Climate Change, Natural Disasters and Adaptation Investments: Inter- and Intra-port Competition and Cooperation

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Abstract

This paper investigates disaster adaptation investments made by two landlord ports with each severing its captive markets while competing for a common hinterland. Each port consists of a private port authority and a private terminal operator. The probability of a natural disaster, which is induced by climate change, is ambiguous at the start of an adaptation investment ("Knightian uncertainty"), but will be known after the investment. We examine the impacts of inter-port and intra-port competition and cooperation on the port adaptation investment. We find that high expectation of the disaster occurrence probability encourages the adaptation, while high variance of the disaster occurrence probability discourages the adaptation. Furthermore, inter-port competition results in more adaptation investments (the "competition effect"), whereas within a port there is free riding on adaptation between the port authority and the terminal operator (the "free-riding effect"). The higher expectation and larger variance of disaster occurrence probability, and a higher inter-port competition intensity (port service homogeneity) would strengthen both the competition effect and the free-riding effect.

Key words: Climate change, Natural disaster, Port disaster adaptation, Knightian uncertainty, Port competition, Inter- and Intra-port cooperation.

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1. Introduction

The past decade has witnessed more frequent extreme weather events and natural disasters around the world, with increasing economic and social costs. The examples include the impacts of hurricanes Katrina (occurred in 2005), Sandy (in 2012), and most recent Harvey (in 2017) on the US coastline. In particular, Harvey brought an estimated US$75 billion economic loss, and Sandy caused an estimated US$36.1 billion loss. Scientific studies suggest that climate change might lead to an increase in both the occurrence and the strength of weather-related natural disasters in the near future (e.g., IPCC, 2013; Keohane and Victor, 2010; Min et al., 2011). According to Morgan Stanley research, until 2015, among the top-ten most costly hurricanes hitting the US, eight occurred after year 2000.[1] Such increasing frequency and strength of hurricanes in North Atlantic Basin can be attributed to temperature rise of the ocean due to global warming (IPCC, 2013). In addition to such "one shot" disasters, there is an increasing risk of coastal and marine natural disasters (in terms of frequency and intensity) such as the sea level rise (SLR) owing to climate change. By the end of this century the sea level may be 75-80 cm higher than today's level (Schaeffer et al., 2012). Marine ports are highly vulnerable to coastal and marine natural disasters, and are exposed to climate hazards such as SLR and resultant flooding and storms due to climate change (OECD, 2016). For example, Kafalenos and Lenonard (2008) estimated the vulnerability of ports in the US Gulf Coast to SLR, and Nicholls et al. (2008) assessed the exposure to flooding for 136 large port cities around the globe. Stenek et al. (2011) and Scott et al. (2013) gauge the vulnerability for port system sub-components to climate-change related navigation, berthing, material handling, vehicle movement, goods storage and transportation. The increasing risk of natural disasters to marine ports may trigger substantial social, economic loss and may lead to shifts in freight transport and passenger flow (Koetse and Rietveld, 2009). Crucially, many ports play a critical role in global supply chains, so that any significant loss or degradation of service due to disaster occurrence would have significant knock-on effects on global supply chain performance (OECD, 2016).

The great uncertainties surrounding climate change have made it more difficult to implement adaptation investment strategies - particularly at the regional and local level (IPCC, 2013; OECD, 2016). Uncertainty about temperature changes increases as the geographical scale shrinks. The rate of SLR also has a wide confidence interval. IPCC (2013)'s estimates for year 2100 range from 0.26 to 0.82 metres, while other estimates can be as high as 2 metres. Local changes to extreme water levels are more uncertain because of

[1] The details about top ten most costly hurricanes in the US can be found in the link http://www.businessinsider.com/hurricane-irma-costliest-hurricanes-us-history-map-2017-9.

sensitivity to potential changes in the track of storm (EUROCONTROL, 2013). Other effects such as changes in rainfall, and the frequency and intensity of storms, are uncertain even if feedback effects in climate can be positive or negative, tipping points are possible, and rapid and catastrophic changes cannot be ruled out. All these uncertainties increase the difficulty of planning and financing adaptation strategies (Haire et al., 2010; Becker and Inoue, 2012). Furthermore, since the adaptation infrastructure is expensive and long-lived, and has few alternative uses, poor decisions will have serious consequences.

Unlike rich literature on the environmental effects of transportation (especially the mitigation of transport sector on climate change; see, e.g., Zhang et al., 2004, Wang et al., 2015), there is a lack of research on the adaptation of transportation sector to climate change related disasters. [2] In addition, theoretical analyses on the interplays between ports and their hinterlands are emerging (e.g. De Borger and Proost, 2012; Wan et al., 2016, 2017). However, these studies focus on the issues of port and hinterland pricing and capacity investment. For example, Basso and Zhang (2007) modelled how two congested facilities compete in price and capacity, acknowledging a downstream oligopoly carrier competition within each facility. De Borger and De Bruyne (2011) examined the impact of vertical integration between terminal operators and trucking firms on optimal road toll and port charge. Homsombat et al. (2013) investigated the market-based policy on pollution control in a region with multiple ports. Other port studies focusing on congestion pricing and/or optimal port capacity investment include Yuen et al. (2008), De Borger et al. (2008) and Wan and Zhang (2013). None of these papers have considered port adaptation to climate change risks. However, McKinnon and Kreie (2010) conjecture that adaptation of logistical systems and supply chains to climate change will become new field of logistics research.

Xiao et al. (2015) model the port adaptation investment by both port authority and terminal operator under the uncertainty of disaster occurrence. They find that there is a free-riding effect of adaptation efforts between the two entities, and that the information of the disaster occurrence is essential for the timing of adaptation investments. Xiao et al. (2015) consider port adaptation of a single port and so inter-port competition is not considered. They further treat port demand and pricing being exogenous to adaptation investments. However, port adaptation and resilience to natural disaster actually can essentially affect port competitiveness and the port choice decision by shippers. For example, Chang (2000) empirically studies

[2] There are several studies on post-disaster relief and transport and logistics system resilience (Chen and Yu, 2016; Huang et al., 2013; Rawls and Turnquist, 2010; Sheu, 2014), while the studies on adaptation strategies are few. In addition, these studies mainly adopt engineering methods to analyze optimal cargo flow and important segment of the supply chain or network for enhancing the network resilience, while the economic analysis is not emphasized.

the impact of the 1995 Great Hanshin earthquake on the port of Kobe in Japan, which was shut down and fully recovered over two years. It is found that due to the earthquake damage, the port of Kobe lost most of transshipment cargo to competing Asian ports, in both short and long-term. Port disruption can cause serious reputational and direct economic loss on shippers (Zhang and Lam, 2015), thus switching shipper demand to a better adapted port. Therefore, it could be necessary and important to model the inter-port competition when analyzing port adaptation investment.

Despite the scanty attempt of analytical modeling, some surveys and qualitative studies have been done to describe port investments and efforts to adapt disaster and extreme weather and to measure port's climate risk (Ng et al., 2016a; Wang, 2014; Yang et al., 2017; Zhang et al., 2017). Becker et al. (2012) surveyed 93 port directors, engineers, environmental managers, and planners representing 82 ports around the world about their adaptation strategies. The results show about half of the ports holds regular meetings to discuss adaptation, and a third of ports has issued guideline of design to deal with climate change threat. Becker et al. (2012) also calculated score of adaptation level for the 89 ports. It is found that public port authorities make more adaptations than the private. Becker et al. (2013) reviewed the climate change adaptation strategies of Port of Rotterdam (Netherlands) and Port of San Diego (California). They find that the effective strategy requires collaborations and supports from a broad range of stakeholders including climate science, engineering, port management, operators and policy.

Although the possible damage is severe, uncertainties of climate-change related disasters are still high, and the adaptation investments are huge. Surveys of Becker et al. (2012) show ports and other stakeholders are reluctant to adapt considering the uncertain return, especially when the expected probability of the disaster occurrence is low. To account for the uncertainty of the climate change related disaster, Weitzman (2009) models the climate change related disaster damage with a fat-tailed probability distribution that high damage events laying on the tail of the distribution. This nature of low probability but high damage disaster makes the conventional cost-and-benefit analysis based on thin-tail probability distribution difficult to be implemented, and imposes challenge to accurately suggest optimum of adaptation and mitigation investments. Xiao et al. (2015) model the disaster uncertainty in a two-period dynamic setting, assuming a uniform distributed disaster occurrence probability at the first period, but a more accurate (a more narrowly bounded uniform distribution) disaster occurrence probability in the second period due to information learning. There is an option value in investing later with better information about the disaster occurrence probability.

The present paper analytically investigates disaster adaptation investment made by two landlord ports with each consisting of a port authority and a terminal operator. We model the climate change related disaster to have a "Knightian uncertainty" (Knight, 1921) at adaptation investment stage, in the sense that probability of the disaster occurrence is uncertain (a random variable) and not accurately knowable. Knightian uncertainty refers to ambiguity in which decision maker has to make decisions when the relevant probabilities are unknown. Our Knightian uncertainty captures a more general and wider family of probability distribution, not limited to the specific assumptions in Weitzman (2009) and Xiao et al. (2015). The effect of this Knightian uncertainty on port adaptation investment is investigated. The other strand of contributions is to explicitly examine the impacts of inter-port competition, intra-port cooperation on port adaptation investment. We explicitly model endogenous port pricing and shippers' demand with port adaptation. The study answers how inter-port competition, intra-port cooperation can increase or decrease the port adaptation.

We find, with Knightian uncertainty assumption, port adaptation investment increases with the expectation of the disaster occurrence probability but decrease with its variance. In other words, a higher expectation of the disaster occurrence probability encourages the adaptation, but the variance of the disaster occurrence probability can discourage the adaptation. This analytical result may provide a nice explanation for why in practice adaptation is much more difficult to implement than mitigation, owing to the fact that our present knowledge about climate change and related disasters is far from reasonable accuracy. Inter-port competition also results in more adaptation investments (i.e., the "competition effect"). There is free-riding on adaptation investments between the port authority and the terminal operator (i.e. the "free-riding effect") within each port. Their intra-port coordination can increase the adaptation by removing such free-riding effect. These two effects can be strengthened by a higher expectation and larger variance of the disaster occurrence probability, and by a more intense inter-port competition (service homogeneity).

The paper is organized as follows. Section 2 introduces the basic economic setup. Section 3 derives the analytical results for optimal port adaptation with different inter-port competition and intra-port coordination conditions. Section 4 examines the effects of inter-port competition intensity (port service homogeneity) on adaptation investments, and Section 5 contains the concluding remarks.

2. Basic Model

We consider two nearby ports sharing a common hinterland that are subject to a threat of common but uncertain disaster (shown in Figure 1). The ports are of the landlord type, each consisting one port authority owning the port basic infrastructure, and a terminal operator as a tenant to directly handle cargo transport (Liu 1992).[3] The landlord port is the the most predominant type of ports in the world (Becker et al., 2012; Xiao et al., 2015). For landlord type port, the terminal operators are private entities. For example, PSA International, Hutchison Port Holding, APM terminals, DP World and China Merchant Holding are the major terminal operator corporations operating worldwide [4]. Port authorities are modeled as private entities as well in this study. Since 1990s, there is trend around the world to privatise port authority from public sector, aiming to relieve government heavy financial burden, and to upgrade port operation efficiency (Liu, 1995; Cullinane et al., 2005). Port authority privatization was pioneered by the UK Thatcher's government (Baird and Valentine, 2006) in 1990s. Later, corporatization of port authorities has been widely applied around the world, especially in Asia and Oceania (Everett, 2005; World Bank, 2011). Even without full privatization, most of port authorities have been largely corporatized, with government controlling partial amount of share. Meanwhile, port governance has also been transferred from the national/state governments to local ones who are responsible for own financial performance (Cheon et al., 2010).[5] As a result, the port authorities would be profit-oriented, resembling a private entity.

The two ports can belong to competing port authorities. Such inter-port competition is exemplified by the Pearl River Delta with Hong Kong port competing against Shenzhen port to be the gateway for South China. The other example may be the west European ports, especially the Hamburg-Le Havre (HLH) port range with several ports competing as the gateway to West and North Europe. One monopoly port authority to control multiple ports is also common. For example, Port Authority of New York and New Jersey

[3] There is no universally accepted framework for port classification. A widely adopted classification is by Liu (1992) to category port into four types: service port, tool port, landlord port and private port. A service port is if the port authority is responsible for the provision of all port facilities; a tool port is if the port authority is public and provides the infrastructure and superstructure, while the provision of services is licensed to private operators; a landlord port is in which the domain of the port authority (public or private) is restricted to the provision of the infrastructure, while investment in the superstructure and port operation is the responsibility of licensed private companies; a private port is if the provision of all the facilities and services is left to one single private entity.

[4] These operators are international corporations having business in many ports around the world. One operator may operate in two nearby ports at the same time (for example, Hutchison Port Holding operates in both Hong Kong and Shenzhen ports). One port can also have multiple terminal operators. To make the model tractable and to focus on the main trade-off issues, we assume that there is only one terminal operator for each port and that the two operators are independent.

[5] According to Cheon et al. (2010), in 1991, 42% of the world's major hub and gateway ports were managed by national or state government bodies; by 2004, the percentage dropped to mere 32%. Corporatized port authorities accounted for less than 1/3 in 1991, but by 2004, the number became 45%.

controls port of Newark, Port of Perth Amboy and Port of New York. Georgia Ports Authority controls Port of Savannah and Port of Brunswick on the east coast of the US.

Analogous to Basso and Zhang (2007), Pels and Verhoef (2004) [6], it is assumed that port charges within a port are determined in a "vertical structure": the port authority decides its charge (concession fee) on the terminal operator first, and then the terminal operator chooses its service charge to be paid by shippers. For landlord port, port authority signs "concession contract" with private terminal operator, stipulating the duration, concession fee scheme and other terms to lease the port land and basic facility to terminal operator. Notteboom (2006) summarizes common types of "concession contracts" between port authority and terminal operator. Detailed concession fee scheme varies among the ports. But commonly, port authority charges a concession fee to the terminal operator based on the throughput it handled, such that the total concession fee is proportional to the cargo volume.

< Figure 1 here>

In this study, we model the impact of port authority inter-port competition and monopoly, and intra-port cooperation between port authority and terminal operator within one port, on port adaptation. A multi-stage game is used to model both an "adaptation investment stage" for the ports, and an "operation stage" when port charges are determined, conditional on adaptation investments.[7] The timeline of economic model is demonstrated in Figure 2. The probability of disaster occurrence is assumed to be ambiguous at adaptation investment stage, which is a Knightian uncertainty (Knight, 1921; Camerer and Weber, 1992; Gao and Driouchi, 2013; Nishimura and Ozaki, 2007). Knightian uncertainty suggests disaster occurrence probability x can be a random variable at adaptation investment stage, with a density function (pdf) $f(x)$, expectation Ω and variance Σ. But this probability only becomes realized later at operation stage when ports decide price and shipper chooses port. This improvement in information reflects a likely setting in which a better knowledge on climate change and related disasters is accumulated during the lengthy period of adaptation investment. At adaptation investment stage, port authorities and terminal operators at the two ports simultaneously determine their adaptation investment I_i^a , I_i^t . Once decided, the adaptation investments are assumed to be fixed since any adjustment would require additional complex evaluation

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[6] Basso and Zhang (2007) study revelry between two congested facilities considering the upstream as the provider of the facility infrastructure and downstream carrier to use the facility. The pricing is determined in a vertical structure with downstream carrier charges the end customer, while upstream facility infrastructure provider charges carrier.

