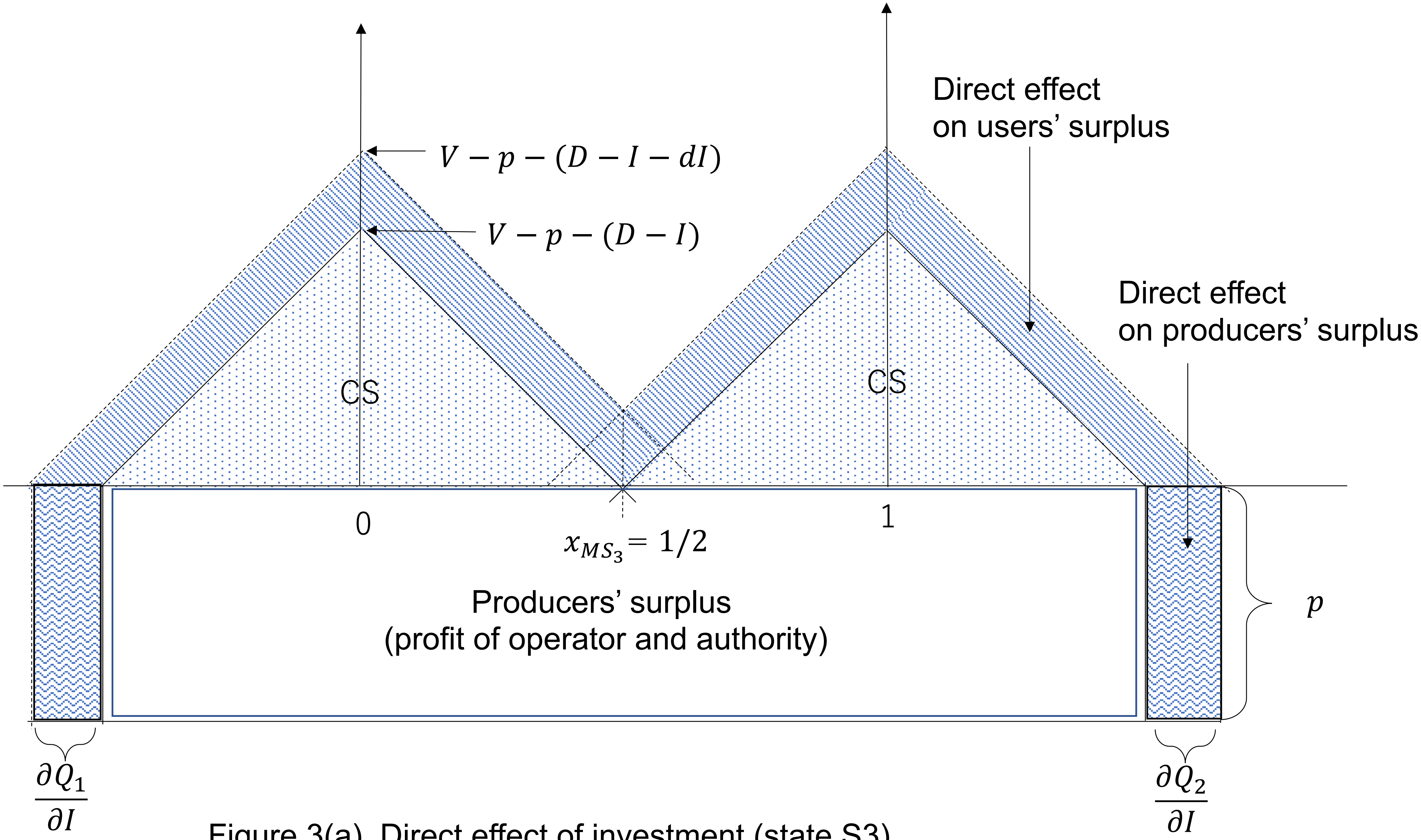

Figure 3(a). Direct effect of investment (state S3)

