Internalization of port congestion: strategic effect behind shipping line delays and implications for terminal charges and investment

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This paper develops a theoretical model to analyze the congestion internalization of the shipping lines, taking into account the "knock on" effect (i.e. the congestion delay passed on from one port-of-call to the next port-of-call). We find that with the presence of the knock-on effect, liners will operate less in terminals, and an increase of a liner's operation in one terminal will decrease its operation in the other. If the liners are involved in a Stackelberg competition, whether they operate more or less in a terminal under the knock-on effect depends on the comparison between the marginal congestion costs of terminals. Furthermore, we find that the coordinated profit-maximizing terminal charges are higher than both the socially optimal terminal charges and the independent profit-maximizing terminal charges. When the knock-on effect is small, the independent profit-maximizing terminal charges are set at higher levels than the socially optimal terminal charges; but when the knock-on effect is sufficiently large, this relationship may reverse. Besides, the capacity investment rules are the same for welfare-maximizing terminal operator and coordinated profit-maximizing terminal operator, while independent profit-maximizing terminal operators invest less in capacity. The larger the knock-on effect, the larger this discrepancy.

Keywords: port congestion; internalization; shipping line; knock-on effect; terminal charge; terminal investment

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1. Introduction

International liner shipping is a sophisticated network of regularly scheduled services that transports goods all around the world at low cost (e.g., Stopford, 2009). In one year, a single large containership may carry over 200,000 container loads of cargo. Liner shipping connects countries, markets, businesses and people, allowing them to buy and sell goods on a scale not previously possible. Today, the liner shipping industry transports goods representing approximately one-third of the total value of global trade (Ng and Liu, 2014). It contributes hundreds of billions of dollars to the global economy annually, increasing gross domestic product in countries throughout the world.

Container shipping is however a very volatile business prone to business cycles and fluctuating freight rates (Luo et al., 2009). The liners are facing several challenges in today's highly competitive environment, one of which being the schedule (un)reliability problem. Based on the monitoring of (at least) 5,410 vessel arrivals on 23 different east/west and north/south trade routes between April and September 2006, a survey performed by leading maritime analyst Drewry Shipping Consultants revealed that more than 40% of the vessels deployed on worldwide liner services arrived one or more days behind schedule. The schedule unreliability has become a major managerial and policy issue, and the problem has also drawn attention from the academia (e.g., Notteboom, 2006; Vernimmen et al., 2007; Chung and Chiang, 2011).

Some argue that vessel delays are largely uncontrollable by the liners. Common reasons include bad weather at sea, congestion or labor strikes at the different ports of call, as well as the "knock-on" effect, which refers to the delay passed on from one port-of-call to the next port-of-call.[1] More serious delays can be caused by fire incidents, ship collisions or ship groundings. Others believe that the schedule unreliability is mainly due to the fact that most liner carriers do not include in their weekly schedules sufficient buffer time for such contingencies as bad weather and port delays, because they regard buffer time as too expensive (Drewry, 2006).

It is therefore interesting to investigate whether a liner will try to control its schedule reliability by internalizing port congestion, as well as the impacts of such behavior. In particular, given that congestion is a phenomenon with negative externality – a shipping line that adds more operations at a port will not bear all the congestion cost – intuition tells that a liner will only care about the congestion cost that falls onto its own operation, while ignoring the costs imposed on other liners. Consequently, if the liner has a significant presence at a port, it might have a strong incentive to eliminate or alleviate the port congestion. From a policy-making perspective, there are also various side benefits to enhance our understanding of port congestion, such as port competition for container transshipments (e.g., Bae et al. 2013) and a more efficient scheme for emission reduction in international shipping which is important for not only the environment per se but also many other aspects of the world economy (Luo, 2013; Luo and Yip, 2013).

In this paper, we develop a theoretical model to analyze the congestion internalization of the shipping lines, taking into account the knock-on effect. We find that with the presence of the knock-on effect, liners will operate less in terminals, and an increase of a liner's operation at one terminal will reduce its operation at the other. If the liners are involved in a Stackelberg competition, whether they operate more or less at a terminal depends on the comparison between the marginal congestion costs of terminals under consideration. We consider three different

[1] To illustrate, consider the following example. In recent years foggy (and smog) days are getting more frequent in Northern China, and the resulting sight limitation delays the ships' docking/departing at Port of Tianjin. This causes a chain reaction of delays at the next stop (port) as well as the following ports, the so-called knock-on effect.

scenarios for both the terminal charges and the terminal capacity investments: a social welfare-maximizing terminal operator, a coordinated profit-maximizing terminal operator, and an independent profit-maximizing terminal operator.[2] We find that the coordinated profit-maximizing terminal charges are higher than both the socially optimal terminal charges and the independent profit-maximizing terminal charges. When the knock-on effect is small, the independent profit-maximizing terminal charges are set at higher levels than the socially optimal terminal charges; but when the knock-on effect is sufficiently large, this relationship may reverse. Besides, the capacity investment rules are the same for the welfare-maximizing and coordinated profit-maximizing cases, while independent profit-maximizing terminal operators invest less in capacity. The stronger the knock-on effect is, the larger this difference would be.

Our results not only suggest the existence of terminal congestion internalization, but also deliver important policy implications. In particular, when comparing the two scenarios of profit-maximizing terminal operators, our results shows that separate ownership is likely to induce better outcome regarding terminal charge, while common ownership is more socially beneficial regarding terminal capacity investment (for given traffic levels).[3] It should be noted that we do not explicitly take into account other policy tools that terminal operators can use to counteract congestion, such as slot reallocation (Lu and Mu, 2016).

According to the air transport literature (e.g., Daniel, 1995; Brueckner, 2002), extra traffic created by a particular user of a transport infrastructure will have a negative externality on the other users by increasing the overall congestion level.[4] In road transport where users are all atomistic, they will not have incentives to take into account this externality in their driving decision. However, at an airport where infrastructure users (airlines) usually operate more than one flight, a proportion of the externality corresponding to their market shares will be taken into consideration in their decision of how many flights to be operated at the airport, and as a consequence airlines with market power tend to operate fewer flights. In other words, these airlines "internalize" some of the congestion externality. Maritime industry resembles the aviation industry in that the infrastructure users (shipping lines) also have market power. In fact, at the global liner industry level, the market is even much more concentrated than the aviation market, dominated by a handful of big players (e.g., Stopford, 2009). One feature that nevertheless distinguishes the maritime industry with the aviation industry regarding infrastructure congestion is the so-called "knock-on" effect, i.e., the congestion delay can be passed on from one port-of-call to the next port-of-call. Industry analysis has shown that stopping at the congested Los Angeles-Long Beach port complex in October made container ships an average of 3.4 days late at the next port of call, even in the case when a vessel arrived on time at Los Angeles-Long Beach (JOC, 2014b). This phenomenon may introduce some new insights regarding the congestion internalization of shipping lines, since it links up separate terminals and forces the liners to strategize over a network instead a single

[2] A third relationship between ports is of competition, that is, a shipping line may have to choose one of the ports (rather than use the ports in the sequential fashion as considered here); see, among others, Anderson et al. (2008), Zhang (2009), Wan and Zhang (2013), Wan et al. (2013). The competitive aspect has been abstracted away from the analysis of this paper; incorporating it in a more complete treatment of the problem would be an interesting area for future research.

[3] See a recent paper (del Saz-Salazar and García-Menéndez, 2016) for an interesting (although less relevant to our paper) discussion about the negative externalities on local residents brought by port capacity expansion.