[7] A multi-stage game is a widely adopted approach to model the capacity investment at early stage and pricing at later stage for transport infrastructure (e.g. marine ports and airports) such as Luo et al. (2012) and Xiao et al. (2013).

and funding approval, thus causes major delay in completion. We do not consider the case where the disaster occurs during the period of adaptation constructions. However, this does not alter strategic behavior of the ports since both port authorities and terminal operators do not adjust pricing until the port adaptation is installed to reduce damage for possible disaster.

<Figure 2 here>

At operation stage, following Basso and Zhang (2007) and Wan et al. (2016), as shown in Figure 3, we adopt an infinite linear city model to derive shipper demand conditional on port service charges p_i and port adaptation investments I_i^a, I_i^t in response to disaster occurrence probability x. The value to the shipper of using the port service V is exogenous. Shippers have to choose which port to use before observing event of disaster occurrence or not.[8] The expected damage incurred on the shipper is x Max$\{0, D - \eta(I_i^a + I_i^t)\}$. D is the damage without any port adaptation when disaster occurs. $\eta(I_i^a + I_i^t)$ is the reduction of damage owing to port authority and terminal operator adaptation. Shippers are assumed to be uniformly distributed on the linear city with density 1. Shippers incur a cost of t per unit distance to transport cargo from its location to the port. This transport cost can also capture any horizontal differentiation (service homogeneity) of two ports' services perceived by the shippers. Shippers choose which port to use, and directly pay the terminal operator. The terminal operator pays port authority a concession fee in exchange to use the port land and basic infrastructure. The port charges within a port are determined in a "vertical structure": the port authority chooses its concession fee ϕ_i on the operator first, and then the operator chooses its service charge p_i on the shippers. Table 1 summarizes notations and parameters definitions in our economic model.

<Figure 3 here> < Table 1 here>

To derive the port demand at operation stage, the expressions for the demand parameters can be derived as follows.

$$|z^l| = \frac{V - p_1 - x\, Max\{0, D - \eta(I_1^a + I_1^t)\}}{t} \tag{1.1}$$

[8] Shippers are assumed to make their port choice decisions before observing the realization of disaster occurrence or not. If the disaster occurs, shippers cannot make the decisions to switch ports. This assumption is based on observations in (Magala and Sommons, 2008; Tongzon, 2009) that shippers/shipping lines often sign long-term contract with terminal operators. Ad hoc re-routing and rescheduling to other ports are difficult. Shippers/shipping lines could commit to particular ports/terminals due to integration and investment in hinterland transport, warehousing and other forms of cooperation with port sector (Chang et al., 2008; Wiegmans et al., 2008; Franc and van der Horst, 2010).

$$z^r = 1 + \frac{V - p_2 - x\, Max\{0, D - \eta(I_2^a + I_2^t)\}}{t} \tag{1.2}$$

$$z^m = \frac{1}{2} + \frac{p_2 - p_1 - x\, Max\{0, D - \eta(I_1^a + I_1^t)\} + x\, Max\{0, D - \eta(I_2^a + I_2^t)\}}{2t} \tag{1.3}$$

The demand for each port at the operation stage is as follows:

$$Q_i(p) |\, x, I^a, I^t \; = \frac{1}{2} + \frac{2V + p_j - 3p_i + x\, Max\,\{0, D - \eta(I_j^a + I_j^t)\} - 3x\, Max\{0, D - \eta(I_i^a + I_i^t)\}}{2t} \tag{2}$$

The profits for terminal operators at operation stage is $\Pi_i | x, I^a, I^t = (p_i - \phi_i) Q_i$. Port authorities' profits at operation stage are $\pi_i |\, x, I^a, I^t = \phi_i Q_i$. For model tractability, we normalize operating cost of port authorities and terminal operators to be zero. At adaptation investment stage, terminal operators' expected profits are $E[\Pi_i] = [\int \Pi_i f(x) dx] - 0.5\omega {I_i^t}^2$ .Port authorities' expected profits are $E[\pi_i] = [\int \pi_i f(x) dx] - 0.5\omega {I_i^a}^2$. At adaptation investment stage, port authorities incur adaptation investment cost $0.5\omega {I_i^a}^2$, and terminal operators incur $0.5\omega {I_i^t}^2$. The adaptation investment cost for both port authorities and terminal operators is assumed to be quadratic form, indicating an increasing marginal cost of adaptation as technology requirement is higher and overall difficulty increases to add more adaptation. ω is the adaptation cost parameter. Port authorities and terminal operators can have different adaptation measures. Port authorities' adaptations are mainly on port's basic infrastructure, such as building breakwaters, storm barriers, flood-control gates (Becker et al., 2012). These adaptations are not specific to protect particular terminals but to benefit entire port. Terminal operator's adaptation is mainly for its own berths and piers, for example, the elevation of terminal, upgrading the drainage system, redesigning, and retrofitting of the terminal facilities (Becker et al., 2012). For model tractability and to focus on main insights, we assume port authorities and terminal operators to have the same adaptation investment cost structure, i.e. the same cost parameter ω. The consumer surplus for the shipper at the operation stage is as follows:

$$CS | x, I^a, I^t = \int_0^{|z^l|} [V - p_1 - x\,\mathrm{Max}\{0, D - \eta(I_1^a + I_1^t\} - z\, t]\, dz + \int_0^{z^m} \; [V - p_1 - x\,\mathrm{Max}\{0, D - \eta(I_1^a + I_1^t\} - z\, t] dz + \int_{z^m}^{1} [V - p_2 - x\,\mathrm{Max}\{0, D - \eta(I_2^a + I_2^t\} - (1 - z)\, t] dz + \int_1^{z^r} [V - p_2 - x\,\mathrm{Max}\{0, D - \eta\,(I_2^a + I_2^t\} - (z - 1)\, t] dz \tag{3}$$

The social welfare for the port system at operation stage is defined as $SW = CS + \sum_{i=1}^{2} \pi_i + \sum_{i=1}^{2} \Pi_i$.

< Table 1 here>

3. Analysis

We adopt backward induction to solve the model. First, operation stage is analyzed on shipper port choice decision and pricing behavior of port authorities and terminal operators (section 3.1). At operation stage, disaster occurrence probability x is realized, and port adaptation is also completed. Second, we analyze port adaptation decisions at adaptation investment stage, where disaster occurrence probability is ambiguous with a Knightian uncertainty (section 3.2).

3.1 Port pricing

At port operation stage, adaptations I^a, I^t have been completed, and the disaster occurrence probability x is also realized. The port charges within a port are determined in a "vertical structure": the port authority decides on its concession fee to terminal operator first as the upstream, and then the terminal operator as the downstream chooses its service charge to be paid by shippers. Terminal operators maximize profit by setting service charge p_i to shippers. They also pay concession fee ϕ_i to port authorities. The profit function of terminal operator is $\underset{p_i}{Max}\, \Pi_i \,|x, I^a, I^t = (p_i - \phi_i)Q_i$.

$$p_i(\phi_i, \phi_j)|x, I^a, I^t \\ = 0.2\left[(2V + t) + 2.57\phi_i + 0.42\phi_j - 2.43x\,\mathrm{Max}\{0, D - \eta(I_i^a + I_i^t)\}\} \\ + 0.42\mathrm{Max}\{0, D - \eta(I_j^a + I_j^t)\}\right] \tag{4}$$

It is noted that $p_i(\phi)|x, I^a, I^t$ is a function of two port authorities' concession fees ϕ_i and ϕ_j due to the interaction of two ports in the common hinterland. But ϕ_i has more impact on the port charge $p_i(\phi)|x, I^a, I^t$ at the same port. While terminal operators at two ports are private and compete, port authorities may compete or cooperate (monopoly). Pricing rules of port authorities thus depend on inter-competition or cooperation (monopoly).

3.1.1 Pricing rule of competing port authorities

The objective of each competing port authorities is $\underset{\phi_i}{\text{Max}}\, \pi_i | x, I^a, I^t = \phi_i Q_i(p_i(\phi_i, \phi_j), p_j(\phi_i, \phi_j))$. It is noted that π_i is a function of $p_i(\phi)$, and $p_j(\phi)$ because shippers directly pay terminal operators. Substituting $p_i(\phi_i, \phi_j)$ and $p_j(\phi_i, \phi_j)$ into π_i such that port authority has $\underset{\phi_i}{\text{Max}}\, \pi_i | x, I^a, I^t = \phi_i Q_i(\phi_i, \phi_j)$. Solving the FOCs, $\frac{\partial \pi_i}{\partial \phi_i} = 0$ and $\frac{\partial \pi_j}{\partial \phi_j} = 0$, the optimal concession fee $\phi_i | x, I^a, I^t$ is as follows. The second-order conditions (SOCs), $\frac{\partial^2 \pi_i}{\partial {\phi_i}^2} < 0$ and $\frac{\partial^2 \pi_j}{\partial {\phi_j}^2} < 0$, are also satisfied.

$$\bar{\phi}_i | x, I^a, I^t = 0.23(2V + t) - x\left[0.50\,\text{Max}\{0, D - \eta(I_i^a + I_i^t)\} - 0.045\,\text{Max}\{0, D - \eta\left(I_j^a + I_j^t\right)\}\right] \quad (5.1)$$

Inserting $\bar{\phi}_1 | x, I^a, I^t$, and $\bar{\phi}_2 | x, I^a, I^t$ to $p_1(\phi)$ and $p_2(\phi)$, and $Q_1(p)$ and $Q_2(p)$ we have,

$$\bar{p}_i | x, I^a, I^t = 0.34(2V + t) - x\left[0.74\,\text{Max}\{0, D - \eta(I_i^a + I_i^t)\} - 0.066\,\text{Max}\{0, D - \eta\left(I_j^a + I_j^t\right)\}\right] \quad (5.2)$$

And

$$\bar{Q}_i | x, I^a, I^t = \frac{0.16\,(2V+t) - x\left[0.36\,\text{Max}\left\{0, D - \eta\left(I_i^a + I_i^t\right)\right\} - 0.032\,\text{Max}\left\{0, D - \eta\left(I_j^a + I_j^t\right)\right\}\right]}{t} \quad (5.3)$$

The following comparative statics are obtained to show the impact of adaptation investment and probability of disaster occurrence on port charges and port demands. Port authority and terminal operator charge more (less) and have more (less) demand if its own port (the other port) makes more adaptation. The disaster occurrence probability x, however, has two countervailing effects on port charges and demands. On one hand, higher disaster occurrence probability increases the expected damage cost for shippers, decreasing port's demand and charge ceteris paribus. On the other hand, with two ports competing in a common hinterland, if one port prevails the other in adaptation (i.e. when $\frac{\text{Max}\{0, D - \eta(I_i^a + I_i^t)\}}{\text{Max}\{0, D - \eta\left(I_j^a + I_j^t\right)\}} \leq 0.089$), higher disaster occurrence probability makes this much better adapted port more appealing to shippers, such that disaster occurrence probability has a positive effect on port charge and demand.

$$\frac{\partial \bar{\phi}_i}{\partial I_i^a} \geq 0; \frac{\partial \bar{\phi}_i}{\partial I_i^t} \geq 0; \frac{\partial \bar{\phi}_i}{\partial I_j^a} \leq 0; \frac{\partial \bar{\phi}_i}{\partial I_j^t} \leq 0$$

$$\frac{\partial \bar{\phi}_i}{\partial x} \leq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \geq 0.089 \;; \frac{\partial \bar{\phi}_i}{\partial x} \geq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \leq 0.089$$

$$\frac{\partial \bar{p}_i}{\partial I_i^a} \geq 0; \frac{\partial \bar{p}_i}{\partial I_i^t} \geq 0; \frac{\partial \bar{p}_i}{\partial I_j^a} \leq 0; \frac{\partial \bar{p}_i}{\partial I_j^t} \leq 0$$

$$\frac{\partial \bar{p}_i}{\partial x} \leq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \geq 0.089 \;; \frac{\partial \bar{p}_i}{\partial x} \geq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \leq 0.089$$

$$\frac{\partial \bar{Q}_i}{\partial I_i^a} \geq 0; \frac{\partial \bar{Q}_i}{\partial I_i^t} \geq 0; \frac{\partial \bar{Q}_i}{\partial I_j^a} \leq 0; \frac{\partial \bar{Q}_i}{\partial I_j^t} \leq 0$$

$$\frac{\partial \bar{Q}_i}{\partial x} \leq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \geq 0.089 \;; \frac{\partial \bar{Q}_i}{\partial x} \geq 0 \text{ if } \frac{\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}} \leq 0.089$$

3.1.2 Pricing rule of monopoly port authority

The monopoly port authority maximizes a joint profit at two ports as $\underset{\phi_1,\phi_2}{\mathrm{Max}} \sum_{i=1}^{2} \pi_i \,|x, I^a, I^t = \sum_{i=1}^{2}(\phi_i Q_i(\phi_i, \phi_j))$. FOCs are $\frac{\partial(\pi_i+\pi_j)}{\partial \phi_i} = 0$ and $\frac{\partial(\pi_i+\pi_j)}{\partial \phi_j} = 0$. SOCs $\frac{\partial^2(\pi_i+\pi_j}{\partial {\phi_i}^2} < 0$ and $\frac{\partial^2(\pi_i+\pi_j)}{\partial {\phi_j}^2} < 0$ are also satisfied. The optimal concession fees are $\tilde{\phi}_i|x, I^a, I^t = 0.25(2V+t) - 0.5x(\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\})$. Substituting $\tilde{\phi}_i\,|x, I^a, I^t$ into $p_i(\phi_i, \phi_j)$ and also $Q_i(\phi_i, \phi_j)$.

$$\tilde{p}_i \mid x, I^a, I^t = 0.35\,(2V+t) - x\left[0.74\,\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\} - 0.043\,\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}\right] \tag{6.1}$$

And

$$\tilde{Q}_i \mid x, I^a, I^t = \frac{0.15\,(2V+t) - x\left[0.36\,\mathrm{Max}\{0, D-\eta(I_i^a+I_i^t)\} - 0.064\,\mathrm{Max}\{0, D-\eta\left(I_j^a+I_j^t\right)\}\right]}{t} \tag{6.2}$$