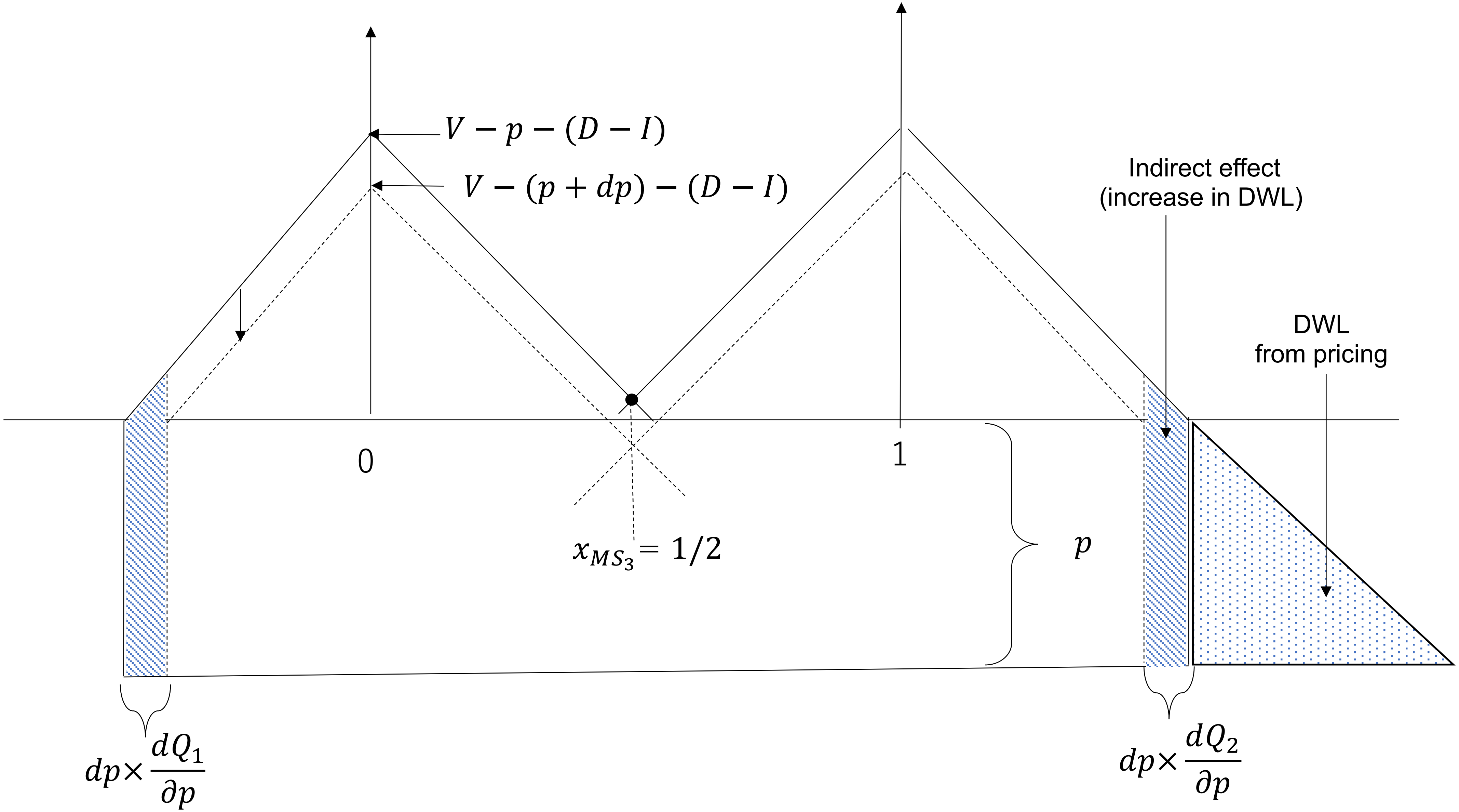

Figure 3(b). Indirect effect of investment (state S3)

