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DISCUSSION PAPER

Private Port Pricing and Public Investment in Port and Hinterland Capacity (*)

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Abstract

We study duopolistic pricing by ports that are congestible, share the same overseas customers and have each a downstream, congestible transport network to a common hinterland. In the central set-up, local (country) governments care about local welfare only and decide on the capacity of the port and of the hinterland network. We obtain the following results. First, profit-maximizing ports internalize hinterland congestion in as far as it affects their customers. Second, investment in port capacity reduces prices and congestion at both ports, but increases hinterland congestion in the region where the port investment is made. Investment in a port's hinterland is likely to lead to more port congestion and higher prices for port use, and to less congestion and a lower price at the competing port. Third, the induced increase in hinterland congestion is a substantial cost of port investment that strongly reduces the direct benefits of extra port activities. Fourth, imposing congestion tolls on the hinterland road network raises both port and hinterland capacity investments. We illustrate all results numerically and discuss policy implications.

Keywords: Port pricing, congestion, investment, cost benefit rules

JEL codes: L92, R4, H71

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1. Introduction

This paper studies pricing and investment decisions in a market where congestible facilities compete for traffic, and where this traffic shares a congestible downstream facility with other users. While highly stylized, the model captures key features of competition among maritime ports that are congestion-prone, and that serve a hinterland to which they are connected by congested transport networks.[1] Consider, for example, European ports such as Rotterdam, Antwerp and Le Havre. These ports compete for traffic in an oligopolistic setting, and both the port facilities and (especially) road and rail networks in the hinterland have become increasingly congested.[2] We analyze investment and pricing decisions in this environment, emphasizing the interaction between the duopolistic port market and hinterland congestion. As such, the analysis is directly relevant to European port pricing and investment policy.

Our analysis considers two congestible ports that compete for traffic in a market for overseas shipments, and focuses on the interaction between two components of the overall costs of such shipments: the costs of using port services and the cost of hinterland transport towards the final destination. We assume that shippers decide on the port of transshipment on the basis of the generalized cost of the complete trip from origin to destination, where the generalized costs includes the costs of sea transport, monetary and time costs at the ports, and the generalized cost of hinterland transport. We allow hinterland transport to be subject to a transport tax or toll; however, consistent with current European policies, due to the absence of road pricing, the hinterland tax is treated as exogenous and not necessarily optimal.

In this setting, we analyze the interaction between the pricing behavior of the ports and optimal investment policies in port and hinterland capacity. The framework used is that of a two stage-game in capacities and prices. Moreover, the main focus of the paper is on a governance structure where capacity decisions are public but pricing is private; this is a simplified representation of actual decision-making structures

[1] To focus on a few well defined aspects of the interaction port-hinterland, we ignore many real-world complications, like the behavior of private operators within ports, the structure of the shipping industry, supply chain considerations, etc. Introducing them into the current model would not affect the main lessons derived from the paper but would strongly complicate the technical analysis.

[2] Similar examples of competing ports with congested hinterlands include ports on the West Coast of the U.S., Mexican and U.S. ports in the Gulf of Mexico, etc. The interaction between the ports of Los Angeles and Long Beach in California is a variation on the theme developed here, in the sense that these ports share the *same* congestible hinterland.

pertaining to many ports in Europe. At the capacity stage, we assume that local (country) governments make optimal decisions with respect to port and hinterland investments, taking into account the pricing behavior of ports. We assume that they take the port and hinterland capacities of the other region as given. At the pricing stage of the game, privately operating ports determine port prices, taking into account potential congestion at the port itself and, as we will see, on the hinterland transport network. For purposes of comparison, at the pricing stage we also briefly compare private pricing with two other pricing regimes: public pricing by the local government and overall surplus-maximizing port pricing.[3] The game is analyzed by backwards induction.

This paper is related to recent work on the interaction between strategic behavior in oligopolistic markets and congestion (see Brueckner, 2002; Basso and Zhang, 2006; De Borger and Van Dender, 2006; Pels and Verhoef, 2007). Moreover, it builds upon earlier work dealing with the pricing of transport services on simple parallel and serial networks that are jointly used by transit (through traffic) and by local traffic (see De Borger, Proost and Van Dender, 2005; De Borger, Dunkerley and Proost, 2007). Essentially, our set-up is that of a parallel network problem, where each alternative consists of two serial links that are only imperfectly controlled by the local government. Our main contribution is that we consider interactions between an upstream duopolistic market and downstream congestion.

The main results are as follows. First, we show that ports will charge their users not only for congestion at the port facilities, but also for that part of the extra hinterland congestion they impose on their other customers. Cases of such "partial internalization" have been noted before, although in a different context. For example, Brueckner (2002) finds that oligopolistic carriers at airports internalize congestion caused by their own flights in as far as it affects their other flights.[4] Our analysis shows that partial internalization applies to hinterland congestion: ports with heavily congested hinterlands will charge higher prices, ceteris paribus. Second, extra investment in one port reduces congestion at both ports (as in De Borger and Van Dender, 2006), but it raises hinterland congestion in the region where the port is located. We further show that investment in a port's hinterland is likely to lead to

[3] The pricing rules are extensions of those derived in Braid (1986), Verhoef et al. (1996) and Van Dender (2005).

[4] The empirical work by Mayer and Sinai (2003) supports the internalization hypothesis, but more recently Harback and Daniel (2007) find evidence against internalization.

more congestion and higher prices for port facility use, and to less congestion and a lower price at the competing port. A third finding is that welfare maximizing local governments will tend to strategically invest to support the local port, but that the induced increase in hinterland congestion is an important cost of port investment. Moreover, in line with the strategic trade literature (e.g. Brander and Spencer (1985) and Barrett (1994)), price competition between ports has relevant implications for public investment decisions. Specifically, the results suggest that duopolistic port pricing induces reduced public provision of port capacity, and more so when downstream congestion is not internalized. The reason is that the reduced capacity leads to higher port profits, and reduces hinterland congestion (which is beneficial when there are no congestion tolls). Fourth, we find that, in a congested hinterland environment, higher transport taxes on the hinterland road network raise both port and hinterland capacity investments.