[4] See Zhang and Czerny (2012) and Basso and Zhang (2007) for recent surveys of these and other studies. For early studies on airport congestion pricing and capacity with atomistic carriers, see, e.g., Levine (1969), Carlin and Park (1970), and Morrison (1983).

infrastructure.[5] In addition, we shall examine the shipping lines' traffic decisions under both the Cournot setting (where the liners make their quantity decisions simultaneously) and the Stackelberg setting with a leader and a follower.[6]

The paper is organized as follows. Section 2 sets up the basic model. Section 3 analyzes the shipping lines' traffic decisions under both the Cournot and Stackelberg settings. Section 4 studies the terminal charge decision with the objectives being global optimum as well as profit maximization. Section 5 discusses the optimal terminal capacity levels under these different objectives. Section 6 contains discussion and concluding remarks.

2. Model

We consider two shipping lines 1 and 2 that serve two ports of call A and B consecutively, which is a stylized case for more general setting of multiple liners and multiple port terminals. The operations (loading and unloading) in the two port terminals are totally independent from each other and connected to a third port terminal. We assume that the congestion in one of the two port terminals under study has an impact on the operations in another through liners that serve them consecutively due to the "knock-on" effect (Drewry, 2006). In particular, we assume that a proportion, denoted as δ, of the congestion delay will be transferred between these two terminals. When the congestion in one of the port terminals causes a ship of a liner to delay, it can (partially) offset the delay by speeding up on the way to the next port terminal. In this case, the knock-on cost consists of two components: the part of delay that is not offset, and the extra cost of speeding up. Therefore, it is reasonable to assume that the knock-on cost is in proportion to the original congestion cost, and this proportion (δ) depends on factors such as the distance between the two terminals, given that the farther away the two terminals from each other, the more easily the ship can offset the delay with a reasonable level of cost. The third port, which is the origin/destination for all the containers unloaded/loaded in both ports A and B, is farther away with no knock-on effect, and thus essentially excluded from our analysis.

Following Brueckner and Van Dender (2008), we further assume that shippers are willing to pay a fixed "full price" p^k for travel in and out of the congested terminal k, reflecting a horizontal demand curve. This assumption is in place to suppress the market-power component so to maintain the simplest possible focus on the congestion phenomenon. Relaxing this assumption will not change the analysis of congestion, as shown by the literature (see Brueckner and Van Dender

[5] Strictly speaking, knock-on effect also exists in the aviation industry in that a delayed flight will usually disrupt the schedule of a busy airport. However, this effect is much milder compared with the maritime sector due to the fact that buffer time between flights are usually longer, and other factors like airport curfew can help to eliminate it at the end of the day.

[6] While Brueckner (2002) demonstrates the internalization idea in a Cournot setting clearly, Daniel (1995) shows, in a Stackelberg setting, that the dominant carrier (leader) may not internalize the self-imposed congestion. Daniel argued that flight cutbacks by a dominant airline aimed at reducing congestion will be offset by the response of fringe carriers, who will schedule more flights so as to leave overall congestion unchanged. As a consequence, the dominant carrier will forego such flight cutbacks, in effect acting atomistically. He showed that the intraday flight patterns at the Minneapolis-St. Paul airport exhibit too much inter temporal peaking to be consistent with internalization by the dominant carrier (Northwest Airlines), and that an atomistic model fits the data better. Daniel and Harback (2008) provided more extensive evidence of this type for a larger number of US airports, while also offering a clearer exposition of model underlying the exercise. Brueckner and Van Dender (2008) constructed a model that attempts to capture the important elements of both the Cournot and Stackelberg settings.

(2008) for a detailed discussion). Since shippers dislike terminal congestion, which imposes additional time costs, the actual fare that the shipping lines charge must be discounted below this full price. We use I^k to denote the capacity level of terminal k.

Let q_i^k denote the operation volumes for liner i (i=1,2) at terminal k (k=A, B), and let $t^k(Q^k, I^k)$, where $Q^k = \sum_{i=1,2} q_i^k$ denote the extra time cost per unit of operation volume due to congestion and the resulting delays, a cost that depends on total operations at the congested terminal. While congestion cost is zero when total operations are low, the function eventually becomes positive, with $\partial t^k/\partial Q^k > 0$, $\partial t^k/\partial I^k < 0$, $\partial^2 t^k/\partial {Q^k}^2 \geq 0$, $\partial^2 t^k/\partial {I^k}^2 \geq 0$ and $\partial^2 t^k/\partial Q^k \partial I^k < 0$ holding over the positive range (so that the marginal congestion cost is constant or rising in operation volumes). With our horizontal full price assumption, all the cost of the shippers will be passed on to the liners, so the liners are able to charge a fare equal to $p^k - t^k(Q^k, I^k) - \delta t^l(Q^l, I^l)$ at terminal k.

In the absence of congestion, liner i incurs a cost per unit of τ_i^k at terminal k. However, terminal congestion raises operating costs, adding an extra cost of $g^k(Q^k, I^k)$ for each unit of operation at terminal k. Like $t^k(\cdot)$, the function g satisfies $g^k \geq 0$, $\partial g^k/\partial Q^k > 0$, $\partial g^k/\partial I^k < 0$, $\partial^2 g^k/\partial {Q^k}^2 \geq 0$, $\partial^2 g^k/\partial {I^k}^2 \geq 0$ and $\partial^2 g^k/\partial Q^k \partial I^k < 0$ when g is positive (g is zero when Q^k is small).

Combining the above information, liner profits can be written as:

$$\pi_i = \sum_{k=A,B} \left[p^k - t^k(Q^k, I^k) - \delta t^l(Q^l, I^l) - \mu_i^k - \tau_i^k - g^k(Q^k, I^k) - \delta g^l(Q^l, I^l)\right] q_i^k \quad (1)$$

where $l = A, B$ and $l \neq k$. μ_i^k is the unit charge of port terminal k operator on liner i. Throughout the paper we assume that the port terminal operators are able to price differentiate the liners. It can be shown that under uniform terminal charges, most of the qualitative results will be preserved.

Equation (1) can be rewritten as:

$$\pi_i = \sum_{k=A,B} \left[p^k - \tau_i^k - \mu_i^k - c^k(Q^k, I^k) - \delta c^l(Q^l, I^l)\right] q_i^k \quad (2)$$

where $c^k(Q^k, I^k) = t^k(Q^k, I^k) + g^k(Q^k, I^k)$.

The operator of terminal k incurs a unit cost of T^k. Meanwhile, the terminal capacity level I^k is a long-term decision variable of the port authorities with a cost $C^k(I^k)$. We follow Zhang and Zhang (2006) to assume that the capacity cost function adopts a linear form, i.e., $C^k(I^k) = rI^k$ with $r > 0$. The objective function of the terminal operators varies depending on the context. In the following analysis we'll consider three scenarios: global optimum, coordinated profit maximizing, as well as independent profit maximizing decisions. For the global optimum, the decision maker of the port charges and the port capacity levels is a global welfare maximizer and takes into account the profits of both liners since consumer surplus has been assumed away. And the objective function in this case is:

$$W = \sum_{k=A,B} \sum_{i=1,2} \left[p^k - \tau_i^k - \mathrm{T}^k - c^k(Q^k, I^k) - \delta c^l(Q^l, I^l)\right] q_i^k - \sum_{k=A,B} C^k(I^k) \quad (3)$$

In the case of coordinated profit maximizing, the terminal operators only care about their own profits, but they act as a single agent. In reality, this is the case for a private port operator with multiple port terminals under control, such as Hutchison Port Holdings, PSA International, DP World and Modern Terminals Limited. In theory, this situation acts as a useful intermediate case between the global optimum and the independent profit maximizing port authorities. Homsombat et al. (2013) show that port coordination is beneficial for pollution control. Zhuang et al. (2014) suggest, among other things, that port coordination can help to facilitate port specialization and avoid overinvestment. In this case, the objective function is:

$$\Pi = \sum_{k=A,B} \sum_{i=1,2} (\mu_i^k - \mathrm{T}^k) q_i^k - \sum_{k=A,B} C^k(I^k) \tag{4}$$

For most of the time the two terminals are not coordinating with each other, so we also consider the independent profit maximizing case, in which the objective function is:

$$\Pi^k = \sum_{i=1,2} (\mu_i^k - \mathrm{T}^k) q_i^k - C^k(I^k) \tag{5}$$

We'll get back to these different scenarios in Sections 4 and 5 when terminal decisions are analyzed. But in the next section let's first focus on the liners.