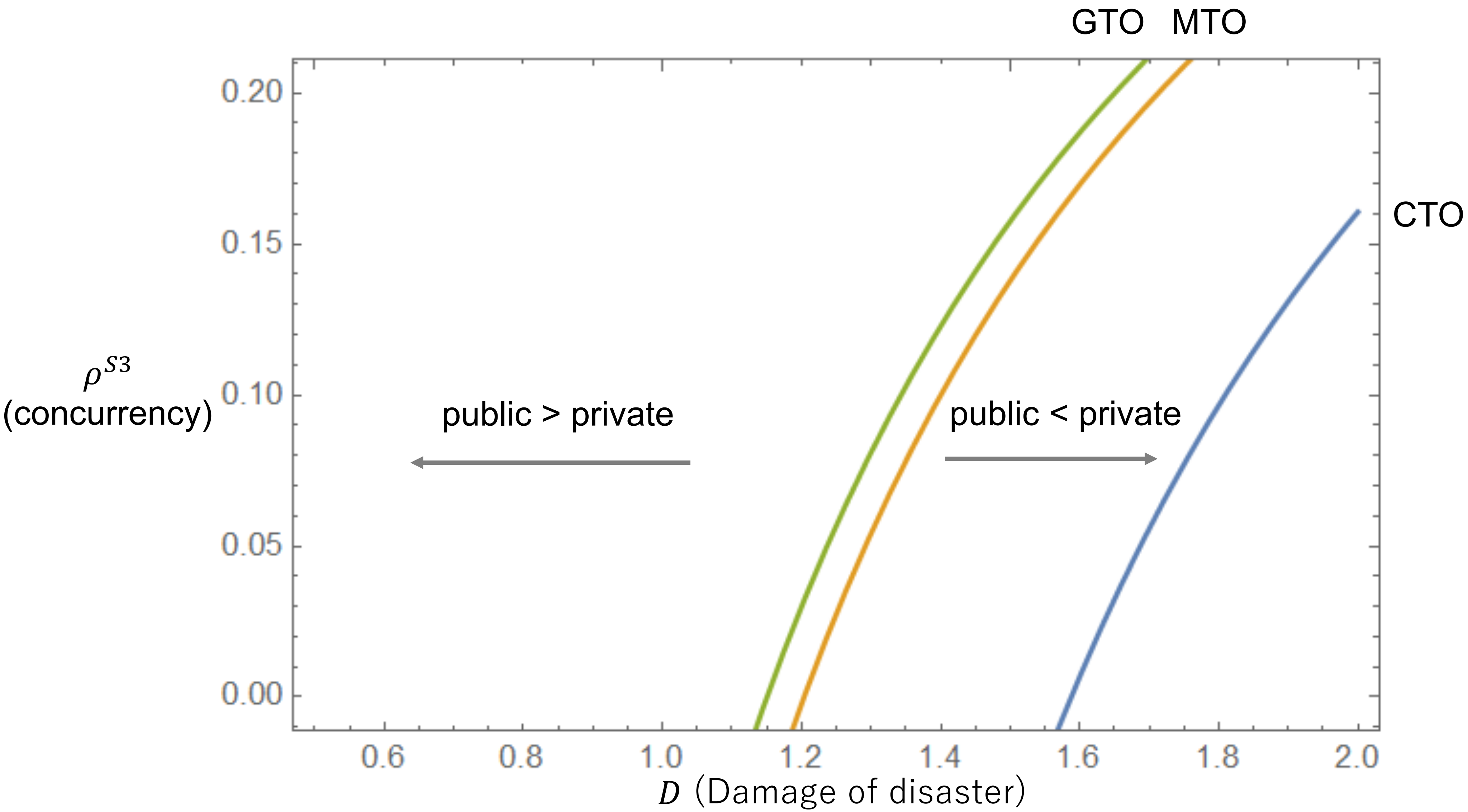

Figure 4. Comparison of public and private investment

Note: In the left side of each curve, public investment is larger in each regime.
For parameter values, $\rho = 0.2, c = 2, V = 5, D = 1, t = 0.5$ are given.

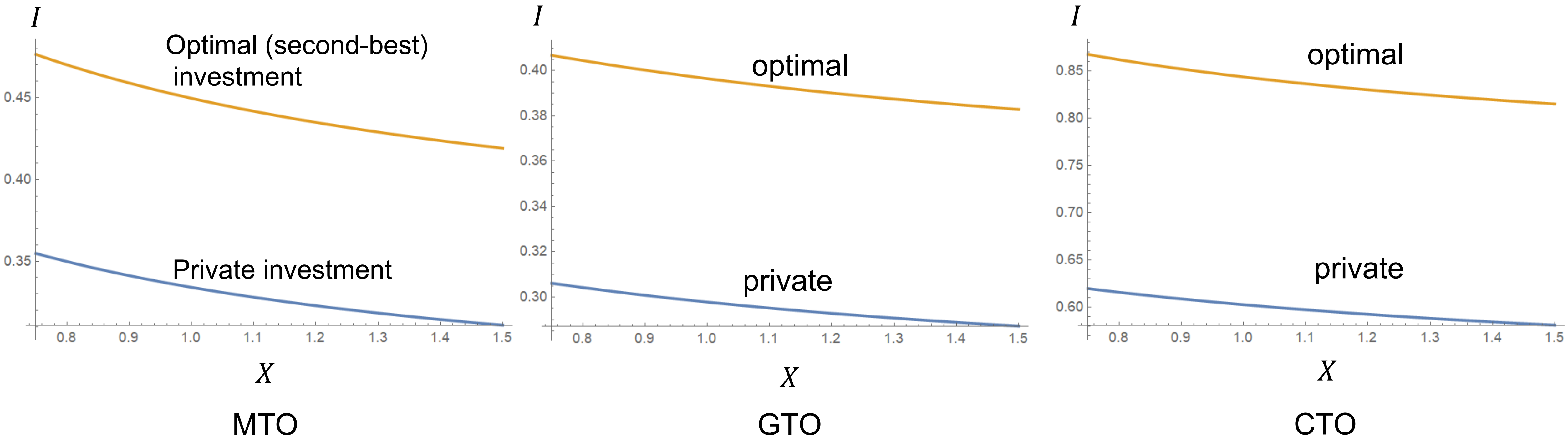

Figure 5. Distance and investment under private operation regimes
(Note: $\rho = 0.2, c = 2, V_1 = V_2 = 5, D = 1, t = 0.5$ are give for the baseline parameter values)