Lastly, comparing the results under private pricing with those obtained under the assumption that pricing as well as capacity decisions are under the control of the local government, we show that private ports do not necessarily charge higher port prices. If hinterland congestion is severe and port-related traffic is only a small fraction of hinterland transport, private ports actually charge less than public ports, because they ignore the welfare losses of local hinterland users when setting prices.

The paper is structured as follows. After a presentation of the model components in section 2, we analyze in section 3 the strategic pricing game between private operators for given capacities. In section 4 we discuss the investment strategies of the government that guide decisions on port capacity and hinterland capacity. In section 5 we numerically illustrate a number of our theoretical findings. The last section discusses policy implications and offers concluding comments.

2. Model structure

We study two congestible facilities (e.g. ports) that compete for traffic; users of these facilities make their decisions based on the generalized cost of the complete trip (which includes, in the case of ports: sea transport, port monetary and time costs, and the generalized cost of hinterland transport). For example, an overseas shipment from New York to the German industrial Ruhr area may use the ports of Antwerp or Rotterdam. If the shipper selects Antwerp, this implies the use of the Belgian road or rail network; if the shipment goes through Rotterdam, it is affected by hinterland conditions on the Dutch network. We assume the decision makers for these shipments take congestion as exogenously given, both at the facility and on the hinterland network.[5] The ports compete for traffic, as it generates port revenue.

Of course, both the assumption of duopolistic ports and the linking of each port to a given hinterland is a bit restrictive: ports are more generally oligopolistic, and in reality several ports may compete for the same hinterland. Although the main reason for the assumptions made is analytical tractability, all qualitative results are likely to carry over to the case of a port duopoly with a competitive fringe. This is a fairly reasonable description of port competition in the Hamburg-Le Havre range, where Rotterdam and Antwerp have a much larger market share than other ports.

We study pricing for port facilities and investment decisions with respect to both port and hinterland capacity. To simplify the analysis, we assume that the government is the main responsible for both investment decisions, but that private operators decide on port prices. This situation is a reasonable, though imperfect, description of the current situation in Europe. Most of the sea access investments (deepening of access routes, investment in locks, etc.) are indeed controlled and financed by the public sector. Port handling operations are often privately controlled by a few operators. We simplify the analysis by aggregating them into one private monopoly operator per port. We further allow for fixed tolls or taxes on the hinterland network. This describes most motorways where pricing takes the form of fuel taxes that are uniform across the country. Note that these hinterland tolls are assumed to be exogenous, and that we do not consider the government's problem of setting optimal tolls. Implementing optimal road pricing is difficult in practice, and very few European countries have attempted to do so; moreover, ignoring the issue of optimal hinterland tolls and focusing on investment decisions for the local (country) government keeps the problem analytically manageable.

We model the decision-making process in each region in two stages: the government of each region first decides on port and hinterland capacities; given these capacities, the private port operators decide on prices for the use of port facilities. In this second stage, given local investment policies, the ports compete for traffic and

[5] This is quite realistic for congestion on the hinterland. It is more debatable for port congestion: in fact, it rules out ports where only a few shipping companies take the bulk of the traffic. If this is the case, theory suggests that shipping companies would partly internalize congestion (Brueckner, 2002).

engage in a pricing game. We study the problem by backward induction. At the port pricing stage, we are interested in the effect of hinterland congestion and capacities on prices. At the capacity investment stage, we are interested in the effects of congestion and the facilities' pricing behavior on the optimal policies of the government. Specifically, we analyze how the optimal investments take on board the pricing game played by ports.

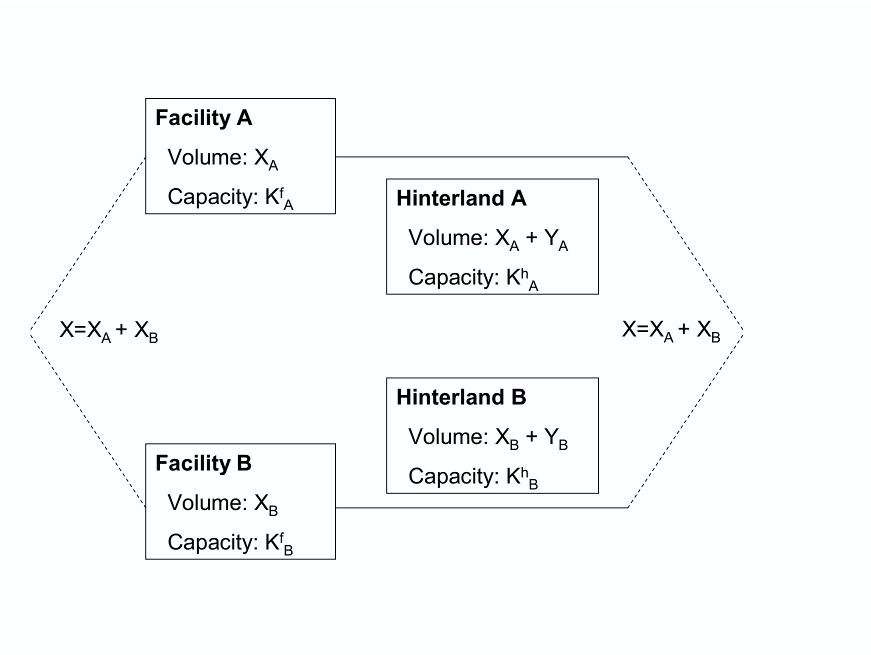
Turning to specifics, consider two possibilities to ship goods from an origin to a destination (see Figure 1 below)[6]. One passes through facility A, the other through B. To save on notation, we similarly denote the routes passing through these facilities as routes A and B. Traffic at facility A is denoted X_A;hinterland road or rail transport, V_A, consists of transport generated by facility A, X_A, plus local traffic on the hinterland network, denoted Y_A. Units of X are measured such that they both capture demand for port services and demand for port-related hinterland transport (think, e.g., of containers).