3. Liner Traffic under Cournot and Stackelberg Models

In the next two sections, we will focus on analyzing the equilibrium traffic volumes of liners at each terminal, as well as the terminal charge decisions, assuming that the terminal capacities are given. In other words, I^k is suppressed in the function $c^k(Q^k, I^k)$. And for simplicity, we use $c^{k'}$ to denote $\partial c^k / \partial Q^k$. Only in Section 5 we'll discuss the impacts of terminal capacity as well as the terminal authorities' capacity decisions.

3.1 Cournot competition

Let's first look at the case where the two liners play a Cournot game in both port terminals. From equation (2), the first order condition of liner *i*'s operation in terminal *k* is given by:

$$p^k - \tau_i^k - \mu_i^k - c^k - \delta c^l - c^{k'}(q_i^k + \delta q_i^l) = 0 \tag{6}$$

The counterpart in terminal *l* is:

$$p^l - \tau_i^l - \mu_i^l - c^l - \delta c^k - c^{l'}(q_i^l + \delta q_i^k) = 0 \tag{7}$$

We assume that the second order conditions also hold:

$$-2c^{k'} - c^{k''}(q_i^k + \delta q_i^l) < 0 \tag{8}$$

$$[2c^{k'} + c^{k''}(q_i^k + \delta q_i^l)][2c^{l'} + c^{l''}(q_i^l + \delta q_i^k)] - \delta^2 (c^{l'} + c^{k'})^2 > 0 \tag{9}$$

We need to make sense of all the components of equations (6) and (7). The first component is the full price, which is the benefit of one extra unit of operation for the liner; the next four components are the cost of this extra unit of operations; the last term measures a proportion of the marginal congestion cost induced by an extra unit of terminal operation. In other words, the last term captures the "internalization" of congestion by the liners, which is the focus of this paper. From equations (6) and (7) we can see that the larger the operations of a liner in a port terminal, the more congestion it internalizes, a finding well identified by the aviation literature. What distinguishes this term from the corresponding part in literature is that due to the knock-on effect, a part of the congestion occurring in the other terminal will also be internalized. In particular, when the two liners are asymmetric, i.e., $q_1^k \neq q_2^k$ in equilibrium (which is common in the liner shipping industry, see Fan and Luo (2013) for an analysis behind liners' capacity decisions), things become more interesting. In this case, it is possible that even if a liner's operations in a particular terminal is not substantial, as long as it has substantial operations in the other terminal and the knock-on effect between these two terminals is significant, the internalization of congestion of the liner in that particular port terminal will still be large. Industry anecdotes seem to verify this result. Consider the example mentioned earlier, due to more frequent foggy days in Northern China, sight limitation has delayed the ships at Port of Tianjin. Some of the ships may have to skip Tianjin (an extreme case of congestion internalization in which the operation is reduced to zero) and go directly to the next stop, Shanghai, and unload Tianjin cargo there instead, because Shanghai is simply too important to be missed. In this case, the liners cut down their operations at Tianjin to avoid the knock-on effect at Shanghai.

Proposition 1: The liners will operate less in terminals with the presence of the knock-on effect. Besides, an increase of a liner's operation in one terminal will decrease its operation in the other.

Proof:
Equation (6) can be transformed into:

$$p^k - \tau_i^k - \mu_i^k - c^k - c^{k'} q_i^k = \delta(c^l + c^{k'} q_i^l)$$

Since $c^l + c^{k'} q_i^l > 0$, we can tell that the equilibrium q_i^k is smaller when $\delta > 0$ compared with the case when $\delta = 0$.
Besides, since $c^{k'} > 0$, the larger q_i^l, the larger $c^l + c^{k'} q_i^l$, and at equilibrium q_i^l will exert a downward pressure to q_i^k.
Q.E.D

For further analysis, we need to have the comparative statics of port charge μ_i^k. Totally differentiating equations (6) and (7) with respect to μ_i^k yields to:

$$1 + \left[2c^{k'} + c^{k''}\left(q_i^k + \delta q_i^l\right)\right] \frac{\partial q_i^k}{\partial \mu_i^k} + \left[c^{k'} + c^{k''}\left(q_i^k + \delta q_i^l\right)\right] \frac{\partial q_j^k}{\partial \mu_i^k} + \delta\left(c^{l'} + c^{k'}\right) \frac{\partial q_i^l}{\partial \mu_i^k} + \delta c^{l'} \frac{\partial q_j^l}{\partial \mu_i^k} = 0 \tag{10}$$

$$\left[2c^{k'} + c^{k''}\left(q_j^k + \delta q_j^l\right)\right] \frac{\partial q_j^k}{\partial \mu_i^k} + \left[c^{k'} + c^{k''}\left(q_j^k + \delta q_j^l\right)\right] \frac{\partial q_i^k}{\partial \mu_i^k} + \delta\left(c^{l'} + c^{k'}\right) \frac{\partial q_j^l}{\partial \mu_i^k} + \delta c^{l'} \frac{\partial q_i^l}{\partial \mu_i^k} = 0 \tag{11}$$

$$\left[2c^{l'} + c^{l''}\left(q_i^l + \delta q_i^k\right)\right] \frac{\partial q_i^l}{\partial \mu_i^k} + \left[c^{l'} + c^{l''}\left(q_i^l + \delta q_i^k\right)\right] \frac{\partial q_j^l}{\partial \mu_i^k} + \delta\left(c^{l'} + c^{k'}\right) \frac{\partial q_i^k}{\partial \mu_i^k} + \delta c^{k'} \frac{\partial q_j^k}{\partial \mu_i^k} = 0 \tag{12}$$

$$\left[2c^{l'} + c^{l''}\left(q_j^l + \delta q_j^k\right)\right]\frac{\partial q_j^l}{\partial \mu_i^k} + \left[c^{l'} + c^{l''}\left(q_j^l + \delta q_j^k\right)\right]\frac{\partial q_i^l}{\partial \mu_i^k} + \delta\left(c^{l'} + c^{k'}\right)\frac{\partial q_j^k}{\partial \mu_i^k} + \delta c^{k'}\frac{\partial q_i^k}{\partial \mu_i^k} = 0 \quad (13)$$