Below are comparative statics of port charges and demands to disaster occurrence probability and port adaptation investment. For monopoly port authority, it increases concession fee at one port when this port increases adaptation i.e. $\frac{\partial \tilde{\phi}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{\phi}_i}{\partial I_i^t} \geq 0$. In addition, with monopoly power, port authority can raise concession fee when disaster occurrence has higher probability i.e. $\frac{\partial \tilde{\phi}_i}{\partial x} \geq 0$. For terminal operator, it can charge more to shipper when its port adapts more i.e. $\frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0$, but charges less when the other port has more adaptation i.e. $\frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0; \frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0$. Similar as the competing port authorities case, the disaster occurrence probability has two countervailing effects on concession fee and terminal operators' charge. When $\frac{\text{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\text{Max}\{0, D-\eta(I_j^a+I_j^t)\}} < 0.057$ holds, which means one port is much better adapted compared to the other port, disaster occurrence has overall positive effect such that port authority and terminal operator at one port can increase charge.

$$\frac{\partial \tilde{\phi}_i}{\partial x} \geq 0; \frac{\partial \tilde{\phi}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{\phi}_i}{\partial I_i^t} \geq 0; \frac{\partial \tilde{\phi}_i}{\partial I_j^a} = 0; \frac{\partial \tilde{\phi}_i}{\partial I_j^t} = 0$$

$$\frac{\partial \tilde{\phi}_i}{\partial x} \leq 0 \text{ if } \frac{\text{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\text{Max}\{0, D-\eta(I_j^a+I_j^t)\}} \geq 0.057; \frac{\partial \tilde{\phi}_i}{\partial x} > 0 \text{ if } \frac{\text{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\text{Max}\{0, D-\eta(I_j^a+I_j^t)\}} \leq 0.057$$

$$\frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0; \frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0; \frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0$$

$$\frac{\partial \tilde{Q}_i}{\partial I_i^a} \geq 0; \frac{\partial \tilde{Q}_i}{\partial I_i^t} \geq 0; \frac{\partial \tilde{Q}_i}{\partial I_j^a} \leq 0; \frac{\partial \tilde{Q}_i}{\partial I_j^t} \leq 0$$

$$\frac{\partial \tilde{Q}_i}{\partial x} \leq 0 \text{ if } \frac{\text{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\text{Max}\{0, D-\eta(I_j^a+I_j^t)\}} \geq 0.057 ; \frac{\partial \tilde{Q}_i}{\partial x} \geq 0 \text{ if } \frac{\text{Max}\{0, D-\eta(I_i^a+I_i^t)\}}{\text{Max}\{0, D-\eta(I_j^a+I_j^t)\}} \leq 0.057$$

Port concession fees and terminal operator charges comparison is $\bar{\phi}_i < \tilde{\phi}_i;\ \bar{p}_i < \tilde{p}_i$ as shown below, which leads to proposition 1.

$$\tilde{\phi}_i - \bar{\phi}_i = 0.0241 \times (2V + t) - x\left[0.0039\text{Max}\{0, D - \eta(I_i^a + I_i^t)\} + 0.044\text{Max}\{0, D - \eta(I_j^a + I_j^t)\}\right] > 0$$
$$\tilde{p}_i - \bar{p}_i = 0.0145 \times (2V + t) - x\left[0.0058\text{Max}\{0, D - \eta(I_i^a + I_i^t)\} + 0.023\text{Max}\{0, D - \eta(I_j^a + I_j^t)\}\right] > 0$$

Proposition 1: *Conditional on disaster occurrence probability and the adaptation investment at two ports, inter-port competition between two port authorities leads to lower concession fee and lower terminal operator charge.*

This proposition holds for general functional form (as shown in Appendix 1), that monopoly price is higher than duopoly competition price. As concession fees at two ports are strategic complements, the monopoly port authority is able to internalize the positive externality of concession fee rise at one port on the other port. This results in a higher concession fee and terminal operator charge for the two ports.

In addition, our comparative statics demonstrate: $\frac{\partial \bar{\phi}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \bar{\phi}_i}{\partial I_i^t} \geq 0$; $\frac{\partial \bar{\phi}_i}{\partial I_j^a} \leq 0$; $\frac{\partial \bar{\phi}_i}{\partial I_j^t} \leq 0$; $\frac{\partial \bar{p}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \bar{p}_i}{\partial I_i^t} \geq 0$; $\frac{\partial \bar{p}_i}{\partial I_j^a} \leq 0$; $\frac{\partial \bar{p}_i}{\partial I_j^t} \leq 0$ and $\frac{\partial \tilde{\phi}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \tilde{\phi}_i}{\partial I_i^t} \geq 0$; $\frac{\partial \tilde{\phi}_i}{\partial I_j^a} = 0$; $\frac{\partial \tilde{\phi}_i}{\partial I_j^t} = 0$; $\frac{\partial \tilde{p}_i}{\partial I_i^a} \geq 0$; $\frac{\partial \tilde{p}_i}{\partial I_i^t} \geq 0$; $\frac{\partial \tilde{p}_i}{\partial I_j^a} \leq 0$; $\frac{\partial \tilde{p}_i}{\partial I_j^t} \leq 0$. These lead to proposition 2 about the impact of port adaptation on port charges.

Proposition 2: *For ports with competing port authorities, concession fee and terminal operator charge increase with own port's adaptation, but decrease with the other port's adaptation. For monopoly port authority, concession fee and terminal operator charge also increase with own port's adaptation, but not affected by the other port's adaptation.*

As shown in Appendix 1, for competing port authorities, when one port increases adaptation (e.g. port i), the best response function of port j's concession fee $\phi_j(\phi_i)$ moves outward due to stronger competing pressure from port i. The best response function of port i's concession fee $\phi_i(\phi_j)$ moves downward. Thus, at new equilibrium, concession fee rises at the port with an increased adaptation (port i), while the concession fee at the other port (port j) decreases. When one port increases adaptation, terminal operator at this port thus has to pay a higher concession fee and also has larger shipper demand, both imposing positive effects on terminal operator charge. When the other port increases adaptation, terminal operator at one port faces lower concession fee and lower shipper demand, thus making it to lower charge to shipper.

For monopoly port authority, when adaptation at one port increases, port authority rises concession fee at this port. Meanwhile, it can internalize the positive externality of concession fee rise on the other port by not reducing the other port's concession fee. For terminal operator, the impact of adaptation change on its charge is the same. When one port increases adaptation, terminal operator at this port pays higher concession fee while also having larger shipper demand, both having positive effects on its charge. When the other port increases adaptation, terminal operator at one port pays a lower concession fee with lower shipper demand, making it to lower charge to shipper.

Taking derivatives of the difference in concession fees and terminal operator charges with respect to adaptation investments, it can be seen $\frac{\partial(\tilde{\phi}_i| x, I^a, I^t - \bar{\phi}_i | x, I^a, I^t)}{\partial I} > 0$; $\frac{\partial(\tilde{p}_i| x, I^a, I^t - \bar{p}_i | x, I^a, I^t)}{\partial I} > 0$, where $I \in \{I_i^a, I_i^t, I_j^a, I_j^t\}$.

Proposition 3: *Increased port adaptation at either port would enlarge the difference in concession fee and terminal operator charge between the ports with competing port authorities and monopoly port authority.*

Detailed explanation of proposition 3 is as follows. With adaptation increased at one port, monopoly port authority internalizes the externality to the other port, thus making the concession fee to rise more than that with the competing port authorities. Terminal operator charge increases with concession fee, such that its charge increases more with monopoly port authority. Therefore, the difference in concession fee and terminal charge between competing and monopoly port authority is enlarged. On the other hand, the other port increases adaptation, the monopoly port authority does not change concession fee at one port, whereas the competing port authorities would reduce concession fee in response. Thus, the difference in concession fee and terminal charge at one port is also enlarged when the other port increases adaptation.

3.2. Adaptation investment

At adaptation investment stage, disaster occurrence probability x has not been realized and has a Knightian uncertainty. Specifically, x is a random variable with a pdf $f(x)$, expectation Ω, variance Σ, and the second moment $\Psi = Ex^2 = \Omega^2 + \Sigma$. Next, analogous to operation stage analyses, we discuss different inter-and intra- port competition and cooperation regimes. Port authorities and terminal operations are assumed to simultaneously make adaptation investment decisions. This is because adaptation projects are lengthy, such that each party makes adaptation decision well in-advance, while only observing completed adaptations by the others after a long-period.

3.2.1 Adaptation of competing port authorities

The pricing rule follows that of two competing port authorities at operation stage i.e. $\bar{\phi}_i$ and $\bar{p}_i$. The expected profits for port authorities at adaptation investment stage are:

$$E[\pi_i] = [\int \pi_i f(x)dx] - 0.5\omega {I_i^a}^2 = 0.15\frac{V^2}{t} + 0.15V + 0.037t \; + \tag{7.1}$$

$$\frac{1}{t}\left\{\begin{matrix} 0.15\begin{bmatrix} 1.1\, Max\ \{0, D - \eta(I_i^a + I_i^t)\} - \\ 0.1\, Max\ \{0, D - \eta(I_j^a + I_j^t)\} \end{bmatrix}^2 \Psi \\ -0.3\Omega(V + 0.5t)\begin{bmatrix} 1.1\, Max\ \{0, D - \eta(I_i^a + I_i^t)\} - \\ 0.1\, Max\ \{0, D - \eta(I_j^a + I_j^t)\} \end{bmatrix} \end{matrix}\right\} - 0.5\omega {I_i^a}^2$$

The expected profits for terminal operators are:

$$E[\Pi_i] = [\int \Pi_i f(x)dx] - 0.5\omega {I_i^t}^2 = 0.072\frac{V^2}{t} + 0.072V + 0.018t + \frac{1}{t}\left\{\begin{array}{c} 0.072\begin{bmatrix} 1.1\,Max\ \{0, D - \eta\left(I_i^a + I_i^t\right)\} - \\ 0.1\,Max\ \{0, D - \eta\left(I_j^a + I_j^t\right)\} \end{bmatrix}^2 \Psi - \\ 0.14\,\Omega\ (V + 0.5t)\begin{bmatrix} 1.1\,Max\ \{0, D - \eta\left(I_i^a + I_i^t\right)\} - \\ 0.1\,Max\ \{0, D - \eta\left(I_j^a + I_j^t\right)\} \end{bmatrix} \end{array}\right\} - 0.5\omega {I_i^t}^2 \quad (7.2)$$

Port authorities and terminal operators maximize expected profits respectively. The constraints $\eta(I_i^a + I_i^t) \leq D$ must be imposed in the sense that ports cannot adapt beyond the total possible level of disaster damage D: $\underset{I_i^a}{\text{Max}}\ \text{E}[\pi_i]; st. \eta(I_i^a + I_i^t) \leq D; \underset{I_i^t}{\text{Max}}\ \text{E}[\Pi_i];\ st. \eta(I_i^a + I_i^t) \leq D.$

To solve above constrained optimization problem, we first assume the constraints are not binding at equilibrium, and then discuss conditions to reach such interior solutions. For port authorities, FOCs with respect to I_i^a are as follows:

$$\frac{\partial E[\pi_i]}{\partial I_i^a} = 0.33\frac{\eta}{t}\ [(V + 0.5t)\Omega - D\Psi] - 0.032\ \frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.36\ \frac{\eta^2}{t}\Psi I_i^t + \left(0.36\ \frac{\eta^2}{t}\Psi - \omega\right) I_i^a \quad (7.3)$$

The SOCs require $\omega \geq 0.36\ \frac{\eta^2}{t}\Psi$. This is to guarantee that port authorities' expected profits are concave in I_i^a. If $\omega \leq 0.36\ \frac{\eta^2}{t}\Psi$, port authorities' expected profit functions are convex in I_i^a such that marginal return of adaptation investment always increases, suggesting port authority to keep investing till reaching the bound $\eta(I_i^a + I_i^t) = D$. FOCs for terminal operators are as follows:

$$\frac{\partial E[\Pi_i]}{\partial I_i^t} = 0.16\frac{\eta}{t}\ [(V + 0.5t)\Omega - D\Psi] - 0.015\ \frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.17\ \frac{\eta^2}{t}\Psi I_i^a + (0.17\ \frac{\eta^2}{t}\Psi - \omega)I_i^t \quad (7.4)$$

SOCs require $\omega \geq 0.17\ \frac{\eta^2}{t}\Psi$ so that terminal operators' expected profit functions are concave in I_i^t. If $\omega \leq 0.17\ \frac{\eta^2}{t}\Psi$, marginal return of adaptation investment for terminal operators always increases, such that they keep investing till reaching the bound $\eta(I_i^a + I_i^t) = D$.

The second-order derivatives indicate $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. Thus, adaptation of port authority and terminal operator at the same port is strategic complement, while adaptation across ports is strategic substitute. In Appendix 2, we plot best response functions of adaptation I_i^a and I_i^t at the same port, and I_i^a and I_j^a at two different ports. The best response functions of I_i^a and I_i^t are positively slopped while those of I_i^a and I_j^a are negatively slopped. Solving the system equations of FOCs, and imposing symmetry, we obtain following symmetric interior equilibrium adaptation investments with competing port authorities.

$$\bar{I}_i^a = \bar{I}_j^a = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{6.1\,\omega t - 3\Psi\eta^2} \geq \bar{I}_i^t = \bar{I}_j^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{2.1\,(6.1\,\omega t - 3\,\Psi\eta^2)} \tag{7.5}$$

Non-negativity of adaptation investment implies $\omega \geq 0.49\,\frac{\eta^2}{t}\Psi$. Existence of interior solution requires $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. It is noted that when constraint $\eta(I_i^a + I_i^t) \leq D$ binds at equilibrium i.e. $\eta(I_i^a + I_i^t) = D$, there would be an infinite number of Nash equilibria of adaptation investment (see Appendix 2 for discussion). This happens when $\omega \leq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$ such that adaptation is not costly enough, such that ports adapt as much as possible to achieve a "full insurance". This case of infinite Nash equilibria with binding constraint makes comparison between $\bar{I}_i^a$ and $\bar{I}_i^t$ and other implications of Knightian uncertainty unclear. In addition, in practise, port adaptation is likely to be extremely costly (OECD, 2016) and as a result, ports seldom fully adapt to a potential disaster (see survey in Becker et al. (2012)). Therefore, to simplify our discussion and to reflect real practice, we exclude discussion on the multiple equilibria under binding constraint. Taking total derivatives of the FOCs, $\frac{\partial E[\pi_i]}{\partial I_i^a} = 0$ and $\frac{\partial E[\Pi_i]}{\partial I_i^t}$, to Ω and Σ respectively, and imposing the symmetry assumption, the expressions of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$, $\frac{\partial \bar{I}_i^t}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$, $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ can be obtained as follows:

$$\frac{\partial \bar{I}_i^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \bar{I}_i^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \bar{I}_i^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \leq 0$$

$$\frac{\partial \bar{I}_i^t}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)} \leq 0$$

Proof of the above comparative statics is in Appendix 3. The sign of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^t}{\partial \Omega}$ is determined by $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$. As a higher expectation of disaster occurrence probability increases the marginal expected profit of port authority and terminal operator to their own adaptation i.e. $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$, the equilibrium port adaptation also increases i.e. $\frac{\partial \bar{I}_i^a}{\partial \Omega} \geq 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Omega} \geq 0$. In addition, the sign of $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma}$ is determined by $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. As larger variance of disaster occurrence probability decreases the marginal expected profit of port authority and terminal operator to their own adaptation, the equilibrium port adaptation decreases as a result, i.e. $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \leq 0$ and $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \leq 0$.