Total shipments from origin to destination are given by $X = X_A + X_B$. It is assumed that the owner of the shipped goods is indifferent as to the route chosen (except for their generalized cost), so the routes are perfect substitutes. This is a heroic assumption for ports that specialize in particular types of trade, but it may be defended in the case of container trade, a strong and growing segment of the shipping market.[7] Overall demand is given by the inverse demand function $p^X(X)$. Similarly, demand for local use of the hinterland network is described by inverse demand functions $p_A^Y(Y_A)$ and $p_B^Y(Y_B)$.

[6] A similar network structure has been used in recent work by Pels and Verhoef (2007). However, they focus on modal competition between road and rail. The focus of our paper is on the interaction between public infrastructure managers and private port operators, and on the role of congestion on one network link (the hinterland) for pricing and investment decisions.

[7] Introducing imperfect substitutability of ports tends to weaken the strength of the effects identified in our analysis, but it does not fundamentally change them; it does add considerable analytical complexity.

Figure 1. Structure of the model



The generalized cost of the use of route A is the sum of three components: (i) the transport (money plus time) cost to facility A, (ii) the monetary and time cost at facility A, and (iii) the money and time cost of the hinterland road network. Since cost component (i) does not play much of a role in our analysis, we set it equal to zero. We define the generalized cost of use of facility A as the sum of the port charges and the time cost, which depends on the demand for the use of port services X_A and the capacity of port facilities at A, denoted as K_A^f. Hence the generalized price of port facility use at A is:

$$p_A + f_A(X_A, K_A^f), \qquad \frac{\partial f_A}{\partial X_A} \quad 0, \frac{\partial f_A}{K_A^f} \quad 0$$

where p_A is the charge for the use of port A, and the function $f_A(.)$ is what we will call for simplicity the ports 'congestion' function. Note, however, that it not only represents the pure time cost of access to and cargo handling within the port, but also all subjective quality elements that affect the generalized cost of the trip.[8] The congestion cost depends positively on demand and negatively on port capacity.

[8] In fact, the port capacity indicator K_A^f can more generally be interpreted as a quality variable that is affected by the deepening of the sea access, lower administration costs etc. What is important is that the function $f(.)$ depends on the flow and capacity indicator.

The generalized cost of hinterland transport in A is denoted as g_A. It is the sum of money (e.g., fuel costs) and time costs of the hinterland trip, plus applicable tolls on the hinterland connection. Since they are not relevant to our analysis, we ignore the money costs. Hence, the generalized cost g_A of hinterland transport is

$$g_A = h_A(X_A + Y_A, K_A^h) + \overline{t}_A$$

In this expression

$$h_A(X_A + Y_A, K_A^h) \equiv h_A(V_A, K_A^h), \qquad \frac{\partial h_A}{\partial V_A} > 0, \frac{\partial h_A}{\partial K_A^h} < 0$$

is the hinterland congestion function, K_A^h is road capacity on the hinterland network, and $V_A = X_A + Y_A$ is the total hinterland transport volume. The time cost of hinterland transport positively depends on the total transport volume in A and negatively on the transport capacity of the hinterland. Finally, $\overline{t}_A$ is the exogenous local toll on the hinterland link. The exogeneity reflects the fact that currently used tax and toll instruments do not allow for an optimal hinterland tax. Notation and definitions are similar for route B.

We assume that in equilibrium, port-related traffic will be distributed over the two routes A and B so as to equalize the overall generalized costs of the complete trips; this includes port (monetary plus time) costs as well as hinterland travel costs. Equilibrium of transit (i.e., traffic passing through the facility) and local traffic then implies the following:

$$\begin{aligned}
p^X(X_A + X_B) &= p_A + f_A(X_A, K_A^f) + h_A(X_A + Y_A, K_A^h) + \overline{t}_A \\
p^X(X_A + X_B) &= p_B + f_B(X_B, K_B^f) + h_B(X_B + Y_B, K_B^h) + \overline{t}_B \\
p_A^Y(Y_A) &= g_A = h_A(X_A + Y_A, K_A^h) + \overline{t}_A \\
p_B^Y(Y_B) &= g_B = h_B(X_B + Y_B, K_B^h) + \overline{t}_B
\end{aligned} \qquad (1)$$

In Appendix 1 we show that the solution of the equilibrium conditions (1) implies reduced-form demand functions:[9]

$$\begin{aligned}
&X_A^r(p_A, p_B, K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B) \\
&X_B^r(p_A, p_B, K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B) \\
&Y_A^r(p_A, p_B, K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B) \\
&Y_B^r(p_A, p_B, K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B)
\end{aligned}$$

[9] We rule out corner solutions in which only one of the routes (and one of the ports) is used. These would introduce non-continuities in the reduced-from demand functions, and would not offer additional insights.

which have the following properties (similar for demand in B):

$$
\begin{aligned}
&\frac{\partial X_A^r}{\partial p_A} < 0 \qquad \frac{\partial X_A^r}{\partial p_B} > 0 \\
&\frac{\partial X_A^r}{\partial K_A^f} > 0 \qquad \frac{\partial X_A^r}{\partial K_B^f} < 0 \\
&\frac{\partial X_A^r}{\partial K_A^h} > 0 \qquad \frac{\partial X_A^r}{\partial K_B^h} < 0
\end{aligned}
\tag{2}
$$

Higher port prices at A reduce demand at A and raise it at port B. Increases in port capacity in port A raise demand at A, and lower demand at B; better hinterland capacity at A raises demand in A and reduces it in B.