Solving the above equation system assuming $c^{k''} = c^{l''} = 0$, we can obtain:

$$\frac{\partial q_i^k}{\partial \mu_i^k} = -\frac{\delta^2\left(c^{k'^2} + c^{l'^2} + 4c^{k'}c^{l'}\right) - 6c^{k'}c^{l'}}{c^{k'}(1-\delta^2)[\delta^2(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}) - 9c^{k'}c^{l'}]} \quad (14)$$

$$\frac{\partial q_j^k}{\partial \mu_i^k} = \frac{\delta^2\left(c^{k'^2} + c^{l'^2} + c^{k'}c^{l'}\right) - 3c^{k'}c^{l'}}{c^{k'}(1-\delta^2)[\delta^2(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}) - 9c^{k'}c^{l'}]} \quad (15)$$

$$\frac{\partial q_i^l}{\partial \mu_i^k} = \frac{\delta[\delta^2\left(2c^{k'^2} + c^{l'^2} + 3c^{k'}c^{l'}\right) - c^{k'^2} - 5c^{k'}c^{l'}]}{c^{k'}(1-\delta^2)\left[\delta^2\left(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}\right) - 9c^{k'}c^{l'}\right]} \quad (16)$$

$$\frac{\partial q_j^l}{\partial \mu_i^k} = -\frac{\delta[\delta^2\left(c^{l'^2} + 2c^{k'}c^{l'}\right) + c^{k'^2} - 4c^{k'}c^{l'}]}{c^{k'}(1-\delta^2)\left[\delta^2\left(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}\right) - 9c^{k'}c^{l'}\right]} \quad (17)$$

When $\delta \neq 0$ and $c^{k'} = c^{l'}$, from equations (14)-(17) we can easily show that $\partial q_i^k / \partial \mu_i^k < 0$, $\partial q_j^k / \partial \mu_i^k > 0$, $\partial q_i^l / \partial \mu_i^k > 0$ and $\partial q_j^l / \partial \mu_i^k < 0$. The first two are expected, since an increase of terminal charge on a liner will naturally decrease the liner's own traffic and increase the traffic of its competitor in this terminal. The last two are more interesting, as they tell that the increase of the charge on a liner in one terminal will increase this liner's traffic but decrease the traffic of its competitor in the other terminal. Note that when $\delta = 0$, $\partial q_i^l/\partial \mu_i^k = \partial q_j^l/\partial \mu_i^k = 0$, suggesting that this connection between the two terminals is from the knock-on effect. This is because a decrease of traffic in one terminal will decrease the congestion knock-on impact on the other terminal hence increasing its traffic there. This increase will also have a secondary impact on the other liner's operations in this other terminal. Summing up equations (14) and (15), as well as (16) and (17), we have:

$$\frac{\partial Q^k}{\partial \mu_i^k} = \frac{3c^{l'}}{\delta^2\left(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}\right) - 9c^{k'}c^{l'}} \quad (18)$$

$$\frac{\partial Q^l}{\partial \mu_i^k} = -\frac{\delta(2c^{k'} + c^{l'})}{\delta^2\left(2c^{k'^2} + 2c^{l'^2} + 5c^{k'}c^{l'}\right) - 9c^{k'}c^{l'}} \quad (19)$$

We can show that $\partial Q^k/\partial \mu_i^k < 0$ and $\partial Q^l/\partial \mu_i^k > 0$ when $\delta \neq 0$ and $c^{k'} = c^{l'}$, suggesting a negative overall impact of a terminal charge increase on the operations in this terminal and a positive overall impact on the operations in the other terminal. Besides, we have $\partial^2 Q^k/\partial \mu_i^k \partial \delta < 0$ while $\partial^2 Q^l/\partial \mu_i^k \partial \delta > 0$. It means that the larger the knock-on effect, the larger the impact of terminal charge change on the port traffic. This is because the larger the knock-on effect, the more closely the two terminals are connected with each other, and the more traffic will be allocated away from a terminal with increasing terminal charge to the other terminal.

3.2 Stackelberg competition

Sometimes liners operating in the same terminal may have different market status. For example, Maersk Line is the dominant player in Algeciras, Tanjung Pelepas and Salalah (Notteboom, 2011). In this case, a Cournot fashion game might not be appropriate. To make sure whether the game structure will have an impact on the results we have obtained so far, let's now consider two liners playing a Stackelberg game instead. We denote the leader as liner 1 and the follower as liner 2.

Liner 2 chooses q_2^k and q_2^l, while observing q_1^k and q_1^l, satisfying the conditions:

$$p^k - \tau_2^k - \mu_2^k - c^k - \delta c^l - c^{k\prime}(q_2^k + \delta q_2^l) = 0 \tag{20}$$

$$p^l - \tau_2^l - \mu_2^l - c^l - \delta c^k - c^{l\prime}(q_2^l + \delta q_2^k) = 0 \tag{21}$$

In order to analyze the leader's behavior, we need to find the response of q_2^k and q_2^l to a change in q_1^k and q_1^l. Therefore, the equations (20) and (21) are totally differentiated with q_1^k, yielding:

$$\left[c^{k\prime} + c^{k\prime\prime}\left(q_2^k + \delta q_2^l\right)\right] + \left[2c^{k\prime} + c^{k\prime\prime}\left(q_2^k + \delta q_2^l\right)\right]\frac{\partial q_2^k}{\partial q_1^k} + \delta(c^{l\prime} + c^{k\prime})\frac{\partial q_2^l}{\partial q_1^k} = 0 \tag{22}$$

$$\delta c^{k\prime} + \left[2c^{l\prime} + c^{l\prime\prime}\left(q_2^l + \delta q_2^k\right)\right]\frac{\partial q_2^l}{\partial q_1^k} + \delta(c^{l\prime} + c^{k\prime})\frac{\partial q_2^k}{\partial q_1^k} = 0 \tag{23}$$

Solving equations (22) and (23) simultaneously, we have

$$\frac{\partial q_2^k}{\partial q_1^k} = -\frac{K_1K_4 - K_3K_5}{K_2K_4 - {K_5}^2} \tag{24}$$

$$\frac{\partial q_2^l}{\partial q_1^k} = -\frac{K_2K_3 - K_1K_5}{K_2K_4 - {K_5}^2} \tag{25}$$

where $K_1 = c^{k\prime} + c^{k\prime\prime}\left(q_2^k + \delta q_2^l\right)$, $K_2 = 2c^{k\prime} + c^{k\prime\prime}\left(q_2^k + \delta q_2^l\right)$, $K_3 = \delta c^{k\prime}$, $K_4 = 2c^{l\prime} + c^{l\prime\prime}\left(q_2^l + \delta q_2^k\right)$ and $K_5 = \delta(c^{l\prime} + c^{k\prime})$.

Second order condition requires that $K_2K_4 - {K_5}^2 > 0$. The full expressions of equations (24) and (25) are rather complex, but interesting observations are embedded. In particular, if we consider the case when $c^{k\prime\prime} = c^{l\prime\prime} = 0$, equations (24) and (25) becomes:

$$\frac{\partial q_2^k}{\partial q_1^k} = -\frac{2c^{k\prime}c^{l\prime} - \delta^2 c^{k\prime}\left(c^{l\prime} + c^{k\prime}\right)}{4c^{k\prime}c^{l\prime} - \delta^2(c^{l\prime} + c^{k\prime})^2} \tag{26}$$

$$\frac{\partial q_2^l}{\partial q_1^k} = -\frac{\delta c^{k\prime}(c^{k\prime} - c^{l\prime})}{4c^{k\prime}c^{l\prime} - \delta^2(c^{l\prime} + c^{k\prime})^2} \tag{27}$$

When knock-on effect is not an issue, i.e., $\delta = 0$, or when the two terminals are equally congestible, i.e., $c^{l\prime} = c^{k\prime}$, we have $\partial q_2^k/\partial q_1^k = -1/2$ as well as $\partial q_2^l/\partial q_1^k = 0$. In fact, this is the same as equation (9) in Brueckner and Van Dender (2008) when the second-order effect of congestion is out of the picture. In other words, the benchmark situation is that the follower liner will offset the increase of the leader liner's operation in a particular terminal by decreasing its own operation in that terminal by half of the amount; meanwhile, the increase of the leader liner's operation in one terminal will not affect the follower liner's operation in the other terminal.