3.2.2 Adaptation of monopoly port authority

The pricing rule at operation stage follows that of monopoly authority regime i.e. $\tilde{\phi}_i$ and $\tilde{p}_i$. For monopoly port authority, the expected joint profit is as follows:

$$E[\pi_1 + \pi_2] = [\int(\pi_1 + \pi_2)f(x)dx] - 0.5\omega({I_1^a}^2 + {I_2^a}^2) = 0.30\frac{V^2}{t} + 0.30V + 0.15 - \frac{0.075}{t} + \frac{1}{t}\begin{bmatrix} 0.18\,(Max\ \{0, D - \eta(I_1^a + I_1^t)\})^2 \\ -0.064\ Max\ \{0, D - \eta(I_1^a + I_1^t)\} \\ Max\ \{0, D - \eta(I_2^a + I_2^t)\} + 0.18\,(Max\ \{0, D - \eta(I_2^a + I_2^t)\})^2 \end{bmatrix}\Psi - \left(0.15 + 0.45\frac{V}{t}\right)\Omega[\,Max\ \{0, D - \eta(I_1^a + I_1^t)\} + Max\ \{0, D - \eta(I_2^a + I_2^t)\}] - 0.5\omega({I_1^a}^2 + {I_2^a}^2) \quad (8.1)$$

Monopoly port authority maximizes the expected joint profit choosing adaptation at two ports together as $\underset{I_1^a, I_2^a}{Max}\, E[\pi_1 + \pi_2]\ st.\, \eta(I_1^a + I_1^t) \leq D$ and $\eta(I_2^a + I_2^t) \leq D$. FOCs for the monopoly port authority are as follows. SOCs require that $\omega \geq 0.36\ \frac{\eta^2}{t}\Psi$.

$$\frac{\partial E[\pi_i+\pi_j]}{\partial I_i^a} = 0.30\frac{\eta}{t}\ [(V+0.5t)\Omega - D\Psi] - 0.064\ \frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.36\ \frac{\eta^2}{t}\Psi I_i^t + (0.36\ \frac{\eta^2}{t}\Psi - \omega)I_i^a \quad (8.2)$$

Terminal operators maximize their expected profit as $\underset{I_i^t}{\mathrm{Max}}\, \mathrm{E}[\Pi_i];\ \mathrm{s.t.}\, \eta\ (I_i^a + I_i^t) \leq D$. FOCs are as follows. The SOCs require $\omega \geq 0.18\ \frac{\eta^2}{t}\Psi$.

$$\frac{\partial\ E[\Pi_i]}{\partial I_i^t} = 0.15\frac{\eta}{t}\ [(V+0.5t)\Omega - D\Psi] - 0.031\ \frac{\eta^2}{t}\Psi\left(I_j^a + I_j^t\right) + 0.18\ \frac{\eta^2}{t}\Psi I_i^a - (\omega - 0.18\ \frac{\eta^2}{t}\Psi)I_i^t \quad (8.3)$$

The second-order derivatives show $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t} \leq 0$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$; $\frac{\partial^2 E[\Pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. The adaptation of port authority and terminal operators within the same port is thus strategic complement, while adaptation across ports is strategic substitute. Solving the system equations of FOCs for symmetric interior Nash equilibrium, following solution is obtained.

$$\tilde{I}_i{}^a = \tilde{I}_j{}^a = \frac{\eta[(2V+t)\ \Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2} \geq\ \tilde{I}_i{}^t = \tilde{I}_j{}^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2} \quad (8.4)$$

The non-negativity of adaptation investment requires $\omega > 0.45\ \frac{\eta^2}{t}\Psi$, while the interior solution requires $\omega \geq \frac{0.22\ \Omega(V+0.5t)\eta^2}{Dt}$. Taking total derivative of the FOCs, $\frac{\partial E[\pi_i+\pi_j]}{\partial I_i^a} = 0$ and $\frac{\partial\ E[\Pi_i]}{\partial I_i^t} = 0$, to Ω and Σ respectively, and imposing the symmetry assumption, $\frac{\partial \tilde{I}_i{}^a}{\partial \Omega}$, $\frac{\partial\ \tilde{I}_i{}^t}{\partial \Omega}$ and $\frac{\partial \tilde{I}_i{}^a}{\partial \Sigma}$, $\frac{\partial\ \tilde{I}_i{}^t}{\partial \Sigma}$ are solved as follows:

$$\frac{\partial \tilde{I}_i{}^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial\ \tilde{I}_i{}^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \tilde{I}_i{}^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}\right)} \leq 0$$

$$\frac{\partial\,\tilde{I}_i^t}{\partial\Sigma}=\frac{\left(\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial I_j^a}+\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial I_j^a}\right)\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial\Sigma}-\left(\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^{a^2}}+\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial I_j^t}\right)\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial\Sigma}}{\left(\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^{a^2}}+\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial I_j^a}\right)\left(\frac{\partial^2E[\Pi_i]}{\partial I_i^{t^2}}+\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial I_j^t}\right)-\left(\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial I_j^a}+\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial I_i^a}\right)\left(\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial I_i^t}+\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial I_j^t}\right)}\leq 0$$

Proof of the above comparative statics is also in Appendix 3. The sign of $\frac{\partial\tilde{I}_i^a}{\partial\Omega}$ and $\frac{\partial\,\tilde{I}_i^t}{\partial\Omega}$ depends on $\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial\Omega}$, $\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial\Omega}$. $\frac{\partial\tilde{I}_i^a}{\partial\Omega}\geq 0$ and $\frac{\partial\,\tilde{I}_i^t}{\partial\Omega}\geq 0$, as $\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial\Omega}\geq 0$ and $\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial\Omega}\geq 0$. That is, as a higher expectation of disaster occurrence probability increases the marginal expected profit of terminal operator, and marginal joint expected profit of the monopoly port authority to own adaptation, the equilibrium adaptation increases as a result. The sign of $\frac{\partial\tilde{I}_i^a}{\partial\Sigma}$, $\frac{\partial\,\tilde{I}_i^t}{\partial\Sigma}$ depends on $\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial\Sigma}$, $\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial\Sigma}$. $\frac{\partial\tilde{I}_i^a}{\partial\Sigma}\leq 0$ and $\frac{\partial\,\tilde{I}_i^t}{\partial\Sigma}\leq 0$, as $\frac{\partial^2E[\pi_i+\pi_j]}{\partial I_i^a\partial\Sigma}\leq 0$ and $\frac{\partial^2E[\Pi_i]}{\partial I_i^t\partial\Sigma}\leq 0$. That is, as larger variance of disaster occurrence probability decreases the marginal expected profit of terminal operator, and marginal expected joint profit of the monopoly port authority to own adaptation, the equilibrium port adaptation decreases as a result.

3.2.3 Adaptation of competing port authorities with intra-port coordination

In this regime, port authorities compete with each other, but they can coordinate with terminal operators at each port on adaptation decision. Pricing rule at operation stage follows that of competing port authorities i.e. $\bar{\phi}_i$ and $\bar{p}_i$. Port authority and terminal operator at the same port now jointly maximize a total expected profit at one port as $\underset{I_i^a,I_i^t}{\mathrm{Max}}\,E[\pi_i+\Pi_i];\ s.t.\,\eta(I_i^a+I_i^t)\leq D$. FOCs for this intra-port coordination problem are as follows. SOCs require $\omega\geq 0.53\frac{\eta^2}{t}\Psi$.

$$\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^a}=\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^t}=0.48\frac{\eta}{t}\,[(V+0.5t)\Omega-D\Psi]-0.048\,\frac{\eta^2}{t}\Psi\left(I_j^a+I_j^t\right)+0.53\,\frac{\eta^2}{t}\Psi\,I_i^t+(0.53\,\frac{\eta^2}{t}\Psi-\omega)I_i^a \tag{9.1}$$

The second-order derivatives show $\frac{\partial^2E[\pi_i+\Pi_i]}{\partial I_i^a\partial I_i^t}\geq 0$; $\frac{\partial^2E[\pi_i+\Pi_i]}{\partial I_i^a\partial I_j^a}\leq 0$; $\frac{\partial^2E[\pi_i+\Pi_i]}{\partial I_i^a\partial I_j^t}\leq 0$ .The adaptation investment of port authority and terminal operator at the same port is strategic complement, while adaptation investment across ports is strategic substitute. Solving the system equations of above FOCs, symmetric interior Nash equilibrium is obtained as follows.

$$\hat{I}_i^a = \hat{I}_j^a = \hat{I}_i^t = \hat{I}_j^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\,\omega t - 4\,\Psi\eta^2} \tag{9.2}$$

The non-negativity of the adaptation investment requires $\omega \geq 0.98\,\frac{\eta^2}{t}\Psi$. The interior Nash equilibrium requires $\omega \geq \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. The derivatives of $\hat{I}_i^a$ and $\hat{I}_i^t$ to Ω is as follows.

Taking total derivative of the FOCs, $\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^a} = 0$ and $\frac{\partial E[\pi_i+\Pi_i]}{\partial I_i^t}$, to Ω and Σ respectively, and imposing the symmetry assumption, $\frac{\partial \hat{I}_i^a}{\partial \Omega}$, $\frac{\partial \hat{I}_i^t}{\partial \Omega}$ and $\frac{\partial \hat{I}_i^a}{\partial \Sigma}$, $\frac{\partial \hat{I}_i^t}{\partial \Sigma}$ can be obtained as follows:

$$\frac{\partial \hat{I}_i^a}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \hat{I}_i^t}{\partial \Omega} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \leq 0$$

$$\frac{\partial \hat{I}_i^a}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \geq 0$$

$$\frac{\partial \hat{I}_i^t}{\partial \Sigma} = \frac{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma}}{\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}\right)} \leq 0$$

Proof of the above comparative statics is also in Appendix 3. The sign of $\frac{\partial \hat{I}_i^a}{\partial \Omega}$ and $\frac{\partial \hat{I}_i^t}{\partial \Omega}$ depends on $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}$. $\frac{\partial \hat{I}_i^a}{\partial \Omega} \geq 0$ and $\frac{\partial \hat{I}_i^t}{\partial \Omega} \geq 0$, as $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$. That is, as a higher expectation of disaster occurrence probability increases the marginal expected joint profit of port authority and terminal operator at one port to their own adaptation, the equilibrium adaptation thus increases. The sign of $\frac{\partial \hat{I}_i^a}{\partial \Sigma}$, $\frac{\partial \hat{I}_i^t}{\partial \Sigma}$ depends on $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma}$. $\frac{\partial \hat{I}_i^a}{\partial \Sigma} \leq 0$ and $\frac{\partial \hat{I}_i^t}{\partial \Sigma} \leq 0$, as $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} \leq 0$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$. That is, as a larger variance of disaster occurrence probability decreases the marginal expected joint profit of port authority and terminal operator to their own adaptation at one port, the equilibrium port adaptation decreases as a result.

Table 2 summarizes the interior equilibrium adaptation, SOCs, non-negativity and condition of interior equilibrium adaptation for the three regimes discussed above. The comparative statics of equilibrium adaptation to the expectation and variance of the disaster occurrence probability are as follows. Proposition 4 is obtained on the impact of Knightian uncertainty on port adaptation.

<Table 2 Here>

$$\frac{\partial \bar{I}_i^a}{\partial \,\Omega} \geq 0; \frac{\partial \tilde{I}_i^a}{\partial \Omega} \geq 0\,;\ \frac{\partial \hat{I}_i^a}{\partial \Omega} \geq 0 \text{ and } \frac{\partial \bar{I}_i^a}{\partial \Sigma} \leq 0; \frac{\partial \tilde{I}_i^a}{\partial \Sigma} \leq 0\,; \frac{\partial \hat{I}_i^a}{\partial \Sigma} \leq 0 \tag{9.3}$$

$$\frac{\partial \bar{I}_i^t}{\partial \,\Omega} \geq 0; \frac{\partial \tilde{I}_i^t}{\partial \Omega} \geq 0\,;\ \frac{\partial \hat{I}_i^t}{\partial \Omega} \geq 0 \text{ and } \frac{\partial \bar{I}_i^t}{\partial \Sigma} \leq 0; \frac{\partial \tilde{I}_i^t}{\partial \Sigma} \leq 0\,; \frac{\partial \hat{I}_i^t}{\partial \Sigma} \leq 0$$

Proposition 4: *Higher expectation of disaster occurrence probability increases adaptation, while larger variance of disaster occurrence probability reduces adaptation.*

This analytical result may provide a nice explanation for why in practice port adaptation is much more difficult to implement than "mitigation", because our present knowledge about climate change and related disasters is far from reasonable accuracy. For example, Becker et al. (2012) and Ng et al. (2016) find that most surveyed ports cite the "inadequate information" and need to know more about the issue as a major reason for slow development of adaptation. On the other hand, the relatively low probability of the climate change related disaster also discourages the port's motivation to adapt. This is exemplified by Gulfport's (Mississippi US) decision to exclusively use the post-Katrina grant (US$ 570 million) allocated by federal government to expand capacity, while canceling terminal elevation project to help protect against another Katrina like hurricane. Although not severely affected by the most recent Hurricanes Harvey and Irma in August 2017, this port has been alerted that disaster occurrence probability may not be as low as it once perceived. The increase in expectation or risk of disaster occurrence probability stimulates adaptation investment. Ng et al. (2016) survey 21 Canadian ports' adaptation and find that ports subject to higher climate change risk adapt more. Our proposition 4 is also consistent with existing economics and decision science literature. Camerer and Weber (1992) model a subjective expected utility (SEU) with Knightian uncertainty on event occurrence probability. They find people prefer to bet on events they know more about, even when their beliefs are held constant as people are averse to ambiguity about the probability. Nishimura and Ozai (2007) investigates the effect of "Knightian uncertainty" on project investment decisions. It is found that ambiguity of Knightian uncertainty decreases the value of irreversible investment while the increase in risk increases it. The ranking of adaptation is $\hat{I}_i^a \geq \bar{I}_i^a \geq \tilde{I}_i^a$, which is because:

$$\hat{I}_i^a - \bar{I}_i^a = \frac{0.079\times\eta(2V\Omega-2D\Psi+\Omega t)\left(\omega t+0.51\Psi\eta^2\right)}{(\omega t-0.97\Psi\eta^2)(\omega t-0.48\Psi\eta^2)} > 0;\ \bar{I}_i^a - \tilde{I}_i^a = \frac{0.0132\times\eta(2V\Omega-2D\Psi+\Omega t)\omega t}{(\omega t-0.48\Psi\eta^2)(\omega t-0.45\Psi\eta^2)} > 0$$

Analogously, one can show $\hat{I}_i^t \geq \bar{I}_i^t \geq \tilde{I}_i^t$.