The effects on local hinterland transport are easily derived as well. We find, see Appendix 1:

$$
\begin{aligned}
&\frac{\partial Y_A^r}{\partial p_A} > 0, \ \frac{\partial Y_A^r}{\partial p_B} < 0 \\
&\frac{\partial Y_A^r}{\partial K_A^f} < 0, \ \frac{\partial Y_A^r}{\partial K_B^f} > 0 \\
&\frac{\partial Y_A^r}{\partial K_A^h} > 0, \ \frac{\partial Y_A^r}{\partial K_B^h} > 0
\end{aligned}
\tag{3}
$$

Higher port prices in A raise local demand on A’s hinterland because they reduce port-related traffic there. The opposite holds for a price increase at port B. Increasing the capacity of port A reduces the local demand for transport on A’s hinterland, and raises it in region B; both effects are again due to congestion effects of port-related traffic. Finally, more hinterland capacity in A raises local demand on A’ hinterland network; moreover, it increases local demand in region B as well, because the shift in port traffic from B to A reduces congestion in B.

3. Pricing behavior of port facilities

In this section, we first consider a private port’s optimal pricing policy. Next, we analyze the Nash equilibrium outcome of price competition between the ports and investigate how it depends on investment in port capacity and in hinterland connections on port prices. Finally, we compare the results with those assuming other pricing regimes.

3.1. Pricing behavior of an individual facility

Throughout this subsection, we consider profit maximizing port facilities. Facility A solves:

$$\underset{p_A}{Max}\ \pi_A = p_A X_A \quad C_A(X_A)$$

where $C_A(.)$ is the facility's cost function, and demand is given by reduced-form demand, i.e., $X_A = X_A^r(p_A; p_B, K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B)$. Port A maximizes with respect to its own price, taking prices at B as well as port capacities and hinterland capacities as exogenously given. The first-order condition is given by:

$$(p_A - MPC_A)\frac{\partial X_A^r}{\partial p_A} \quad X_A^r \quad 0 \qquad (4)$$

where $MPC_A = \dfrac{\partial C_A(X_A)}{\partial X_A}$ is the marginal production cost of an increase in port services at A.

In Appendix 2 we show that (4) implies the following pricing rule:

$$p_A = MPC_A \quad MEC_A^f \quad \frac{X_A}{V_A} MEC_A^h (1 \quad \frac{\partial z_A}{\partial X_A}) \quad X_A \frac{\partial p^X}{X} (\ \theta_B \qquad (5)$$

where

$$MEC_A^f = X_A \frac{\partial f_A}{\partial X_A} \qquad\qquad MEC_A^h = V_A \frac{\partial h_A}{\partial V_A}$$

are the marginal external costs at the port facility and on the hinterland road network, respectively. The functions $z_i(X_i, K_i^h; \overline{t}_i)$, defined in Appendix 1, express demand for local hinterland transport as a function of hinterland capacity, the level of port-related traffic and the hinterland tax. It follows from (A1.3) in Appendix 1 that $0 < (1 + \frac{\partial z_A}{\partial X_A}) < 1$. Finally, the coefficient θ_B is given by:

$$\theta_B = \frac{\left[\ \right]\frac{\partial p^X}{\partial X} - M_B}{\left[\ \right] M_B}$$

where $M_B = \frac{\partial p^X}{\partial X} + \frac{\partial f_B}{\partial X_B} + \frac{h_B}{X_B}(1 + \frac{\partial z_B}{\partial X_B}) < 0$. Simple algebra shows that this implies that $-1 \leq \theta_B \leq 0$. Note that $\theta_B = 0$ if there is no congestion at the competing port B.

To interpret pricing rule (5) note that, if there is no hinterland congestion, we reproduce the pricing rules found in Braid (1986), Verhoef et al. (1996) and Van Dender (2005); they studied pricing behavior in the absence of a downstream market.. Indeed, for zero hinterland congestion, simple algebra shows that (5) reduces to:

$$p_A = MPC_A + MEC_A^f + X_A \frac{\partial p^X}{\partial X}\left(1 + \frac{\frac{\partial f_B}{\partial X_B}}{\frac{\partial p^X}{\partial X} - \frac{f_B}{X_B}}\right)$$

This pricing rule implies that ports charge a double markup above the marginal port cost. First, they charge the marginal external cost MEC_A^f at the port itself: the facility charges its users for the reduction in quality (increase in time costs) they impose on other port users. That the port fully internalizes the external cost makes intuitive sense, as the externality is imposed on the port's own customers. Raising the price above private cost reduces demand, but it also reduces congestion (or, alternatively, it facilitates access). Second, congestion allows the port to charge more than marginal external cost. If overall shipping demand is not very elastic and the competing port is congested then a port can increase profits by raising price substantially above marginal social cost. Doing so does not strongly reduce overall demand, and the price increase will not shift many customers to the competing, but congested, port. The second markup is therefore higher the smaller the price elasticity of demand and the higher the congestibility of the competing facility (see, e.g., Van Dender (2005) for more discussion).

Of particular interest in this paper is the role of hinterland congestion in the port pricing rule (5). Introducing hinterland transport and hinterland congestion has two effects on pricing. The first one is due to hinterland congestion in *A* itself; it is captured by the term

$$\frac{X_A}{V_A} MEC_A^h (1 + \frac{\partial z_A}{\partial X_A}).$$

The port facility charges port users for the marginal congestion cost they cause on the hinterland, but only to the extent that it affects other port users. To see this, note that the marginal congestion cost on the hinterland, due to an exogenous increase in port-related traffic, is given by:

$$V_A \frac{\partial h_A}{\partial V_A}\left(1+\frac{z_A}{X_A}\right) = MEC_A^h\left(1+\frac{z_A}{X_A}\right)$$

More port use raises hinterland congestion, but the ultimate increase in traffic volume is limited as more port-related traffic reduces the demand for road use by locals. Hence, an increase in port-related hinterland transport generates less than the full marginal external cost of an exogenous increase in total traffic flow V_A; as noted above, the bracketed term is smaller than 1 (also see A1.3 in Appendix 1). Further note that he facility ignores external costs suffered by local transport on the hinterland network; they only charge for the fraction suffered by other port users (see the term X_A / V_A).