However, when $\delta \neq 0$ and $c^{l\prime} \neq c^{k\prime}$, we can see that $\partial q_2^k/\partial q_1^k > -1/2$ and $\partial q_2^l/\partial q_1^k < 0$ if and only if $c^{l\prime} < c^{k\prime}$. In other words, when the marginal congestion cost of one terminal is higher than that of the other, the decrease of the follower liner's operation in response to the increase of the leader liner's operation in this particular terminal is less than the benchmark level. Meanwhile, the increase of the leader liner's operation in this terminal can also force the follower liner to decrease its operations in the other terminal. This means that with the knock-on effect, when the two terminals become a system, the negative impacts of the leader liner's traffic change in the more congested terminal on the follower liner's traffic change is weaker in the terminal with higher marginal congestion cost but stronger in the terminal with lower marginal congestion cost. This effect is more significant when the knock-on effect is stronger. This result has practical importance since there are many factors that can affect the congestion function of a terminal. Other than the capacity level and technology, different policies adopted by the terminal operators can also play an important role. For example, different terminals have different caps of capacity usage. For those which keep the cap well below 100% of the maximum operating capacity, the congestion will not go up as fast as those which allow the cap to be very close to the 100% level.

Lemma 1: With the presence of the knock-on effect, when the leader liner increases its traffic in the terminal with higher (lower) marginal congestion cost, the follower liner will decrease its traffic in that terminal by less (more) than half of that amount and decrease (increase) its traffic in the other terminal.

Proof:

From equations (26) and (27), we can see that when $c^{l'} < c^{k'}$,

$$\frac{\partial q_2^k}{\partial q_1^k} > -\frac{2c^{k'}c^{l'} - \delta^2 c^{k'}\left(c^{l'} + c^{k'}\right)}{2\left[2c^{k'}c^{l'} - \delta^2 c^{k'}\left(c^{l'} + c^{k'}\right)\right]} = -\frac{1}{2}$$

$$\frac{\partial q_2^l}{\partial q_1^k} < 0$$

On the other hand, when $c^{l'} > c^{k'}$,

$$\frac{\partial q_2^k}{\partial q_1^k} < -\frac{2c^{k'}c^{l'} - \delta^2 c^{k'}\left(c^{l'} + c^{k'}\right)}{2\left[2c^{k'}c^{l'} - \delta^2 c^{k'}\left(c^{l'} + c^{k'}\right)\right]} = -\frac{1}{2}$$

$$\frac{\partial q_2^l}{\partial q_1^k} > 0$$

Q.E.D

Lemma 1 is very interesting, since the results are not only driven by the knock-on effect, but also by the inequality in the congestion situation of the two terminals linked by the knock-on effect. When the leader liner increases its traffic in the less congested terminal, the follower liner will respond by decreasing its traffic in this terminal more than the benchmark level to mitigate the knock-on congestion cost to the more congested terminal. Moreover, the follower will also increase its traffic in the more congested terminal since the knock-on congestion to the less congested terminal is less significant.

Knowing the response of liner 2 to its choice, liner 1 maximizes its profit, and the first-order condition with respect to q_1^k is:

$$p^k - \tau_1^k - \mu_1^k - c^k - \delta c^l - c^{k'}\left(1 + \frac{\partial q_2^k}{\partial q_1^k}\right)\left(q_1^k + \delta q_1^l\right) - c^{l'}\frac{\partial q_2^l}{\partial q_1^k}\left(q_1^l + \delta q_1^k\right) = 0 \qquad (28)$$

while the second-order conditions are also assumed to hold. The strategic effect between the two liners is captured by the last two terms of equation (28). When $c^{l'} = c^{k'}$, we have the benchmark case where $\partial q_2^k/\partial q_1^k = -1/2$ while $\partial q_2^l/\partial q_1^k = 0$, and these two terms go towards different directions when $c^{l'} \neq c^{k'}$.

Proposition 2: With the presence of the knock-on effect, a Stackelberg leader liner will decrease its operations in the terminal with lower marginal congestion cost, but may either increase or decrease its operations in the terminal with higher marginal congestion cost.

Proof:
Equation (28) can be rewritten as

$$p^k - \tau_1^k - \mu_1^k - c^k - \delta c^l - \frac{1}{2}c^{k'}\left(q_1^k + \delta q_1^l\right) = c^{k'}\left(\frac{1}{2} + \frac{\partial q_2^k}{\partial q_1^k}\right)\left(q_1^k + \delta q_1^l\right) + c^{l'}\frac{\partial q_2^l}{\partial q_1^k}\left(q_1^l + \delta q_1^k\right)$$

When $\delta = 0$, the right-hand-side of the equation is equal to 0.
Substituting equations (26) and (27) into the above equation, we have

$$p^k - \tau_1^k - \mu_1^k - c^k - \delta c^l - \frac{1}{2}c^{k'}\left(q_1^k + \delta q_1^l\right) = \delta c^{k'}\left(c^{k'} - c^{l'}\right)\frac{\delta\left(c^{k'} - c^{l'}\right)q_1^k - \left[2c^{l'} - \delta^2\left(c^{k'} + c^{l'}\right)\right]q_1^l}{2\left[4c^{k'}c^{l'} - \delta^2\left(c^{k'} - c^{l'}\right)^2\right]}$$

When $c^{l'} = c^{k'}$, the RHS is 0; while when $c^{l'} > c^{k'}$, the RHS is positive since $c^{k'} - c^{l'} < 0$ as well as $-\left[2c^{l'} - \delta^2\left(c^{k'} + c^{l'}\right)\right] < 0$. Thus, the equilibrium q_1^k decreases as $c^{l'}$ exceeds $c^{k'}$. However, when $c^{l'} < c^{k'}$, the RHS is ambiguous as the sign of $-\left[2c^{l'} - \delta^2\left(c^{k'} + c^{l'}\right)\right]$ is ambiguous and hence the equilibrium q_1^k may increase or decreases as $c^{k'}$ exceeds $c^{l'}$.
Q.E.D

Proposition 2 is closely related to Lemma 1. From Lemma 1 we can see that no matter in which terminal the leader liner increases traffic, the follower liner will respond less aggressively in the terminal with lower marginal congestion cost and more aggressively in the terminal with higher marginal congestion cost. Therefore, it would be sensible for the leader liner to operate less in the terminal with lower marginal congestion cost to induce traffic cut by the follower in the more congested terminal and gain an overall benefit by reducing congestion significantly without losing too much market share. However, in the terminal with higher marginal congestion cost, this tradeoff is not as clear, since if the leader decreases its traffic, the follower's traffic decrease is less than the benchmark case so may not be large enough to compensate the leader for the increase of congestion in the less congested terminal and its lost market share in both terminals, leaving the result ambiguous.

From this section we can see that a Stackelberg setting is different from a Cournot setting only in that the two liners will have different levels of operations, but the general rules pointed out by Proposition 1 still hold. In fact we can show:

$$p^k - \tau_1^k - \mu_1^k - c^k - \frac{1}{2}c^{k'}q_1^k = \delta c^l + \frac{1}{2}c^{k'}\delta q_1^l + c^{k'}\left(\frac{1}{2} + \frac{\partial q_2^k}{\partial q_1^k}\right)\left(q_1^k + \delta q_1^l\right) + c^{l'}\frac{\partial q_2^l}{\partial q_1^k}\left(q_1^l + \delta q_1^k\right)$$

$$= \delta c^l + \frac{\delta^2 c^{k'}\left(c^{k'} - c^{l'}\right)^2 q_1^k}{2\left[4c^{k'}c^{l'} - \delta^2\left(c^{l'} + c^{k'}\right)^2\right]} + \frac{\delta c^{k'}(1-\delta^2)2c^{l'}\left(c^{k'} + c^{l'}\right)q_1^l}{2\left[4c^{k'}c^{l'} - \delta^2\left(c^{l'} + c^{k'}\right)^2\right]}$$

which is always positive when $\delta > 0$ and RHS increases as q_1^l increases. We can obtain something similar for the follower. In other words, Proposition 1 also holds with Stackelberg setting.