Proposition 5: *Competing port authorities lead to higher adaptation (the "competition effect") i.e.* $\bar{I}_i^a \geq \tilde{I}_i^a$;. $\bar{I}_i^t \geq \tilde{I}_i^t$. *Intra-port coordination between port authority and terminal operator at each port also increases adaptation i.e.* $\hat{I}_i^a \geq \bar{I}_i^a$; $\hat{I}_i^t \geq \bar{I}_i^t$. *Thus, without intra-port coordination, port authority and terminal operator at the same port "free-ride" each other on adaptation by investing less adaptation (the "free-riding effect").*

Adaptation across ports is strategic substitute such that an increase in one port's adaptation imposes negative externality on the other port's expected profit. When two ports are controlled by a monopoly port authority, they coordinate to internalize such negative externality through reducing adaptation investment at two ports. Thus, inter-port competition between private terminal operators increase port adaptation investments of two ports (the "competition effect"). On the other hand, port authorities' adaptation and terminal operator's adaptation within one port is strategic complement such that an increase in adaptation by one party benefits the other. As a result, port authority and terminal operator free-ride each other with a less incentive to adapt (the "free-riding effect").

The ratio of the adaptation between competing port authorities and monopoly port authority is $\frac{\bar{I}_i^a}{\tilde{I}_i^a} = 1.088 \times \frac{(\omega t-0.445\Psi\eta^2)}{(\omega t-0.485\Psi\eta^2)}$, which measures the degree of the "competition effect". $\frac{\partial}{\partial\Omega}\left(\frac{\bar{I}_i^a}{\tilde{I}_i^a}\right) = \frac{0.085\times\Omega\eta^2\omega t}{(\omega t-0.485\Psi\eta^2)^2} > 0$; $\frac{\partial}{\partial\Sigma}\left(\frac{\bar{I}_i^a}{\tilde{I}_i^a}\right) = \frac{0.042\times\Omega\eta^2\omega t}{(\omega t-0.485\Psi\eta^2)^2} > 0$. Analogously, $\frac{\partial}{\partial\Omega}\left(\frac{\bar{I}_i^t}{\tilde{I}_i^t}\right) > 0$, $\frac{\partial}{\partial\Sigma}\left(\frac{\bar{I}_i^t}{\tilde{I}_i^t}\right) > 0$. The ratio of the adaptation between intra-port coordination and no coordination for competing port authorities is $\frac{\hat{I}_i^a}{\bar{I}_i^a} = 1.485 \times \frac{(\omega t-0.485\Psi\eta^2)}{(\omega t-0.970\Psi\eta^2)}$, which measures the degree of the "free-riding effect". $\frac{\partial}{\partial\Omega}\left(\frac{\hat{I}_i^a}{\bar{I}_i^a}\right) = \frac{1.441\times\Omega\eta^2\omega t}{(\omega t-0.970\Psi\eta^2)^2} > 0$; $\frac{\partial}{\partial\Sigma}\left(\frac{\hat{I}_i^a}{\bar{I}_i^a}\right) = \frac{0.720\times\Omega\eta^2\omega t}{(\omega t-0.970\Psi\eta^2)^2} > 0$. Analogously, it can be proved that $\frac{\partial}{\partial\Omega}\left(\frac{\hat{I}_i^t}{\bar{I}_i^t}\right) > 0$; $\frac{\partial}{\partial\Sigma}\left(\frac{\hat{I}_i^t}{\bar{I}_i^t}\right) > 0$.

Proposition 6: *Higher expectation and larger variance of disaster occurrence strengthen both the "competition effect" and the "free-riding effect.*

Proposition 6 suggests that a higher expectation and larger variance of disaster occurrence probability enhance the "competition effect" and the "free-riding" effect. For the "competition effect", when two port authorities compete on adaptation, if the expectation of disaster occurrence probability increases, they have a stronger incentive to adapt compared to the monopoly port authority, strengthening the "competition effect". When the variance of disaster occurrence probability increases, as suggested by proposition 4, two ports reduce adaptation investment. However, when port authorities compete, they reduce adaptation less compared to that of monopoly port authority. As a result, an increased variance of disaster occurrence probability also enlarges difference in adaptation for competing port authorities and monopoly port authority, enhancing the "competition effect". For the "free-riding effect", when the expectation of disaster occurrence probability increases, the marginal expected profit of adaptation investment is larger, such that one party (port authority or terminal operator) benefits more from the other party's adaptation, thus enhancing the "free-riding" incentive. When the variance of disaster occurrence probability increases, each party reduces adaptation. Without coordination, such reduction is more significant, thus also enlarging the difference with and without intra-port coordination. This strengthens the "free-riding effect".

Last, we investigate the implications of inter-port competition and intra-port cooperation on the expected social welfare of the two-port system. $E[\overline{SW}]$ is the expected social welfare with competing port authorities; $E[\widetilde{SW}]$ is the expected social welfare with monopoly port authority; $E[\widehat{SW}]$ is the expected social welfare with competing port authorities and with intra-port coordination. The expression of $E[\widehat{SW}] - E[\overline{SW}]$ is as below.

$$E[\widehat{SW}] - E[\overline{SW}] = \frac{0.048\omega(t^2\omega^2 - 0.962\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2)\eta^2(2\Omega V - 2D\Psi + \Omega t)^2}{(\omega t - 0.485\Psi\eta^2)^2(\omega t - 0.970\Psi\eta^2)^2} > 0$$

The sign of $E[\widehat{SW}] - E[\overline{SW}]$ is determined by the term $t^2\omega^2 - 0.962\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2$ in the numerator, which is a convex quadratic function of ω. The two solutions of $t^2\omega^2 - 0.962\Psi\eta^2 t\omega + 0.068\Psi^2\eta^2 = 0$ are $0.096\,\frac{\eta^2}{t}\Psi$ and $0.86\,\frac{\eta^2}{t}\Psi$. The non-negativity condition for $\hat{I}_i^a$ and $\hat{I}_i^t$ suggests $\omega \geq 0.98\,\frac{\eta^2}{t}\Psi$. Thus $E[\widehat{SW}] - E[\overline{SW}] > 0$. The expression of $E[\overline{SW}] - E[\widetilde{SW}]$ is as below, which is apparently positive.

$$E[\overline{SW}] - E[\widetilde{SW}] = \frac{0.0056\times\omega^2\eta^2 t(2\Omega V-2D\Psi+\Omega t)^2(\omega t-0.466\Psi\eta^2)}{(\omega t-0.445\Psi\eta^2)^2(\omega t-0.485\Psi\eta^2)^2} > 0$$

Thus, the ranking of expected social welfare is $E[\widehat{SW}] > E[\overline{SW}] > E[\widetilde{SW}]$.

Proposition 7: *The expected social welfare increases with the port adaptation. Intra-port coordination between port authorities and terminal operators results in the highest expected social welfare by overcoming the "free-riding effect". Monopoly port authority, on the contrary, leads to the smallest expected social welfare with the lowest level of port adaptation.*

Proposition 7 may have several policy implications. First, from the social welfare perspective, with uncertain natural disaster threat, it is better to have the ports controlled by different port authorities. Inter-port competition between port authorities results in more adaptation, and higher expected total social welfare. Regulators thus may need to avoid granting monopoly power of a single port authority in a multiple-port region. Second, intra-port coordination on adaptation between port authority and terminal operator should be encouraged to address the "free-riding effect" on adaptation. Unlike anti-trust concern on pricing collision, regulators should allow and even facilitate intra-port coordination between port authority and terminal operator to jointly plan port adaptation. When the revenue-sharing mechanism can be figured out between port authority and terminal operator, they have incentive to coordinate adaptation as the total expected profit is maximized. The experience of the port of San Diego can be learnt by more ports to better develop framework and mechanism to involve terminal operators to discuss, plan and implement port adaptation.

4. Effects of Port Competition Intensity

In practice, ports can provide differentiated services. Ports providing more homogenous services compete more fiercely (Wang et al., 2012). For example, the largest port in Europe, port of Rotterdam, focuses on container cargo, while the other port in the same region, the port of Antwerp, mainly handles bulk cargo. Port service heterogeneity can reduce inter-port competition intensity and thus should also affect the port adaptation investment. In this section, we explicitly model such inter-port competition intensity by allowing shipper in the common hinterland of the two ports to have a different transport cost parameter compared to each port's captive catchment area. Specifically, we let the shipper in the common hinterland to have a different transport cost t' compared to the transport cost t for shippers in two ports' own captive catchment. The parameter t' thus helps capture port service heterogeneity in the common hinterland market. A smaller t' suggests a higher port service homogeneity, equivalent to a more intense inter-port competition. With new parameter t', the pricing rule at operation stage and optimal adaptation investment at the adaptation investment stage can be solved. The new equilibrium adaptation with competing port authorities are obtained as follows:

$$\bar{I}_i^a(t') = \bar{I}_j^a(t') = \frac{\eta(4t'+t)(4t'+3t)(2t'+t)(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4)[(2V+t)\,\Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2(16t'^2+18t't+3t^2)(16t'^2+14t't+t^2)^2\omega t-8(6t'^2+6t't+t^2)(8t'^2+8t't+t^2)(2t'+t)(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4)\Psi\eta^2}$$

$$\bar{I}_i^t(t') = \bar{I}_j^t(t') = \frac{\eta(2t'+t)(8t'^2+8t't+t^2)^2(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4)[(2V+t)\,\Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2(16t'^2+18t't+3t^2)(16t'^2+14t't+t^2)^2\omega t-8(6t'^2+6t't+t^2)(8t'^2+8t't+t^2)(2t'+t)(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4)\Psi\eta^2}$$

The equilibrium adaptation with monopoly port authority is obtained as follows:

$$\tilde{I}_i^a(t') = \tilde{I}_j^a(t') = \frac{0.25\eta(4t'+3t)(2t'+t)(4t'+t)[(2V+t)\,\Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2\omega t-(6t'^2+6t't+t^2)(2t'+t)\Psi\eta^2}$$

$$\tilde{I}_i^t(t') = \tilde{I}_j^t(t') = \frac{0.25\eta(2t'+t)(8t'^2+8t't+t^2)[(2V+t)\,\Omega-2D\Psi]}{(4t'+3t)(4t'+t)^2\omega t-(6t'^2+6t't+t^2)(2t'+t)\Psi\eta^2}$$

The "competition effect" is reflected by ratio $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$. The comparative statics $\frac{\partial}{\partial t'}\left(\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}\right)$ and $\frac{\partial}{\partial t'}\left(\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}\right)$ shed light on the impact of inter-port competition intensity (port service homogeneity) on the "competition effect" of port adaptation. However, $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ is a high order polynomial of t', such that the analytical result on comparative statics $\frac{\partial}{\partial t'}\left(\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}\right)$ and $\frac{\partial}{\partial t'}\left(\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}\right)$ is difficult to reach. Numerical simulation is conducted with the parameter values: $\Psi = 0.1$, $\eta = 2$, $\omega = 25$, $t = 0.1$. Figure 4 shows the numerical values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ with changes in t'. When t' increases, the values of ratios $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ decrease. That is, when two ports are more competitive, or port services are more homogenous, the "competition effect" on port adaptation is strengthened. Robustness check is also done trying different parameter values, and the conclusions are not changed qualitatively.

< Figure 4 Here>

In addition, the equilibrium adaptation with competing port authorities but allowing intra-port coordination can be obtained.

$$\hat{I}_i^{a}(t') = \hat{I}_j^{a}(t') = \hat{I}_i^{t}(t') = \hat{I}_j^{t}(t')$$
$$= \frac{\left[\begin{array}{c} 4\eta(2t'+t)\left(6t'^2+6t't+3t^2\right)\left(8t'^2+8t't+3t^2\right)\left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right) \\ \left[(2V+t)\,\Omega-2D\Psi\right] \end{array}\right]}{\left[\begin{array}{c} (4t'+3t)(4t'+t)^2\left(16t'^2+18t't+3t^2\right)\left(16t'^2+14t't+t^2\right)^2\omega t - \\ 16\left(6t'^2+6t't+t^2\right)\left(8t'^2+8t't+t^2\right)(2t'+t) \\ \left(128t'^4+256t'^3t+156t'^tt^2+28t't^3+t^4\right)\Psi\eta^2 \end{array}\right]}$$

The "free-riding effect" is reflected by the ratio $\frac{\hat{I}_i^{a}(t')}{\bar{I}_i^{a}(t')}$ and $\frac{\hat{I}_i^{t}(t')}{\bar{I}_i^{t}(t')}$. The inter-port competition intensity (port service homogeneity) might also affect incentive of the port authority and terminal operator to free-ride each other on adaptation at one port. Numerical simulation demonstrates the relation between values of $\frac{\hat{I}_i^{a}(t')}{\bar{I}_i^{a}(t')}$, $\frac{\hat{I}_i^{t}(t')}{\bar{I}_i^{t}(t')}$ and the parameter t' (as Figure 5). It is noted when t' increases, the values of ratios $\frac{\hat{I}_i^{a}(t')}{\bar{I}_i^{a}(t')}$, $\frac{\hat{I}_i^{t}(t')}{\bar{I}_i^{t}(t')}$ decrease as well. This suggests that more intense inter-port competition (more service homogeneity) can strengthen the "free-riding effect" on adaptation between port authority and terminal operator at the same port. This finding could make sense as when two ports compete more fiercely in the common hinterland market, one port's adaptation contributes more to gain advantage in this competing market. Therefore, within one port, port authority and terminal operator have stronger incentive to free-ride each other on adaptation. We summarize the effect of inter-port competition intensity (port service homogeneity) on the "competition effect" and "free-riding effect" on adaptation as proposition 8.

<Figure 5 Here>

Proposition 8: *The more intense inter-port competition (service homogeneity) strengthens both the "competition effect" on adaptation between two ports, and the "free-riding effect" on adaptation between port authority and terminal operator within one port.*

5. Concluding Remarks

With 80% of the global trade carried by international shipping, coastal ports resilience to climate change related disaster is important to maintain reliable global supply chain. Ports around the world are increasingly aware of adaptation to threat of such disasters. This study contributes to existing literature in port adaptation on several aspects. First, we model the climate-change related disaster to have a general-form Knightian uncertainty (Knight 1921) in the sense that the probability of the disaster occurrence is per se a random variable and not accurately knowable. Our Knightian uncertainty captures a more general and wider family of probability distribution, not limited to the specific assumptions in Weitzman (2009) and Xiao et al. (2015). The other strand of contributions is to explicitly examine the impacts of inter-port competition and cooperation, intra-port cooperation on port adaptation investment. We explicitly model endogenous port pricing cooperation, intra-port cooperation can increase or decrease the adaptations; and whether public ports invest more in adaptions and can always result in higher social welfare.