The intuition for internalizing part of the hinterland congestion is again easily understood. A price increase by a port will reduce demand, but this reduction will be limited by the associated reduction in hinterland congestion. Hence the port will charge more than it would in the absence of hinterland congestion.

The second effect of hinterland congestion is that it raises the elasticity related markup. Here hinterland congestion at the competing port B is the driving force. This follows from considering the definition of θ_B in the final term of (5). If demand is not very elastic and the competing port's hinterland suffers from severe congestion, port A knows it can raise prices without losing much demand, so stronger price increases are obtained in the profit maximum.

Clearly, pricing rule (5) implies that prices will exceed private marginal production costs even if there is no congestion at the port facilities itself, due to hinterland congestion. Charging for part of the hinterland congestion cost reduces hinterland congestion and makes the corresponding port more attractive. Of course, the numerical importance of this effect depends on the share of port-related transport in total hinterland transport. A further implication of (5) is that, if one considers two identical facilities with different hinterland congestion problems, then prices will be higher and demand lower at the facility in the country with high hinterland congestion.

3.2. Comparison with other pricing regimes

We conclude this subsection with a brief discussion of other port pricing regimes. First, assume that the government of a given region directly controlled the prices of the local port of that region. Let the objective function of the regional government consist of the net benefits of the local users of the hinterland infrastructure, plus the profits of the local port and the tax revenues on the hinterland[10]. The analytical results for this regime are derived in Appendix 3. Interestingly, we find that optimal pricing behavior in this case differs from the behavior of a profit maximizing port only in the response to hinterland congestion. As shown before, a private port charges for the external cost to the extent that it affects its own customers. The local government on the other hand charges for hinterland congestion only to the extent that the toll on the hinterland is below the marginal external cost of hinterland road use. This has an interesting implication to which we return in the numerical analysis below. It implies that, if hinterland congestion is severe, no tolls are charged on the hinterland and port-related traffic is a small fraction of hinterland transport, then private ports may well charge less than the public local authority. The conditions described may actually capture the current European situation.

Second, consider optimal pricing by a supra-national authority (this could be an institution such as the European Union, or even covering the world level) that not only controls port prices in both regions but also cares about the welfare of shippers: it maximizes global welfare in the two regions jointly, and it incorporates the welfare of shippers in its objective function. The analytical results are derived in Appendix 4. Compared with the pricing rule of private port operators, we find two important but expected differences. One is that, contrary to the private operator, the supranational authority does not charge an elasticity-related markup. The other is that a private operator ignores the time losses of local hinterland traffic; the supranational port authority does take these into account, but again only corrects for hinterland congestion to the extent that tolls on the hinterland are suboptimal. If market power is

[10] It is assumed here for simplicity that the regional government ignores the welfare of shippers. Strictly speaking, this will only be realistic if all shippers welfare goes to foreign firms. Although the share of foreign shippers in European ports is large, part of port-related traffic obviously has its departure or destination in the corresponding region (for the port of Antwerp, e.g., think about deliveries for General Motors). Although we could have introduced local shipments into the analysis, it would have cluttered the main lines of the arguments made in this paper without affecting the main insights.

non-trivial and the former effect dominates, the private operator will therefore charge higher prices.

We summarize the main differences between regimes in Table 1.

3.3. Port competition: Nash equilibrium prices

We return to pricing under private duopoly and study the effects of hinterland and port capacities on Nash equilibrium prices. Note that the optimal pricing rule for a given port implicitly gives the reaction function to price changes at the competing port. Solving the reaction functions yields the Nash equilibrium in prices, which we can write in general as:

$$p_A^{NE}(K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B), \quad p_B^{NE}(K_A^f, K_B^f, K_A^h, K_B^h; \overline{t}_A, \overline{t}_B).$$

The equilibrium obviously depends on all capacities and on the exogenous tolls in both hinterland regions. To discuss the effects of the various capacities on Nash equilibrium port prices, we make some simplifying assumptions. Therefore, we assume in this subsection linear demand functions (both for overall shipping demand X from origin to destination and for local hinterland demands Y_A, Y_B); moreover, we assume both port and hinterland congestion are linear functions of the relevant volume-capacity ratio.

Using these assumptions, we show in Appendix 5 hat investment in port capacity unambiguously induces both ports to reduce prices:

$$\frac{\partial p_A^{NE}}{\partial K_A^f} < 0 \qquad \frac{\partial p_A^{NE}}{\partial K_B^f} < 0 \tag{6}$$

In a sense, this is as expected, because port capacity investments not only reduce port congestion in the port where investment takes place, it also reduces overall shipping demand and hence congestion at the competing port (see, e.g., De Borger and Van Dender, 2006). Unfortunately, the impact of expanding hinterland capacity on port prices is ambiguous, even under the assumed linearity of demand and costs. Unless port-related traffic on the hinterland is very important, however, we show (see Appendix 5 that:

$$\frac{\partial p_A^{NE}}{\partial K_A^h} > 0, \qquad \frac{\partial p_A^{NE}}{\partial K_B^h} < 0 \tag{7}$$

Better hinterland connections in A raise the price of port A, because it raises demand and congestion at port A and this more than compensates the reduction in congestion in the hinterland of A. The same investment in A's hinterland capacity reduces port prices of the competitor, because it reduces demand and both port and hinterland congestion at B.