Therefore, for analytical simplicity, in the next section we'll only discuss the Cournot setting, with extension to Stackelberg setting easily to obtain.

4. Terminal Charges

4.1 Global optimum

Now let's look at the first best traffic. From equation (3), the first-order-condition of q_i^k for port *k* is:

$$p^k - \tau_i^k - T^k - c^k - \delta c^l - c^{k'}(Q^k + \delta Q^l) = 0 \quad (29)$$

It is easy to see that the differences between equations (6) and (29) are in the third terms and the last terms. The difference in the third terms is simply due to the different port usage costs faced by the terminal and the liners. The point of interest lies in the last terms. In equation (29), for social optimum, all congestion externality, within a terminal and across terminals, are required to be internalized. While in equation (6), for profit maximization, a liner will only consider the externality on its own operations. When τ_i^k's are not identical for liners, the traffic levels of the two liners in the two terminals will not be identical. A few interesting observations can thus be drawn.

If the two liners are not symmetric, then a single port charge cannot induce social optimum. The social optimum inducing port charge needs to be discriminative:

$$\mu_i^k = T^k + c^{k'} q_j^k + \delta c^{k'} q_j^l = T^k + c^{k'}(Q^k + \delta Q^l)\left(1 - \frac{q_i^k + \delta q_i^l}{Q^k + \delta Q^l}\right) \quad (30)$$

From equation (30) we can see that with the knock-on effect, the socially optimal terminal charge on a liner depends on not only its traffic in this terminal, but also its traffic in the other terminal. The larger the knock-on effect, the higher the socially optimal terminal charges. Apparently, when we compare the internalization of the two liners in terminal *k*, we need to know not only their traffic in this particular terminal, but also their traffic in the other terminal, as well as the influence of the knock-on effect on both liners.

A crucial policy implication is embedded. The fact that a liner has a relatively low operation level than the other liner in a terminal doesn't necessarily mean the liner should be charged a higher congestion cost. As long as it has a high level of operation in the other terminal, and the knock-on effect for the liner is significant, it still has a very strong incentive to internalize the congestion to a large extent.

4.2 Profit-maximizing terminals

Next let's have a look at the case when the terminal operators are mere profit maximizers. There are two different scenarios in this case. First, the two terminals are under the same profit-maximizing agent and thus coordinated. Second, the two terminals operate independently from each other.

4.2.1 Coordinated terminal operator

From equation (4), the first order conditions for μ_i^k, μ_j^k, μ_i^l and μ_j^l are:

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_i^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_i^k} + \left(\mu_i^l - T^l\right)\frac{\partial q_i^l}{\partial \mu_i^k} + \left(\mu_j^l - T^l\right)\frac{\partial q_j^l}{\partial \mu_i^k} + q_i^k = 0 \quad (31)$$

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_j^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_j^k} + \left(\mu_i^l - T^l\right)\frac{\partial q_i^l}{\partial \mu_j^k} + \left(\mu_j^l - T^l\right)\frac{\partial q_j^l}{\partial \mu_j^k} + q_j^k = 0 \quad (32)$$

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_i^l} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_i^l} + \left(\mu_i^l - T^l\right)\frac{\partial q_i^l}{\partial \mu_i^l} + \left(\mu_j^l - T^l\right)\frac{\partial q_j^l}{\partial \mu_i^l} + q_i^l = 0 \quad (33)$$

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_j^l} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_j^l} + \left(\mu_i^l - T^l\right)\frac{\partial q_i^l}{\partial \mu_j^l} + \left(\mu_j^l - T^l\right)\frac{\partial q_j^l}{\partial \mu_j^l} + q_j^l = 0 \quad (34)$$

Substituting equations (14)-(17), as well as their counterparts for l, into equations (31)-(34), we can obtain:

$$\mu_i^k = T^k + c^{k'}\left(2q_i^k + q_j^k\right) + \delta(c^{k'}Q^l + c^{l'}q_i^l) \quad (35)$$

$$\mu_j^k = T^k + c^{k'}\left(2q_j^k + q_i^k\right) + \delta(c^{k'}Q^l + c^{l'}q_j^l) \quad (36)$$

$$\mu_i^l = T^l + c^{l'}\left(2q_i^l + q_j^l\right) + \delta(c^{l'}Q^k + c^{k'}q_i^k) \quad (37)$$

$$\mu_j^l = T^l + c^{l'}\left(2q_j^l + q_i^l\right) + \delta(c^{l'}Q^k + c^{k'}q_j^k) \quad (38)$$

When we compare equations (30) and (35), we can clearly find that the coordinated profit maximizing terminal operator charges a higher price than the socially optimal level. This is consistent with literature (e.g., Zhang and Zhang, 2006). The most interesting observation from this comparison is that the larger the knock-on effect, the larger the charge difference. A coordinated profit maximizing charge is higher than a welfare maximizing charge, because a big part of the benefit from lowering the terminal charge hence increasing traffic will be grabbed by the liners, while the increased terminal congestion cost will affect the terminal operators' ability to extract profit as the amount that shippers are willing to pay the liners for the shipping services reduces. The larger the knock-on effect, the larger the congestion cost in a particular terminal, and the less traffic the terminal operator find it optimal to have.

4.2.2 Independent terminal operators.

From equation (5), the first order conditions for μ_i^k and μ_j^k are:

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_i^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_i^k} + q_i^k = 0 \quad (39)$$

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial \mu_j^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial \mu_j^k} + q_j^k = 0 \quad (40)$$

Substituting equations (14) and (15), as well as their counterparts for l, into equations (39) and (40), we can obtain:

$$\mu_i^k = T^k + c^{k'}\left(2q_i^k + q_j^k\right) - \frac{\delta^2[c^{k'}c^{l'}\left(4q_i^k + q_j^k\right) + \left(c^{l'^2} + c^{k'^2}\right)Q^k]}{3c^{l'}} \quad (41)$$

$$\mu_j^k = T^k + c^{k'}\left(2q_j^k + q_i^k\right) - \frac{\delta^2[c^{k'}c^{l'}\left(4q_j^k + q_i^k\right) + \left(c^{l'^2} + c^{k'^2}\right)Q^k]}{3c^{l'}} \quad (42)$$

Contradictory to what we have seen in Section 4.2.1, the larger δ, the smaller μ_i^k and μ_j^k will be. This is because the stronger the knock-on effect, the more conservative the liners will be regarding their traffic under any particular terminal charge. Therefore, to induce the optimal traffic level, the independent terminal operators need to set its charge at a lower level when the knock-on effect is stronger.

If we compare equations and (35) and (41), we can easily see that when $\delta = 0$, the coordinated charges are equal to the independent charges, because without the knock-on effect, the connection between the two terminals is gone and the two scenarios are equivalent to each other. When $\delta \neq 0$, the coordinated operator charges a higher fee to the liners, since the first two components are the same while the third component is positive for coordinated operator and negative for independent operators. This is because the coordinated decision maker will take into account the negative congestion externality that the cargos handled in terminal k exert on cargos handled in terminal l through the knock-on effect, hence it has a stronger incentive to discourage too much traffic in both terminals when compared with the independent decision makers.