We find, with Knightian uncertainty assumption, the port adaptation investments increase with the expectation of the disaster occurrence probability but decrease with its variance. In other words, a higher expectation of the disaster occurrence probability encourages the adaptation, but the variance of the disaster occurrence probability at the adaptation investment stage can discourage the adaptations. Inter-port competition results in more adaptation investments (i.e. the "competition effect"). There is free-riding between the port authority and the terminal operator (i.e. the "free-riding effect") within each port. Their coordination can increase the adaptations by removing the "free-riding effect". The expected social welfare of the two-port region increases with ports' adaptation, such that inter-port competition and cooperation. and intra-port coordination lead to higher expected social welfare. We also find that the "competition" and "free-riding" effects on port adaptation can be strengthened by a higher expectation and larger variance of disaster occurrence probability, and by increasing inter-port competition intensity (port service homogeneity).

This study also opens new avenue for future research. First, the market structure of private terminal operators needs better exploration. We assume each port has a single terminal operator, which can be restrictive. One port can have more than one terminal operator, either private or owned by port authority. Some shipping lines also operate dedicated terminals in the port. In addition, multinational terminal operators such as PSA International, Hutchison Port Holding, APM terminals, DP World and China Merchant Holding can operate in nearby ports. Such intra- and inter-port competition and cooperation among the private terminal operators should also have implications on port adaptation investment. Second, the public ownership of port authority and its implication on port adaptation can be investigated. Although we explained in the model setup section that more port authorities nowadays have been corporatized and been self-responsible for the financial performance, port authority can still bear some social responsibility to account for social welfare. It is conjectured that public port authority could invest more adaptation, especially when port adaptation can have positive externality to protect nearby neighbourhood community and contribute to more resilient local economy beyond shippers' economic benefits. In addition, public ownership of port authority may reduce the "free-riding effect" between port authority and terminal operator within one port. This is because, a public port authority would also account for terminal operator's profit as part of the social welfare. Last, our study exclusively focuses on port adaptation decision, while port can have multi-dimensional long-term decisions, such as capacity expansion, facilities upgrading etc. With a limited resource, port thus needs to trade off among adaptation, capacity expansion and other development. A more comprehensive economic model is therefore called to model port optimal resource allocation.

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Table 1. Notational glossary

Parameter	Definition
V	Utility to shipper of using the port service
D	Level of disaster damage to the shipper; we assume $D < V$
η	Effectiveness of adaptation investment to reduce damage
I_i^a	Adaptation investment made by port authority
I_i^t	Adaptation investment made by terminal operator
x	Random variable denoting probability that a disaster occurs
Ω	The expectation of x at adaptation investment stage
Σ	The variance of x at adaptation investment stage
Ψ	The second moment of x, which is equal to $\Omega^2 + \Sigma$
p_i	The service fee charged by terminal operator to shippers
ϕ_i	The fee charged by port authority to terminal operator
Q_i	The demand for service at port i at the operation stage
Π_i	Profit of terminal operator in port i at operation stage
π_i	Profit of port authority in port i at operation stage

Table 2. The summary of the Nash equilibrium of different inter-port competition and intra-port coordination regimes

Regimes	**Port authority adaptation**	**Terminal operator adaptation**	**SOCs and Non-negativity**	**Interior solution requirement**
Competing Port Authorities	$\bar{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{6.1\omega t - 3\Psi\eta^2}$	$\bar{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{2.1\,(6.1\,\omega t - 3\,\Psi\eta^2)}$	$\omega > 0.49\,\frac{\eta^2}{t}\Psi$	$\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$
Monopoly Port Authority	$\tilde{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{6.7\omega t - 3\,\Psi\eta^2}$	$\tilde{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{13.7\,\omega t - 6.1\,\Psi\eta^2}$	$\omega > 0.45\,\frac{\eta^2}{t}\Psi$	$\omega \geq \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$
Competing Port Authorities with Intra-port Coordination	$\hat{I}_i^a = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\omega t - 4\,\Psi\eta^2}$	$\hat{I}_i^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\omega t - 4\,\Psi\eta^2}$	$\omega > 0.98\,\frac{\eta^2}{t}\Psi$	$\omega \geq \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$

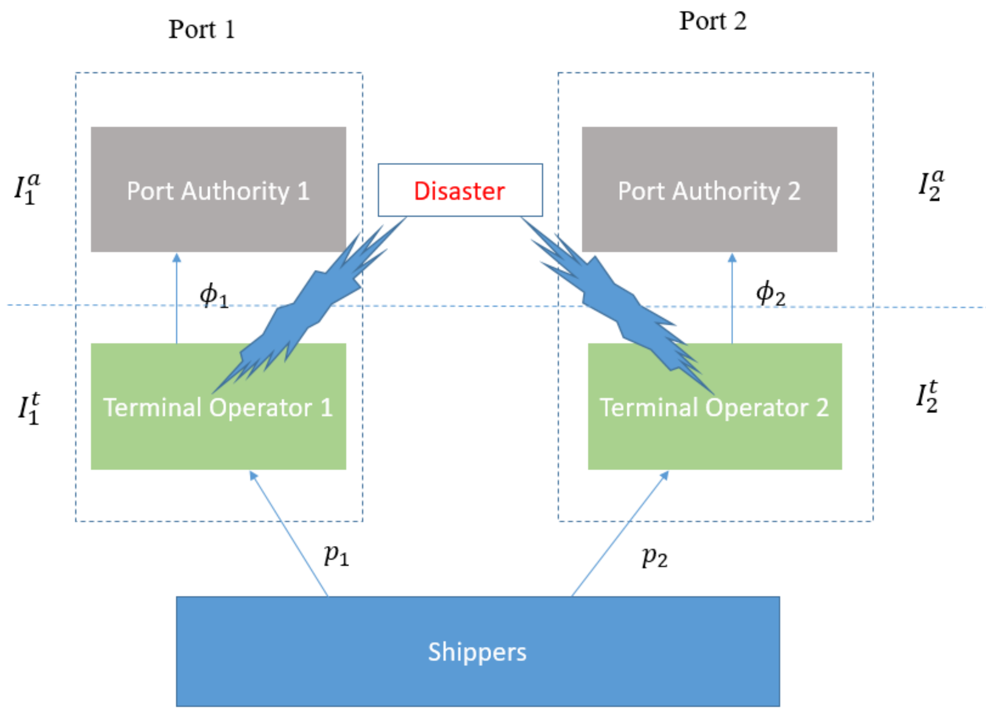

Figure 1. The market structure of the two-port system

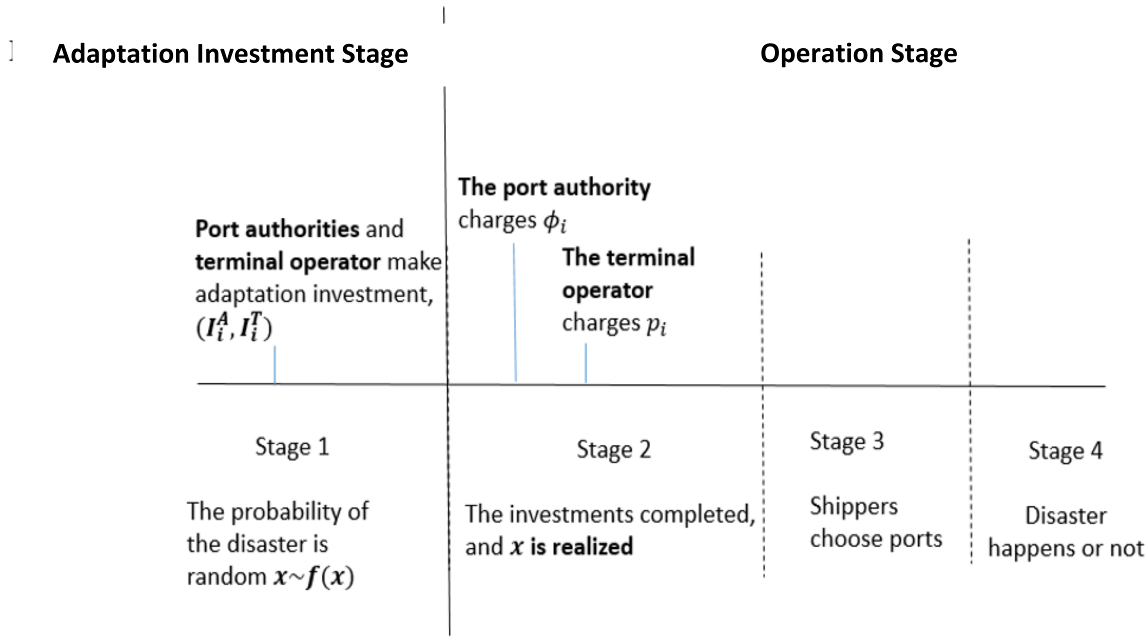

Figure 2. The timeline of the decisions of different parties

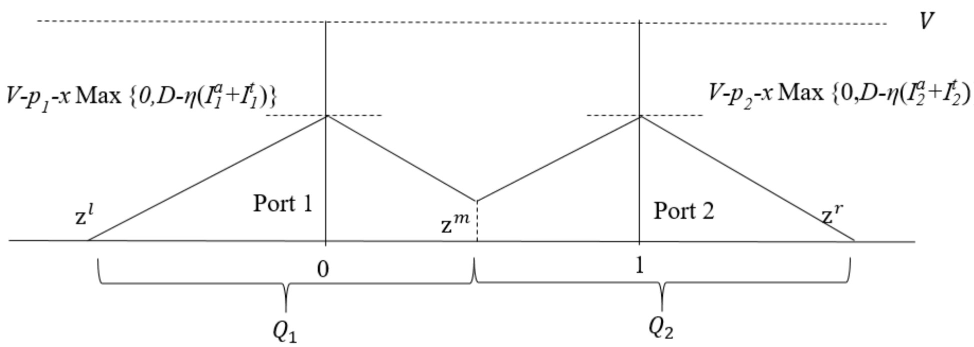

Figure 3. Shipper's utility at each port after completion of adaptation investments

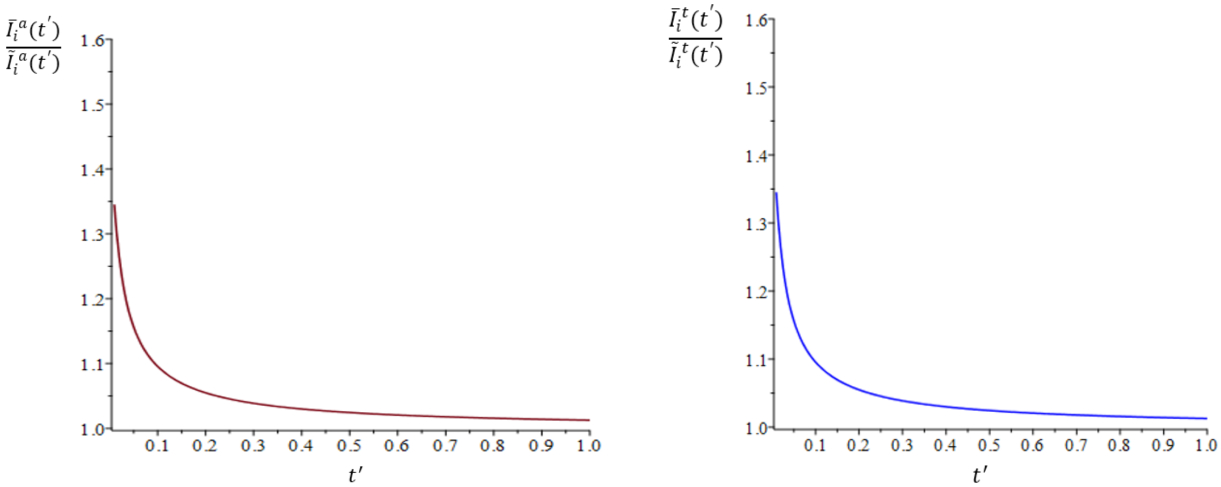

Figure 4. Numerical values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ with changing t' ($\Psi = 0.1, \eta = 2, \omega = 25, t = 0.1$)

Note: Larger values of $\frac{\bar{I}_i^a(t')}{\tilde{I}_i^a(t')}$ and $\frac{\bar{I}_i^t(t')}{\tilde{I}_i^t(t')}$ suggest a stronger "competition effect" on port adaptation.

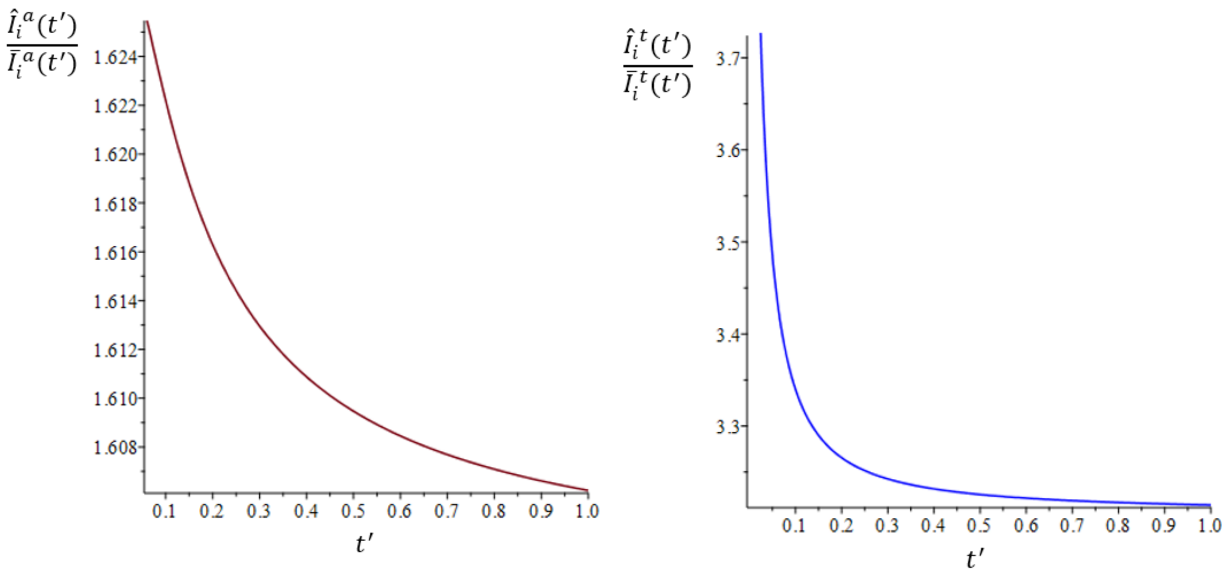

Figure 5. Numerical values of $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$ and $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ with changing t' ($\Psi = 0.1, \eta = 2, \omega = 25, t = 0.1$)

Note: Larger values of $\frac{\hat{I}_i^a(t')}{\bar{I}_i^a(t')}$ and $\frac{\hat{I}_i^t(t')}{\bar{I}_i^t(t')}$ suggest a stronger "free-riding effect" on port adaptation.