4. Optimal capacity investment in ports and in hinterland networks

We assume the government is responsible for decisions on investments in port as well as hinterland capacities. Of course, optimal investment rules will strongly depend on the objective function one assumes for the government in a particular region. Here, we assume that government takes into account the profits of intra-regional port activities; moreover, it cares about the welfare of the local users of the hinterland network. The assumption is that, for example, Belgium cares about surplus from port activities in the port of Antwerp, but also about the welfare of Belgian users of the hinterland road network. Importantly, we assume the Belgian government does not specifically care about the time losses that shippers suffer on the network, but it does care about the tax revenues it receives from their use of the hinterland capacity, and about the profits the regional port can earn on their use of port facilities. In this sense, our setup reflects an extreme case, where any surplus from shippers accrues to foreign firms.[11]

Specifically, the government is assumed to maximize the following social welfare function:

$$\underset{K_A^f, K_A^h}{Max} \int_o^{Y_A} p_A^Y(y)dy - g_A Y_A^r + [p_A X_A^r \quad C_A(X_A^r) \quad k_A^f K_A^f \quad k_A^h K_A^h \quad \overline{t}_A(X_A^r \quad Y_A^r)$$

where $g_A = h_A(X_A \quad Y_A, K_A^h) \quad \overline{t}_A$, and the $k_j^i \; (i = f, h; j \quad A, B)$ denote the unit capacity costs, assumed to be constant. Note that we impose constant returns to scale in port and hinterland capacity.

[11] An alternative setup would be to include shippers' surplus in the local welfare function, to the extent that shipping companies are locally owned. Anticipating on results, doing so will reduce the difference between local and global surplus-maximizing solutions, while increasing the difference between the duopoly outcome and the local surplus maximizing outcome.

In analyzing the joint problem of optimal choices of port and hinterland capacity, it will be instructive to work in two steps[12]. This seems useful in order to identify the implications of duopolistic pricing behavior by ports for government investment policies. In a first step, we describe the optimal investment rules assuming that the government treats port prices as given. This yields the optimal capacity rules under the conditions of exogenous prices, ignoring the possible reactions of ports' pricing behavior to capacity decisions and the implications of this behavior for investment decisions. In a second step, we then focus on how capacity decisions are affected if the government explicitly anticipates the pricing behavior at the ports.

4.1. Optimal investment policies: exogenous port prices

Treating port prices as given, the first-order conditions for optimal investment in port and hinterland capacities are given by, respectively:

$$\left[p_Y^A(Y_A) - g_A\right]\frac{\partial Y_A}{\partial K_A^f} \quad Y_A^r \frac{dh_A}{dK_A^f} \quad (p_A \quad MPC_A)\frac{X_A^r}{K_A^f} \quad k_A^f \quad \bar{t}_A\left(\frac{X_A^r}{K_A^f} \quad \frac{Y_A^r}{K_A^f}\right) \quad 0 \qquad (8a)$$

$$\left[p_Y^A(Y_A) - g_A\right]\frac{\partial Y_A}{\partial K_A^h} \quad Y_A^r \frac{dh_A}{dK_A^h} \quad (p_A \quad MPC_A)\frac{X_A^r}{K_A^h} \quad k_A^h \quad \bar{t}_A\left(\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h}\right) \quad 0 \qquad (8b)$$

We know generalized prices and costs are equal (see (1)), so the first term on the left-hand-side of both equations is zero. Moreover, note that:

$$\frac{dh_A}{dK_A^f} = \frac{\partial h_A}{\partial V_A}\left[\frac{\partial X_A^r}{\partial K_A^f} \quad \frac{Y_A^r}{K_A^f}\right] \quad \frac{h_A}{V_A}\frac{X_A^r}{K_A^f} \quad 1 \quad \frac{z_A}{X_A} \quad >0 \qquad (9a)$$

$$\frac{dh_A}{dK_A^h} = \frac{\partial h_A}{\partial K_A^h} \quad \frac{h_A}{V_A}\left[\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h}\right] <0 \qquad (9b)$$

More port capacity generates extra port activities and this increases congestion on the hinterland. More hinterland capacity has a direct, negative, effect on the generalized cost of hinterland transport, plus indirect effects on costs due to changes in transport volumes. Overall, using the results derived in Appendix 1, the effect is easily shown to be negative, however. Hinterland investment reduces hinterland congestion.

Substituting (9a)-(9b) in expressions (8a-8b), we obtain

[12] See, among others, Barrett (1994) for a similar two-step procedure in the analysis of strategic environmental standards.

$$(p_A - MC_A)\frac{\partial X_A}{\partial K_A^f} - Y_A\left\{\frac{\partial h_A}{\partial V_A}\left[\frac{\partial X_A^r}{\partial K_A^f}+\frac{\partial Y_A^r}{\partial K_A^f}\right]\right\} + \bar{t}_A\left(\frac{\partial X_A^r}{\partial K_A^f}+\frac{\partial Y_A^r}{\partial K_A^f}\right) = k_A^f \qquad (10a)$$

$$(p_A - MC_A)\frac{\partial X_A}{\partial K_A^h} - Y_A\left\{\frac{\partial h_A}{\partial K_A^h}+\frac{\partial h_A}{\partial V_A}\left[\frac{\partial X_A^r}{\partial K_A^h}+\frac{\partial Y_A^r}{\partial K_A^h}\right]\right\} + \bar{t}_A\left(\frac{\partial X_A^r}{\partial K_A^h}+\frac{\partial Y_A^r}{\partial K_A^h}\right) = k_A^h \qquad (10b)$$

These rules simply state that port and hinterland capacity are determined by comparing marginal benefits and costs. From the viewpoint of the local government's welfare function, marginal benefits consist of three elements: potential reductions in hinterland transport costs for the local users, the extra port profits generated by capacity expansions and, finally, the induced extra tax revenues on hinterland transport. However, despite the very similar structure of the government's first-order conditions, note the important difference referred to above (see (9a)-(9b)). Port capacity expansions raise the generalized cost of hinterland transport. This implies that port capacity expansions result in an extra cost from the viewpoint of the government. However, capacity investments in the hinterland road or rail network reduce hinterland congestion, generating an extra benefit. So, ceteris paribus, policy-makers may be more inclined to invest in hinterland capacity than in port capacity.