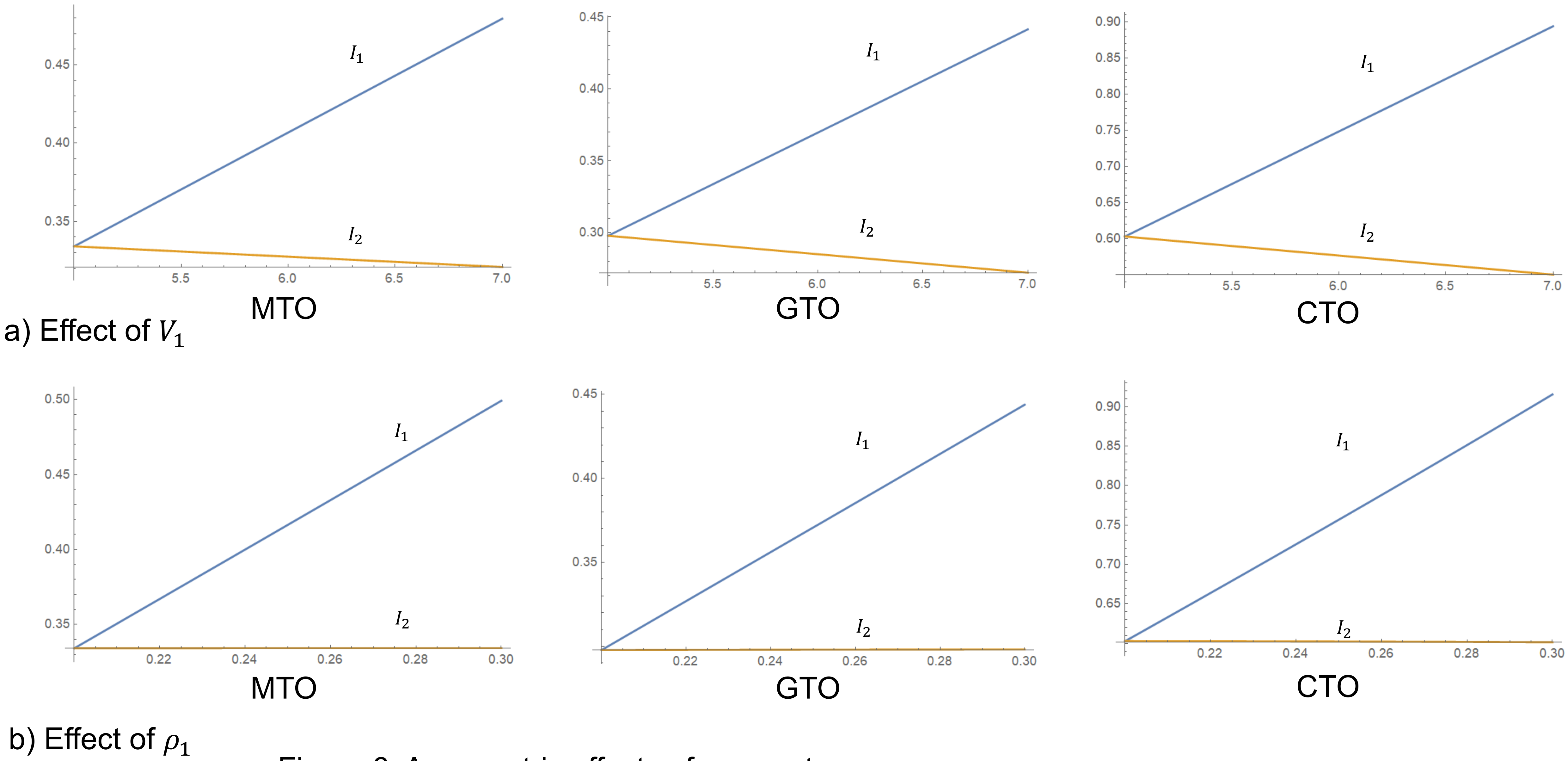

Figure 6. Asymmetric effects of parameters

(Note: $\rho_1 = \rho_2 = 0.2, c = 2, V_1 = V_2 = 5, D = 1, t = 0.5$ are give for the baseline parameter values)