By comparing the three charging rules analyzed above, we can derive the following proposition.

Proposition 3: The coordinated profit-maximizing terminal charges are higher than both the socially optimal terminal charges and the independent profit-maximizing terminal charges. When the knock-on effect is small, the independent profit-maximizing terminal charges are set at higher levels than the global optimum terminal charges; but when the knock-on effect is sufficiently large, this relationship may reverse.

Proof:

Comparing equation (35) with equations (30) and (41) respectively, we have

$$T^k + c^{k'}\left(2q_i^k + q_j^k\right) + \delta\left(c^{k'}Q^l + c^{l'}q_i^l\right) > T^k + c^{k'}q_j^k + \delta c^{k'}q_j^l$$

as well as

$$T^k + c^{k'}\left(2q_i^k + q_j^k\right) + \delta\left(c^{k'}Q^l + c^{l'}q_i^l\right) > T^k + c^{k'}\left(2q_i^k + q_j^k\right) - \frac{\delta^2\left[c^{k'}c^{l'}\left(4q_i^k + q_j^k\right) + \left({c^{l'}}^2 + {c^{k'}}^2\right)Q^k\right]}{3c^{l'}}$$

Comparing equations (30) and (41), the result is ambiguous, depending on the value of δ. On the one hand, $T^k + c^{k'}q_j^k + \delta c^{k'}q_j^l$ increases in δ. On the other hand, $T^k + c^{k'}\left(2q_i^k + q_j^k\right) - \delta^2\left[c^{k'}c^{l'}\left(4q_i^k + q_j^k\right) + \left({c^{l'}}^2 + {c^{k'}}^2\right)Q^k\right]/3c^{l'}$ decreases in δ.

When $\delta = 0$,

$$T^k + c^{k'}\left(2q_i^k + q_j^k\right) - \frac{\delta^2\left[c^{k'}c^{l'}\left(4q_i^k + q_j^k\right) + \left({c^{l'}}^2 + {c^{k'}}^2\right)Q^k\right]}{3c^{l'}} > T^k + c^{k'}q_j^k + \delta c^{k'}q_j^l$$

But the difference decreases with δ and the relationship may reverse when δ is sufficiently large.

Q.E.D

Proposition 3 has important policy implications. In particular, with the presence of knock-on effect, it is very likely that independent profit-maximizing terminal operators set terminal charges that are closer to the socially optimum levels than the coordinated profit-maximizing terminal operator. In this case, if public ownership is not a viable option, it will probably be beneficial to hand over terminals to different operators instead of one single company even if the terminals are not substitutes and hence there is no anti-competitive issue. Under some constellations, it is not even necessary to use policy tools to enforce socially optimal terminal charge, since the independent profit-maximizing charges might be very close to the global optimum.

5. Terminal Capacity

Now let's consider the terminal operators' decisions regarding terminal capacity. In this case, we need to consider c^k in its complete form as $c^k(Q^k, I^k)$. Accordingly, we need to use the notation $\partial c^k/\partial Q^k$ instead of $c^{k\prime}$ as in Sections 3 and 4. Equations (6) and (7) thus become:

$$p^k - \tau_i^k - \mu_i^k - c^k - \delta c^l - \frac{\partial c^k}{\partial Q^k}(q_i^k + \delta q_i^l) = 0 \quad (6')$$

$$p^l - \tau_i^l - \mu_i^l - c^l - \delta c^k - \frac{\partial c^l}{\partial Q^l}(q_i^l + \delta q_i^k) = 0 \quad (7')$$

5.1 Comparative statics of liner traffic

First we'll study the impacts of capacity change on a port terminal. We totally differentiate equations (6') and (7') with I^k, yielding:

$$\frac{\partial c^k}{\partial I^k} + \frac{\partial c^k}{\partial Q^k}\left(2\frac{\partial q_i^k}{\partial I^k} + \delta\frac{\partial q_i^l}{\partial I^k} + \frac{\partial q_j^k}{\partial I^k}\right) + \delta\frac{\partial c^l}{\partial Q^l}\left(\frac{\partial q_i^l}{\partial I^k} + \frac{\partial q_j^l}{\partial I^k}\right) = 0 \quad (43)$$

$$\delta\left[\frac{\partial c^k}{\partial I^k} + \frac{\partial c^k}{\partial Q^k}\left(\frac{\partial q_i^k}{\partial I^k} + \frac{\partial q_j^k}{\partial I^k}\right)\right] + \frac{\partial c^l}{\partial Q^l}\left(2\frac{\partial q_i^l}{\partial I^k} + \delta\frac{\partial q_i^k}{\partial I^k} + \frac{\partial q_j^l}{\partial I^k}\right) = 0 \quad (44)$$

$$\frac{\partial c^k}{\partial I^k} + \frac{\partial c^k}{\partial Q^k}\left(2\frac{\partial q_j^k}{\partial I^k} + \delta\frac{\partial q_j^l}{\partial I^k} + \frac{\partial q_i^k}{\partial I^k}\right) + \delta\frac{\partial c^l}{\partial Q^l}\left(\frac{\partial q_i^l}{\partial I^k} + \frac{\partial q_j^l}{\partial I^k}\right) = 0 \quad (45)$$

$$\delta\left[\frac{\partial c^k}{\partial I^k} + \frac{\partial c^k}{\partial Q^k}\left(\frac{\partial q_i^k}{\partial I^k} + \frac{\partial q_j^k}{\partial I^k}\right)\right] + \frac{\partial c^l}{\partial Q^l}\left(2\frac{\partial q_j^l}{\partial I^k} + \delta\frac{\partial q_j^k}{\partial I^k} + \frac{\partial q_i^l}{\partial I^k}\right) = 0 \quad (46)$$

Solving the equation system simultaneously, we'll have:

$$\frac{\partial q_i^k}{\partial I^k} = \frac{\partial q_j^k}{\partial I^k} = -\frac{\frac{\partial c^k}{\partial I^k}\left[3\frac{\partial c^l}{\partial Q^l} - \delta^2\left(\frac{\partial c^k}{\partial Q^k} + 2\frac{\partial c^l}{\partial Q^l}\right)\right]}{9\frac{\partial c^k}{\partial Q^k}\frac{\partial c^l}{\partial Q^l} - \delta^2\left(\frac{\partial c^k}{\partial Q^k} + 2\frac{\partial c^l}{\partial Q^l}\right)\left(2\frac{\partial c^k}{\partial Q^k} + \frac{\partial c^l}{\partial Q^l}\right)} \quad (47)$$

$$\frac{\partial q_i^l}{\partial I^k} = \frac{\partial q_j^l}{\partial I^k} = \frac{\delta\frac{\partial c^k}{\partial I^k}\left(\frac{\partial c^l}{\partial Q^l} - \frac{\partial c^k}{\partial Q^k}\right)}{9\frac{\partial c^k}{\partial Q^k}\frac{\partial c^l}{\partial Q^l} - \delta^2\left(\frac{\partial c^k}{\partial Q^k} + 2\frac{\partial c^l}{\partial Q^l}\right)\left(2\frac{\partial c^k}{\partial Q^k} + \frac{\partial c^l}{\partial Q^l}\right)} \quad (48)$$

When $\partial c^l/\partial Q^l = \partial c^k/\partial Q^k$, we can show that $\partial q_i^k/\partial I^k = \partial q_j^k/\partial I^k > 0$ as well as $\partial q_i^l/\partial I^k = \partial q_j^l/\partial I^k = 0$. The first part is straightforward, as the increase of terminal capacity naturally leads to the increase of traffic. The second part is more interesting, as it tells that even with the existence of knock-on effect, i.e., $\delta \neq 0$, the capacity decision of a terminal has no effect on the traffic level of the other terminal as long as they share the same marginal cost of congestion.