The policy implications easily follow if we slightly reformulate the optimal capacity rules (10a)-(10b) as follows:

$$(p_A - MC_A)\frac{\partial X_A}{\partial K_A^f} + \left(\bar{t}_A - Y_A\frac{\partial h_A}{\partial V_A}\right)\left(\frac{\partial X_A^r}{\partial K_A^f}+\frac{\partial Y_A^r}{\partial K_A^f}\right) = k_A^f \qquad (11a)$$

$$(p_A - MC_A)\frac{\partial X_A}{\partial K_A^h} - Y_A\frac{\partial h_A}{\partial K_A^h} + \left(\bar{t}_A - Y_A\frac{\partial h_A}{\partial V_A}\right)\left(\frac{\partial X_A^r}{\partial K_A^h}+\frac{\partial Y_A^r}{\partial K_A^h}\right) = k_A^h \qquad (11b)$$

Note that we can interpret $Y_A\frac{\partial h_A}{\partial V_A}$ as the local marginal cost of congestion: it captures the impact of extra traffic on the time cost of hinterland transport for all local users.

First consider the optimal port capacity rule. The first term on the left hand side suggests that the local government in A has an incentive to invest in extra port capacity to stimulate activities and profits of the local port. The second term, however, indicates that the extra hinterland traffic that is induced by port expansion is to be considered a cost if the local toll falls short of the local marginal external congestion cost on the hinterland. As this is probably true for most European hinterland networks, where formal tolls have not been introduced, port expansions generate an extra cost on the hinterland, making port investments less attractive.

To interpret the hinterland capacity rule, we again note that the government will stimulate investment to support port activities. A first benefit of investment is indeed again the effect on port profits, see the first term on the left hand side. Moreover, a second benefit of investment is that providing more hinterland capacity directly reduces congestion, for given traffic volumes (see the term $\frac{\partial h_A}{\partial K_A^h}$). The third term on the left hand side captures the indirect effects of capacity on hinterland congestion. The lower congestion levels on the hinterland will itself attract extra traffic. If the tax is below local marginal external cost, then the effect of induced traffic is a cost of the capacity investment. Note the role of existing hinterland taxes. Expressions (11a)-(11b) suggest that regions with high hinterland taxes (high fuel taxes, tolls for road use, etc.) relative to the external costs imposed on local traffic will, ceteris paribus, be more inclined to invest, both in port and in hinterland capacity.

4.2. Optimal investment policies: the role of pricing policies by ports

Reconsider the problem of optimal capacity choices, but now also explicitly incorporate the effects of pricing reactions to capacity changes by the duopolistic ports. When deciding on their investments, we assume that governments now fully anticipate the effects of capacity changes on the Nash pricing game played by the private ports.

Consider first hinterland capacity; the first-order condition now becomes:

$$(p_A - MPC_A)\frac{dX_A^r}{dK_A^h} \quad X_A\frac{\partial p_A^{NE}}{\partial K_A^h} \quad Y_A^r\frac{dh_A}{dK_A^h} \quad k_A^h \quad \bar{t}_A\left(\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h}\right) \quad 0 \qquad (12)$$

where the total effects are given by:

$$\frac{dh_A}{dK_A^h} = \frac{\partial h_A}{\partial K_A^h} \quad \frac{\partial h_A}{\partial V_A}\left[\frac{V_A}{K_A^h}\right] \quad \frac{h_A}{V_A} \quad \frac{V_A}{p_A}\frac{p_A^{NE}}{K_A^h} \quad \frac{V_A}{p_B}\frac{p_B^{NE}}{K_A^h}$$

$$\frac{dX_A^r}{dK_A^h} = \frac{\partial X_A^r}{\partial K_A^h} \quad \frac{X_A^r}{p_A}\frac{p_A^{NE}}{K_A^h} \quad \frac{X_A^r}{p_B}\frac{p_B^{NE}}{K_A^h}$$

Substituting these relations into (12), and using the first-order condition for optimal pricing by the port authority, (viz. $(p_A - MPC_A)\frac{\partial X_A^r}{\partial p_A} + X_A^r = 0$), we easily show that:

$$
(p_A - MPC_A)\frac{\partial X_A}{\partial K_A^h} + Y_A\frac{\partial h_A}{\partial K_A^h} + \left(t_A - Y_A^r\frac{\partial h_A}{\partial V_A}\right)\left[\frac{\partial X_A^r}{\partial K_A^h} + \frac{\partial Y_A^r}{\partial K_A^h}\right]
$$
$$
+ (p_A - MPC_A)\frac{\partial X_A}{\partial p_B}\frac{\partial p_B^{NE}}{\partial K_A^h} + \left(t_A - Y_A^r\frac{\partial h_A}{\partial V_A}\right)\left\{\frac{\partial V_A}{\partial p_A}\frac{\partial p_A^{NE}}{\partial K_A^h} + \frac{\partial V_A}{\partial p_B}\frac{\partial p_B^{NE}}{\partial K_A^h}\right\} = k_A^h \tag{13a}
$$

As before, the left-hand side summarizes potential marginal benefits of hinterland capacity expansion. The first three terms are the same as in (11b) above, the two final terms summarize the effects of taking into account the pricing reactions by ports to capacity expansion for hinterland transport.

First, the price responses in B affect port profits in A, as captured by the fourth term. Suppose, e.g., that better hinterland connections via investment in roads or rail in region A lead port B to reduce its price; note that this was found to be highly plausible (see section 2.2 above). This will in turn decrease port profits at A. The pricing response therefore reduces the benefits of extra hinterland investment, and the government's optimal policy will be to invest less than it would in the absence of strategic pricing behavior. Second, however, there is another effect captured by the final term in (13a). Indeed, capacity-induced price changes in ports also have implications for the volume of traffic. If hinterland investment in A raises prices at port A and reduces the price at port B, then the hinterland traffic volume will decline. If the hinterland toll is below marginal external cost for local users, this provides an extra benefit of hinterland investment, and this will induce the government to invest more. In a certain sense, the induced traffic problem, typical for under-priced infrastructure, is mitigated by the pricing reactions at the competing port. The ultimate overall effect depends on the sign and magnitude of the third and fourth term. In regions with high un-priced hinterland congestion, the latter effect may well dominate; in that case the government strategically invests more in hinterland capacity because this induces ports to change prices in a way that reduces hinterland congestion.