Appendix 1

For the competing port authorities, the FOCs satisfy $\frac{\partial \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i}=0$. For the monopoly port authority, the FOCs satisfy $\underbrace{\frac{\partial \pi_i(\tilde{\phi}_i,\tilde{\phi}_j)}{\partial \phi_i}}_{<0}+\underbrace{\frac{\partial \pi_j(\tilde{\phi}_i,\tilde{\phi}_j)}{\partial \phi_i}}_{>0}=0$. For monopoly port authority, when it sets concession fee at one port, it internalizes the positive externality on the other port i.e. $\underbrace{\frac{\partial \pi_j(\tilde{\phi}_i,\tilde{\phi}_j)}{\partial \phi_i}}_{>0}$ and $\underbrace{\frac{\partial \pi_i(\tilde{\phi}_i,\tilde{\phi}_j)}{\partial \phi_j}}_{>0}$. The second-order derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i\,\partial \phi_j}>0$, as concession fee at ports is strategic complement. The second-order derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial {\phi_i}^2}<0$ as required by SOC. Because of the symmetry, we have $\tilde{\phi}_i=\tilde{\phi}_j$ and $\bar{\phi}_i=\bar{\phi}_j$. In magnitudes it is true that $\left|\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial {\phi_i}^2}\right|>|\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i\,\partial \phi_j}|$. In other words, the second-order derivative $\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial {\phi_i}^2}$ is the main effect. Because $\frac{\partial \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i}=0$ and $\frac{\partial \pi_i(\tilde{\phi}_i,\tilde{\phi}_j)}{\partial \phi_i}<0$, then $\tilde{\phi}_i=\tilde{\phi}_i>\bar{\phi}_i=\bar{\phi}_j$. Terminal operators' charge $p_i(\phi_i,\phi_j)$ and $p_j(\phi_i,\phi_j)$ are increasing function of ϕ_i and ϕ_j, such that $\tilde{p}_i(\tilde{\phi}_i,\tilde{\phi}_i)>\tilde{p}_i(\bar{\phi}_i,\bar{\phi}_j)$ and $\tilde{p}_j(\tilde{\phi}_i,\tilde{\phi}_i)>\tilde{p}_j(\bar{\phi}_i,\bar{\phi}_j)$ .Taking total derivatives of FOCs of competing port authorities with respect to I_i^a

$$\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i\,\partial I_i^a}+\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial {\phi_i}^2}\frac{\partial \bar{\phi}_i}{\partial I_i^a}+\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i\,\partial \phi_j}\frac{\partial \bar{\phi}_j}{\partial I_i^a}=0$$

$$\frac{\partial^2 \pi_j(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_j\,\partial I_i^a}+\frac{\partial^2 \pi_i(\bar{\phi}_i,\bar{\phi}_j)}{\partial \phi_i\,\partial \phi_j}\frac{\partial \bar{\phi}_i}{\partial I_i^a}+\frac{\partial^2 \pi_j(\bar{\phi}_i,\bar{\phi}_j)}{\partial {\phi_j}^2}\frac{\partial \bar{\phi}_j}{\partial I_i^a}=0$$

Solving $\frac{\partial \bar{\phi}_i}{\partial I_i^a}$ as follows,

$$\frac{\partial \bar{\phi}_i}{\partial I_i^a}=\frac{-(\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial I_i^a})+\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_j\,\partial I_i^a}}{\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}-\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}\frac{\partial^2 \pi_j}{\partial \phi_i\,\partial \phi_j}}>0$$

The denominator $\underbrace{\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}}_{<0}\underbrace{\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}}_{<0}-\underbrace{\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}}_{>0}\underbrace{\frac{\partial^2 \pi_j}{\partial \phi_i\,\partial \phi_j}}_{>0}$ is positive, as $\left|\frac{\partial^2 \pi_i}{\partial {\phi_i}^2}\right|>|\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}|$ and $|\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}|>|\frac{\partial^2 \pi_j}{\partial \phi_i\,\partial \phi_j}|$. The numerator $-(\underbrace{\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}}_{<0}\underbrace{\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial I_i^a}}_{>0})+\underbrace{\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}}_{>0}\underbrace{\frac{\partial^2 \pi_j}{\partial \phi_j\,\partial I_i^a}}_{<0}$ is also positive, as $\left|\frac{\partial^2 \pi_j}{\partial {\phi_j}^2}\right|>|\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial \phi_j}|$ and $|\frac{\partial^2 \pi_i}{\partial \phi_i\,\partial I_i^a}>\frac{\partial^2 \pi_j}{\partial \phi_j\,\partial I_i^a}|$.

$$\frac{\partial\bar{\phi}_j}{\partial I_i^a}=\frac{\frac{\partial^2\pi_j}{\partial\phi_i\partial\phi_j}\frac{\partial^2\pi_i}{\partial\phi_i\partial I_i^a}-\frac{\partial^2\pi_i}{\partial{\phi_i}^2}\frac{\partial^2\pi_j}{\partial\phi_j\partial I_i^a}}{\frac{\partial^2\pi_i}{\partial{\phi_i}^2}\frac{\partial^2\pi_j}{\partial{\phi_j}^2}-\frac{\partial^2\pi_i}{\partial\phi_i\partial\phi_j}\frac{\partial^2\pi_j}{\partial\phi_i\partial\phi_j}}$$

The denominator of $\frac{\partial\bar{\phi}_j}{\partial I_i^a}$ is the same as $\frac{\partial\bar{\phi}_i}{\partial I_i^a}$, which is positive. Numerator $\underbrace{\frac{\partial^2\pi_j}{\partial\phi_i\partial\phi_j}}_{>0}\underbrace{\frac{\partial^2\pi_i}{\partial\phi_i\partial I_i^a}}_{>0}-\underbrace{\frac{\partial^2\pi_i}{\partial{\phi_i}^2}}_{<0}\underbrace{\frac{\partial^2\pi_j}{\partial\phi_j\partial I_i^a}}_{<0}$ has uncertain sign, which depends on the relative magnitude of $\frac{\partial^2\pi_j}{\partial\phi_i\partial\phi_j}\frac{\partial^2\pi_i}{\partial\phi_i\partial I_i^a}$ and $\frac{\partial^2\pi_i}{\partial{\phi_i}^2}\frac{\partial^2\pi_j}{\partial\phi_j\partial I_i^a}$. As shown in following Figure A1, when I_i^a increases, the best response function $\phi_j(\phi_i)$ moves outward, and the best response function $\phi_i(\phi_j)$ also moves outward. If $\phi_i(\phi_j)$ does not move too much with I_i^a, the new equilibrium concession fees increase for both ϕ_i and ϕ_j. If $\phi_i(\phi_j)$ moves more with I_i^a, the new equilibrium concession fee ϕ_i will still increase, but concession fee ϕ_j decrease. If we impose the functional form of our model setup, we can derive $\frac{\partial\bar{\phi}_j}{\partial I_i^a}<0$.

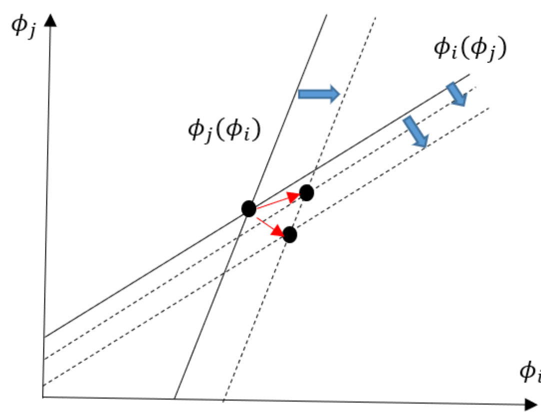

Figure A1. The impact of increased port authority adaptation I_i^a on the best response functions of competing port authorities' concession fee at operation stage

Analogously, we can prove $\frac{\partial\bar{\phi}_i}{\partial I_i^t}>0$ and the sign $\frac{\partial\bar{\phi}_j}{\partial I_i^t}$ depends on the relative magnitude of $\frac{\partial^2\pi_j}{\partial\phi_i\partial\phi_j}\frac{\partial^2\pi_i}{\partial\phi_i\partial I_i^t}$ and $\frac{\partial^2\pi_i}{\partial{\phi_i}^2}\frac{\partial^2\pi_j}{\partial\phi_j\partial I_i^t}$. With our functional form setup, $\frac{\partial\bar{\phi}_j}{\partial I_i^t}<0$. Taking total derivatives of FOCs of monopoly port authority with respect to I_i^a,

$$\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial\phi_i\,\partial I_i^a}+\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial{\phi_i}^2}\frac{\partial\tilde{\phi}_i}{\partial I_i^a}+\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial\phi_i\,\partial\phi_j}\frac{\partial\tilde{\phi}_j}{\partial I_i^a}=0$$

$$\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial\phi_j\,\partial I_i^a}+\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial\phi_i\,\partial\phi_j}\frac{\partial\tilde{\phi}_i}{\partial I_i^a}+\frac{\partial^2(\pi_i(\tilde{\phi}_i,\tilde{\phi}_j)+\pi_j(\tilde{\phi}_i,\tilde{\phi}_j))}{\partial{\phi_j}^2}\frac{\partial\tilde{\phi}_j}{\partial I_i^a}=0$$

Solving for $\frac{\partial\tilde{\phi}_i}{\partial I_i^a}$,

$$\frac{\partial\tilde{\phi}_i}{\partial I_i^a}=\frac{-\left(\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\,\partial I_i^a}}^{<0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j}}^{>0}\right)+\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial I_i^a}}^{>0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}}^{<0}}{\underbrace{(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j})^2-(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2})(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2})}_{<0}}>0$$

The denominator $(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j})^2-\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}\right)\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}\right)<0$, as suggested by the Hessian condition for monopoly port authority to maximize profit. For the numerator, $\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}\right|>\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j}\right|$, and $\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial I_i^a}\right|>\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\,\partial I_i^a}\right|$, such that the numerator is positive as well. Solving for $\frac{\partial\tilde{\phi}_i}{\partial I_j^a}$,

$$\frac{\partial\tilde{\phi}_i}{\partial I_j^a}=\frac{\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\,\partial I_i^a}}^{<0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}}^{<0}-\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j}}^{>0}\overbrace{\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial I_i^a}}^{>0}}{\underbrace{(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j})^2-(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2})(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2})}_{<0}}$$

The denominator $(\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j})^2-\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}\right)\left(\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_j}^2}\right)<0$ .For numerator, $\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\,\partial I_i^a}\right|<\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial I_i^a}\right|$ and $\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}\right|<\left|\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j}\right|$, thus the sign of the numerator is uncertain. We thus have to depend on our functional setup to determine the sign of $\frac{\partial\tilde{\phi}_i}{\partial I_j^a}$, with the result as $\frac{\partial\tilde{\phi}_i}{\partial I_j^a}=0$.

Analogously, it can be shown that $\frac{\partial\tilde{\phi}_i}{\partial I_i^t}>0$ and the sign of $\frac{\partial\tilde{\phi}_j}{\partial I_i^t}$ depends on the relative magnitude of $\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_j\,\partial I_i^a}\ \frac{\partial^2(\pi_i+\pi_j)}{\partial{\phi_i}^2}$ and $\frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial\phi_j}\ \frac{\partial^2(\pi_i+\pi_j)}{\partial\phi_i\,\partial I_i^a}$.

The charge by terminal operators, the signs of derivatives of $\tilde{p}_i(\bar{\phi}_i, \bar{\phi}_j, I)$; $\tilde{p}_j(\bar{\phi}_i, \bar{\phi}_j, I)$ and $\tilde{p}_i(\tilde{\phi}_i, \tilde{\phi}_i, I)$; $\tilde{p}_j(\tilde{\phi}_i, \tilde{\phi}_i, I)$ to I_i^a and I_i^t can only be judged with functional setup.

Appendix 2

With competing port authorities, for port authority i, the best response function of its own adaptation investment I_i^a to I_i^t conditional on the other ports' investment I_j^a and I_j^t is as,

$$I_i^a | I_j^a, I_j^t = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] - 0.032\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi} + \frac{0.36\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi} I_i^t = A + BI_i^t$$

where $A = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] - 0.032\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi}$ and $B = \frac{0.36\ t\eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}$.

For terminal operator i, the best response function of its own adaptation investment in response to I_i^a is as,

$$I_i^t | I_j^a, I_j^t = \frac{0.16\eta\ [(V+0.5t)\Omega - D\Psi] - 0.015\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.17\eta^2\Psi} + \frac{0.17\ \eta^2\Psi}{\omega t - 0.17\ \eta^2\Psi} I_i^a = C + FI_i^a \quad (3)$$

where $C = \frac{0.16\eta\ [(V+0.5t)\Omega - D\Psi] - 0.015\ \eta^2\Psi\left(I_j^a + I_j^t\right)}{\omega t - 0.17\eta^2\Psi}$ and $F = \frac{0.17\ \eta^2\Psi}{\omega t - 0.17\ \eta^2\Psi}$.

B and F are positive as the SOCs suggest $\omega > 0.36\ \frac{\eta^2}{t}\Psi$. The two best response functions are positively sloped, suggesting that the port adaptation investments at the same ports are strategic complements. The plots of best response functions are as follows.

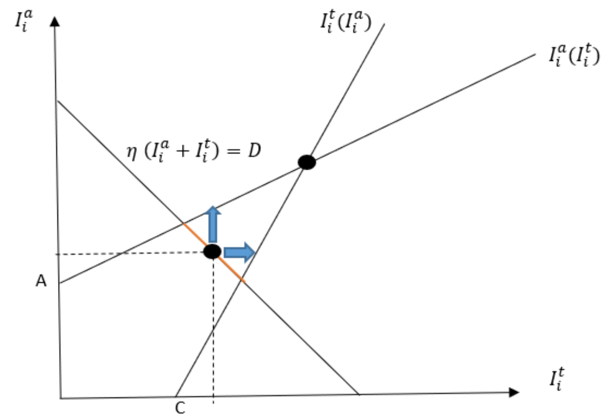

Figure A2. The best response adaptation investment functions for port authority and terminal operators at the same port

As shown in above figure, if $\omega < \frac{0.48\ \Omega(V+0.5t)\eta^2}{Dt}$, the constraint $\eta\ (I_i^a + I_i^t) = D$ indicated by the orange line cuts two best response lines inside of the interior Nash equilibrium. Any point on the orange line is a Nash equilibrium, as port authority i and terminal operator i have the incentive to increase adaptation investment but already the constraint $\eta\ (I_i^a + I_i^t) = D$. Each party does not have incentive to deviate from its adaptation investment on the constraint. Thus, there are infinite Nash equilibria if the constraint $\eta\ (I_i^a + I_i^t) \leq D$ is binding.

For the port authority i, the best response function to the adaptation investment of the other port authority I_j^a, conditional on two ports' terminal operators' adaptation investments is as

$$I_i^a | I_i^t, I_j^t = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi\left(11I_i^a - I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi} - \frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi} I_j^a = G + HI_j^a$$

Where $G = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi\left(11I_i^a - I_j^t\right)}{\omega t - 0.36\ \eta^2\Psi}$ and $H = -\frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi}$.