5.2 Global optimum

Differentiating equation (3) with respect to I^k and applying Crammer's rule, the first-order-condition that characterizes the optimal port terminal capacity decision is given by:

$$-\frac{\partial c^k}{\partial I^k}\left(Q^k + \delta Q^l\right) = r \quad (49)$$

From equation (49) we can see that the larger δ, the larger the LHS. Since $r > 0$ and $\partial^2 c^k / \partial {I^k}^2 \leq 0$, we can conclude that the larger δ, the larger the socially optimal terminal capacity level. This is intuitive, since a global welfare maximizer cares not only the congestion level of one port but also its externality on the other port. Therefore, the larger the knock-on effect, the higher the incentive of the decision maker to decrease the congestion in a particular terminal through more investment in terminal capacity.

5.3 Profit-maximizing terminals

5.3.1 Coordinated terminal operator.

Differentiating equation (4) with respect to I^k, we have:

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial I^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial I^k} + \left(\mu_i^l - T^l\right)\frac{\partial q_i^l}{\partial I^k} + \left(\mu_j^l - T^l\right)\frac{\partial q_j^l}{\partial I^k} - r = 0 \tag{50}$$

Substituting equations (35)-(38), (47) and (48) into equation (50) and imposing the condition $\partial c^l / \partial Q^l = \partial c^k / \partial Q^k$, we can obtain:

$$-\frac{\partial c^k}{\partial I^k}\left(Q^k + \delta Q^l\right) = r \tag{51}$$

Surprisingly, equations (49) and (51) are exactly the same in forms, which means that the optimal capacity rules are the same under global optimum and coordinated profit maximizing. In fact, this is also consistent with literature (e.g., Zhang and Zhang, 2006) when market power is abstracted away.

5.3.2 Independent terminal operator

Differentiating equation (5) with respect to I^k, we obtain:

$$\left(\mu_i^k - T^k\right)\frac{\partial q_i^k}{\partial I^k} + \left(\mu_j^k - T^k\right)\frac{\partial q_j^k}{\partial I^k} - r = 0 \tag{52}$$

Substituting equations (41), (42), (47) and (48) into equation (52) and imposing the condition $\partial c^l / \partial Q^l = \partial c^k / \partial Q^k$, we will have:

$$-\frac{\partial c^k}{\partial I^k} Q^k (1 - \delta^2) = r \tag{53}$$

In rule the LHS of equation (53) is smaller than the LHS of equations (49) and (51). When $\delta = 0$, the three investment rules are equal to each other; but when $\delta > 0$, the independent capacity rule is smaller than the other two rules. So the independent terminal operators will under-invest.

Proposition 4: The capacity investment rules are the same for welfare-maximizing terminal operator and coordinated profit-maximizing terminal operator, while independent profit-maximizing terminal operators invest less in capacity. The larger the knock-on effect, the larger the difference.

Proof:

Equations (49) and (51) are identical in forms.

Comparing the LHS of equation (49)/(51) with that of equation (53), we have

$$Q^k + \delta Q^l \geq (1 - \delta^2) Q^k$$

Since $\partial c^k/\partial I^k < 0$ and $\partial^2 c^k/\partial {I^k}^2 \geq 0$, we can conclude that the optimal I^k in equation (53) is smaller than that in equation (49)/(51).
When $\delta = 0$,

$$\Delta = Q^k + \delta Q^l - (1-\delta^2)Q^k = 0$$

And Δ increases with δ.
Q.E.D

Intuitively speaking, independent profit-maximizing terminal operators tend to under-invest in terminal capacity because they ignore the connection between different terminals. In particular, they fail to take into account the positive externality of capacity investment, i.e., the decrease in the congestion cost spilled over to other terminals through knock-on effect.

Proposition 4 is particularly interesting when combined with Proposition 3. Comparing the two scenarios of profit-maximizing terminal operator, Proposition 3 suggests that separate ownership is likely to induce better outcome regarding terminal charge, while Proposition 4 hints that common ownership is more socially beneficial regarding terminal capacity investment (for given traffic levels). In other words, from the perspective of policy makers, it is not straightforward to conclude that one scenario is more desirable than the other.

6. Discussion and Concluding Remarks

In this paper we have developed a simple theoretical model to analyze the congestion internalization of the shipping lines, taking into account the knock-on effect. We found that with the presence of the knock-on effect, liners will operate less at congested terminals, and an increase of a liner's operation in one terminal will decrease its operation in the other. In a Stackelberg competition, whether the liners operate more or less in a terminal with the presence of the knock-on effect depends on the comparison between the marginal congestion costs of terminals under consideration. Furthermore, we found that the coordinated profit-maximizing terminal charges are higher than both the socially optimal terminal charges and the independent profit-maximizing terminal charges. Whether the independent profit-maximizing terminal charges are set at higher levels than the overall optimum terminal charges depends on the magnitude of the knock-on effect. Besides, the capacity investment rules are the same for the welfare-maximizing terminal operator and coordinated profit-maximizing terminal operator, while the independent profit-maximizing terminal operators invest less in capacity. The larger the knock-on effect, the larger the difference. Important policy implications can be drawn from these results: when comparing the coordinated as well as independent profit-maximizing terminal operators, our results suggest that separate ownership is likely to induce a better outcome regarding terminal charges, while common ownership is more socially beneficial regarding terminal capacity investments (for given traffic levels).

This paper may serve as the first step in analyzing terminal congestion with the presence of the knock-on effect. We note that for analytical simplicity, certain assumptions have been made in this paper. First, we assume that the shipping lines face a horizontal demand curve. This assumption is in place to remove the impact of market power in pricing, thus limiting the analysis to the impacts of congestion. It can be removed easily, which will not affect the qualitative results of the paper. Second, in many parts of the analysis we have ignored the second-order effect of the terminal congestion. By doing so we reduced the complexity of the analysis significantly. Adding back the second-order effect might slightly alter some of the results but the general conclusions should still hold qualitatively. For example, in a Stackelberg game with the second-order effect of congestion, the benchmark case for the follower's best response is slightly different from -1/2, but the knock-on effect will drive the results away from the benchmark case in exactly the same fashion irrespective of the exact level of this benchmark.

Another venue of further study is to empirically test whether liners actually do internalize terminal congestion, and the relationship between this internalization and the knock-on effect. While internalization of airport congestion has been discussed extensively in the air transport literature, whether airlines do internalize congestion remains a largely unanswered question due to conflicting empirical evidence (see Zhang and Czerny (2012) for a recent survey of the literature). For example, Brueckner (2002) and Mayer and Sinai (2003) offer empirical evidences in support of the internalization hypothesis, showing that flight delays are lower at highly concentrated airports, where the dominant carrier is likely to internalize much of the congestion it creates, thus limiting its extent. On the other hand, Daniel (1995), despite identifying the potential for congestion in terminalization, argued that an atomistic model, where carriers ignore the congestion impact of their scheduling decisions, is more empirically relevant. It appears that the port industry may offer a more natural setting for such an empirical test than the airport industry. As documented in, among others, Talley (2009) and Ng and Liu (2014), some container lines have their own dedicated terminals while others use common-use terminals. Based on the theory of self-internalization, we should find empirically that lines encounter less congestion at the former than at the latter case (after taking account of the knock-on effect and controlling for traffic volumes and other factors).

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