For the port authority j, the best response function to the adaptation investment of that of port authority i is as,

$$I_j^a | I_i^t, I_j^t = \frac{0.33\eta\ [(V+0.5t)\Omega - D\Psi] + 0.032\ \eta^2\Psi\left(11I_j^a - I_i^t\right)}{\omega t - 0.36\ \eta^2\Psi} - \frac{0.032\ \eta^2\Psi}{\omega t - 0.36\ \eta^2\Psi} I_i^a = J + KI_j^a$$

where $J = \frac{0.33\eta\,[(V+0.5t)\Omega - D\Psi] + 0.032\,\eta^2\Psi\left(11 I_j^a - I_i^t\right)}{\omega t - 0.36\,\eta^2\Psi}$ and $K = -\frac{0.032\,\eta^2\Psi}{\omega t - 0.36\,\eta^2\Psi}$.

H and K are negative as SOCs suggest $\omega > 0.36\,\frac{\eta^2}{t}\Psi$. The two best response functions are negatively sloped, suggesting that the port authorities' adaptation investments at two different ports are strategic substitutes. In addition, the non-negativity condition indicates that $\omega > 0.49\,\frac{\eta^2}{t}\Psi$. Therefore $|H| < 1$ and $|K| < 1$.

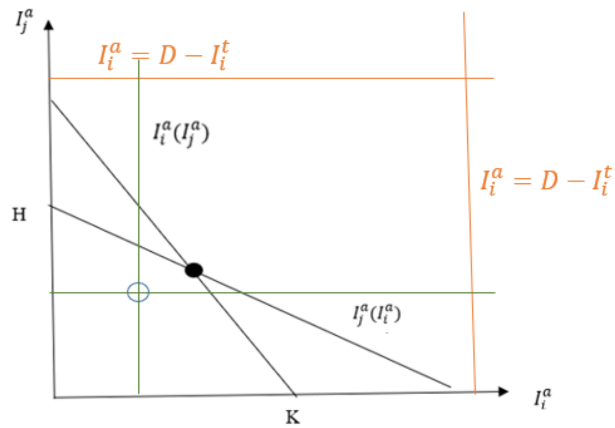

Figure A3. The best response adaptation investment functions for port authorities at two ports

Appendix 3

Taking $\frac{\partial \bar{I}_i^a}{\partial \Omega}$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma}$ as example for the proof of $\frac{\partial \bar{I}_i^a}{\partial \Omega} \geq 0$, $\frac{\partial \bar{I}_i^t}{\partial \Omega} \geq 0$ and $\frac{\partial \bar{I}_i^a}{\partial \Sigma} \leq 0$, $\frac{\partial \bar{I}_i^t}{\partial \Sigma} \leq 0$.

$$\frac{\partial \bar{I}_i^a}{\partial \Omega} = \frac{\overbrace{\left(\overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}}^{\geq 0}+\overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}}^{\leq 0}\right)}^{\geq 0}\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}^{\geq 0} - \overbrace{\left(\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}}^{\leq 0}+\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}^{\leq 0}\right)}^{\leq 0}\overbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}}^{\geq 0}}{\underbrace{\underbrace{\left(\underbrace{\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2}}_{\leq 0}+\underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}}_{\leq 0}\right)}_{\leq 0}\underbrace{\left(\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}}_{\leq 0}+\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}_{\leq 0}\right)}_{\leq 0} - \underbrace{\left(\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}}_{\leq 0}+\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}}_{\geq 0}\right)}_{\geq 0}\underbrace{\left(\underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}}_{\geq 0}+\underbrace{\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}}_{\leq 0}\right)}_{\geq 0}}_{\geq 0}} \geq 0$$

For the denominator $\left(\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right)\left(\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right) - \left(\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} + \frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right)\left(\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} + \frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right)$, the second-order derivatives suggest $\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2} \leq 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a} \leq 0$, $\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2} \leq 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t} \leq 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a} \leq 0$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a} \geq 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t} \geq 0$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t} \leq 0$. $\left|\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^a}\right| = \left|\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_j^t}\right|$ and $\left|\frac{\partial^2 E[\pi_i]}{\partial {I_i^a}^2}\right| \geq \left|\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial I_i^t}\right|$, $\left|\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}\right| \geq \left|\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right|$ and $\left|\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}\right| = \left|\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}\right|$. Thus, it is concluded that the denominator is positive. The sign of $\frac{\partial \bar{I}_i^a}{\partial \Omega}$, therefore, depends on the sign of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$.

The proof of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ is as follows. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\,\Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} = \frac{\eta[0.26\omega t^2 + [(0.12\psi - 0.24\Omega^2)\eta^2 + (0.5V - 0.99D\Omega)\omega]t + (0.48\Omega^2 - 0.24\psi)V\eta^2]}{1.60\omega t - 0.75\eta^2\psi}$. The denominator of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega}$ is $1.60\omega t - 0.75\eta^2\psi > 0$. For the numerator, it is an increasing function in ω . The non-negativity condition requires $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} = \frac{0.16(2V+t)\eta}{t} > 0$. Therefore, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Omega} \geq 0$ when $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can also show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\,\Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{\eta[0.24(V+0.5t)(2\Omega^2 - \psi)\eta^2 + (0.5V + 0.25t - D\Omega)\omega t]}{3.2\omega t - 1.6\eta^2\psi}$, with the denominator $3.2\omega t - 1.6\eta^2\psi$ to be positive, and numerator as an increasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{0.15(2V+t)\eta}{t} > 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$ when $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$.

It can also been shown that the sign of $\frac{\partial \bar{I}_i{}^a}{\partial \Sigma}$ and $\frac{\partial \bar{I}_i{}^t}{\partial \Sigma}$ depends on $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. The proof of $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} \leq 0$ is as follows. Substituting $\tilde{I}_i{}^a = I_j^a = \frac{\eta[(2V+t)\,\Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i{}^t = \tilde{I}_j{}^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} = \frac{\eta[0.48(V+0.5t)\Omega\eta^2 - D\omega t]}{t(3.1\omega t - 1.5\psi\eta^2)}$. The denominator $t(3.1\omega t - 1.5\psi\eta^2)$ is positive, and the numerator is a decreasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$ when $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can also show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\,\Omega - 2D\Psi]}{6.7\omega t - 3\Psi\eta^2}$, $\tilde{I}_i{}^t = \tilde{I}_j{}^t = \frac{\eta[(2V+t)\Omega - 2D\Psi]}{14\omega t - 6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = \frac{\eta[0.48(V+0.5t)\Omega\eta^2 - D\omega t]}{t(6.4\omega t - 3.1\psi\eta^2)}$. The denominator $t(6.4\omega t - 3.1\psi\eta^2)$ is positive, and the numerator is a decreasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$ when $\omega \geq \frac{0.48\,\Omega(V+0.5t)\eta^2}{Dt}$. Analogously, the sign of $\frac{\partial \bar{I}_i{}^t}{\partial \Sigma}$ also depends on $\frac{\partial^2 E[\pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$, which is negative.

Taking $\frac{\partial \tilde{I}_i{}^a}{\partial \Omega}$ and $\frac{\partial \tilde{I}_i{}^a}{\partial \Sigma}$ as an example for the proof of $\frac{\partial \tilde{I}_i{}^a}{\partial \Omega} \geq 0$, $\frac{\partial \tilde{I}_i{}^t}{\partial \Omega} \geq 0$ and $\frac{\partial \tilde{I}_i{}^a}{\partial \Sigma} \leq 0$, $\frac{\partial \tilde{I}_i{}^t}{\partial \Sigma} \leq 0$.

$$\frac{\partial \tilde{I}_i{}^a}{\partial \Omega} = \frac{\left(\overbrace{\overbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t}}^{\geq 0} + \overbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}}^{\leq 0}}^{\geq 0}\right)\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}}^{\geq 0} - \left(\overbrace{\overbrace{\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}}^{\leq 0} + \overbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}^{\leq 0}}^{\leq 0}\right)\overbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega}}^{\geq 0}}{\underbrace{\left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial {I_i^a}^2}}_{\leq 0} + \underbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^a}}_{\leq 0}}_{\leq 0}\right)\left(\underbrace{\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial {I_i^t}^2}}_{\leq 0} + \underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^t}}_{\leq 0}}_{\leq 0}\right) - \left(\underbrace{\underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_j^a}}_{\leq 0} + \underbrace{\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial I_i^a}}_{\geq 0}}_{\geq 0}\right)\left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_i^t}}_{\geq 0} + \underbrace{\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial I_j^t}}_{\leq 0}}_{\geq 0}\right)}_{\geq 0}} \geq 0$$

It can be shown that the sign of $\frac{\partial \tilde{I}_i^a}{\partial \Omega}$ depends on sign of $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$. The proof of $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega} \geq 0$ is as follows. Substituting $\tilde{I}_i^a = \tilde{I}_j^a = \frac{\eta[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega-2D\Psi]}{14\omega t-6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega} = \frac{\eta[0.25\mathrm{t}^2\omega+[(0.11\psi-0.22\Omega^2)\eta^2+(0.5V-D\Omega)\omega]t+0.223(\Omega^2-\psi)V\eta^2]}{t(1.67\omega t-0.74\eta^2\psi)}$, with the denominator to be positive, and with numerator as an increasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega} = \frac{0.15(2V+t)\eta}{t}$. Therefore, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Omega} \geq 0$ when $\omega \geq \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$. Substituting $\tilde{I}_i^a = I_j^a = \frac{\eta[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega-2D\Psi]}{14\omega t-6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{\eta[0.25\mathrm{t}^2\omega+[(0.11\psi-0.22\Omega^2)\eta^2+(0.5V-D\Omega)\omega]t+0.223(\Omega^2-\psi)V\eta^2]}{t(3.43\omega t-1.53\eta^2\psi)}$, with the denominator to be positive, and the numerator as an increasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{0.15(2V+t)\eta}{t}$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Omega} \geq 0$ when $\omega \geq \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$.

It can also been shown that the sign of $\frac{\partial \tilde{I}_i^a}{\partial \Sigma}$ and $\frac{\partial \tilde{I}_i^t}{\partial \Sigma}$ depends on $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. The proof of $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma} \leq 0$ is as follows. Substituting $\tilde{I}_i^a = \tilde{I}_j^a = \frac{\eta[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega-2D\Psi]}{14\omega t-6.\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma} = \frac{\eta[0.446(V+0.5t)\Omega\eta^2-D\omega t]}{t(3.33\omega t-1.49\psi\eta^2)}$, with the denominator to be positive, and the numerator as a decreasing function in ω. The non-negativity condition requires $\omega \geq \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i+\pi_j]}{\partial I_i^a \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$ when $\omega \geq \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$.

Similarly, one can also show $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \leq 0$. Substituting $\tilde{I}_i^a = \tilde{I}_j^a = \frac{\eta[(2V+t)\,\Omega-2D\Psi]}{6.7\omega t-3\Psi\eta^2}$, $\tilde{I}_i^t = \tilde{I}_j^t = \frac{\eta[(2V+t)\Omega-2D\Psi]}{14\omega t-6.\Psi\eta^2}$ into $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma}$. $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = \frac{\eta[0.446(V+0.5t)\Omega\eta^2-D\omega t]}{t(6.86\omega t-3.06\psi\eta^2)}$, with the denominator to be positive, and the numerator as a decreasing function in ω. The non-negativity condition requires $\omega \geq$

$\frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.44\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} = 0$. Therefore, $\frac{\partial^2 E[\Pi_i]}{\partial I_i^t \partial \Sigma} \le 0$ when $\omega \ge \frac{044\,\Omega(V+0.5t)\eta^2}{Dt}$.

Taking $\frac{\partial \hat{I}_i{}^a}{\partial \Omega}$ and $\frac{\partial \hat{I}_i{}^a}{\partial \Sigma}$ as example for the proof of $\frac{\partial \hat{I}_i{}^a}{\partial \Omega} \ge 0$, $\frac{\partial \hat{I}_i{}^t}{\partial \Omega} \ge 0$ and $\frac{\partial \hat{I}_i{}^a}{\partial \Sigma} \le 0$, $\frac{\partial \hat{I}_i{}^t}{\partial \Sigma} \le 0$.

$$\frac{\partial \hat{I}_i{}^a}{\partial \Omega} = \frac{\left(\overbrace{\overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t}}^{\ge 0} + \overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}}^{\le 0}}^{\ge 0}\right)\overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}}^{\ge 0} - \left(\overbrace{\overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2}}^{\le 0} + \overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}}^{\le 0}}^{\le 0}\right)\overbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}}^{\ge 0}}{\underbrace{\left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^a}^2}}_{\le 0} + \underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^a}}_{\le 0}}_{\le 0}\right)\left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial {I_i^t}^2}}_{\le 0} + \underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^t}}_{\le 0}}_{\le 0}\right) - \left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_j^a}}_{\le 0} + \underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial I_i^a}}_{\ge 0}}_{\ge 0}\right)\left(\underbrace{\underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_i^t}}_{\ge 0} + \underbrace{\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial I_j^t}}_{\le 0}}_{\ge 0}\right)}_{\ge 0}} \ge 0$$

It can be shown that the sign of $\frac{\partial \hat{I}_i{}^a}{\partial \Omega}$ depends on the sign of $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega}$. The proof of $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} \ge 0$ is as follows. Substituting $\hat{I}_i{}^a = \hat{I}_j{}^a = \hat{I}_i{}^t = \hat{I}_j{}^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\,\omega t - 4\,\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} = \frac{\eta[0.25\mathrm{t}^2\omega + [(0.48\Omega^2 - 0.24\psi)\eta^2 + (0.5V - D\Omega)\omega]t + 0.48(2\Omega^2 - \psi)V\eta^2]}{t(\omega t - \eta^2\psi)}$, with the denominator to be positive, and the numerator to be an increasing function in ω. The non-negativity condition requires $\omega \ge \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.97\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} = \frac{0.24(2V+t)\eta}{t}$. Therefore $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} \ge 0$ when $\omega \ge \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. In addition, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Omega} = \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Omega} \ge 0$.

It can also been shown that the sign of $\frac{\partial \hat{I}_i{}^a}{\partial \Sigma}$ and $\frac{\partial \hat{I}_i{}^t}{\partial \Sigma}$ depends on the sign of $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}$ and $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma}$. The proof of $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} \le 0$ is as follows. Substituting $\hat{I}_i{}^a = \hat{I}_j{}^a = \hat{I}_i{}^t = \hat{I}_j{}^t = \frac{\eta\,[(2V+t)\,\Omega - 2D\Psi]}{4.1\,\omega t - 4\,\Psi\eta^2}$ into $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} = \frac{\eta[0.97(V+0.5t)\Omega\eta^2 - D\omega t]}{t(2.1\omega t - 2\psi\eta^2)}$, with the denominator to be positive, and the numerator to be a decreasing function in ω. The non-negativity condition requires $\omega \ge \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. When $\omega = \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} = 0$. Therefore $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} \le 0$ when $\omega \ge \frac{0.97\,\Omega(V+0.5t)\eta^2}{Dt}$. In addition, $\frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^a \partial \Sigma} = \frac{\partial^2 E[\pi_i+\Pi_i]}{\partial I_i^t \partial \Sigma} \le 0$.