Going through a similar analysis for port capacity, again using the port's first-order condition for maximum profit, we obtain:

$$(p_A - MPC_A)\frac{\partial X_A}{\partial K_A^f} - t_A\left[Y_A^r \frac{h_A}{V_A}\left(\frac{X_A^r}{K_A^f} - \frac{Y_A^r}{K_A^f}\right)\right]$$
$$+ (p_A - MPC_A)\frac{\partial X_A}{\partial p_B}\frac{\partial p_B^{NE}}{\partial K_A^f} - t_A\left\{Y_A^r \frac{h_A}{V_A}\left(\frac{V_A}{p_A}\frac{p_A^{NE}}{K_A^f} - \frac{V_A}{p_B}\frac{p_B^{NE}}{K_A^f}\right)\right\} = k_A^f \qquad (13b)$$

As before, the first three terms are the same as in (11a). The fourth term states that, if providing more port capacity in A induces port B to lower prices (which we found to be the case under linearity of demand and costs), then this reduces the benefit of the port investment, and optimal investment goes down. The reason is that the profit effect of higher port capacity is diluted by price reductions in the competing port. Moreover, the final term on the left-hand side implies that if, as suggested above, prices go down at both ports after the capacity increase and own price effects dominate, then this gives a further reduction in benefit, again leading to lower port capacity. This shows that strategic pricing by ports leads the government to invest less in port capacity than it otherwise would. Underinvestment raises profits and reduces hinterland congestion.

4.3. Comparison of different other regimes

To conclude this section, we again briefly compare capacity rules in different other regimes. A summary of findings is in Table 2. When port prices are determined by private port operators, capacity rules followed by the regional government take account of the induced port profits, as just explained above. Of course, this is not the case if local governments decide on prices as well as capacities; they just follow the rules (11a-11b). Finally, suppose a global authority controlled both regions and that takes account of the welfare of shippers. The capacity rules for this case are developed in Appendix 4. Interestingly, we find that it would follow standard first-best rules for optimal capacity: the marginal capacity cost equals the marginal benefit of capacity investment. The benefits just consist of the direct reduction in the time costs of port use (for port investment) and the reduction in hinterland time costs enjoyed by all hinterland users, local as well as port-related (case of hinterland investment). That the authority would follow first-best capacity rules, despite the absence of an optimal hinterland toll, can be explained by the availability of an extra pricing instrument, viz., port prices. The result implies that the authority would correct inappropriate pricing of hinterland traffic by adjusting port prices, not by adjusting capacity rules.

5. Numerical illustration

In this section, we use a numerical version of the model to illustrate the main interactions contained in the analytical model. Moreover, the numerical exercise allows us to investigate the role of some crucial parameters, such as the slope of the demand and congestion functions, and to point at the role of hinterland tolls. Finally, we briefly consider asymmetries between regions.

5.1. Properties of the numerical model

For simplicity, we assume initially that the two regions are perfectly symmetrical, so that the traffic flows on the respective hinterlands and the transport flows passing through the two ports are equal in the equilibrium. The parameter values used do not describe any particular real world example, but they are selected to obtain reasonable orders of magnitude for price elasticities and estimates of marginal external costs of port and hinterland congestion. They imply an elasticity of overall shipping demand with respect to the generalized price of about -0.2; the price elasticity of demand for local hinterland road use was approximately -0.1. The former is higher, on the assumption that shippers have other options than the two ports A and B explicitly considered by the model. For example, the model could describe competition between Antwerp and Rotterdam for shipping demand from overseas to the German Ruhr area; obviously, then, shippers have other options in the Le Havre – Hamburg range for their shipments.[13] Precise information on the demand elasticities relevant for this model is hard to come by; as will be shown, however, changing elasticities of demand for port and for local traffic by the same proportion only affects the size of differences between scenarios, but not the nature of the differences.

The situation captured in the illustration is one where port-related hinterland transport is important, accounting for about half of total transport demand on the hinterland. For road transport, this implies a focus on the vicinity of the port, where

[13] Restricting attention to the interaction between Antwerp and Rotterdam makes sense, however, because of their proximity and their large market share (see, e.g., Notteboom, 2006)

the contribution of port traffic to congestion is prominent. For rail, it reflects the situation on particular rail lines connecting ports with industrial areas, where the shares of port-related traffic are large. The calibrated marginal external costs in the reference situation are about 50% of the private time cost of port and road use. The marginal port handling cost and the marginal operating cost of hinterland transport (excluding time costs) are constant and, without further loss of generality, are set equal to zero. We also set hinterland tolls equal to zero, except where mentioned.

5.2. Key Results for the base scenario

Table 3 summarizes the results for the base scenario; three cases are considered. The first one, labeled "private", is the situation discussed extensively in the theoretical section of the paper: what pricing and investment policies can one expect if the two ports are privately operated and they compete in a Cournot structure, but country governments decide on port and hinterland capacities. The welfare function of the country governments is the one studied in the theoretical section; it captures the surplus of local hinterland users, profits of the local port, toll revenues (if any) and port and hinterland capacity costs. The second case, denoted "local surplus", considers the situation where the two local governments decide on port prices as well as capacities, again maximizing the country welfare function. The third case is that of "global surplus" maximization, where a central decision-maker maximizes overall surplus for the whole network; this includes the surplus of all port users in the two ports plus the local surplus on the two hinterlands. Note that this third case does not correspond to the first-best, as hinterland tolls are constrained and generally differ from marginal congestion costs.

The bottom line of Table 3 shows that, as expected, the total surplus increases as the objective function becomes 'more inclusive': it is lowest for the "private ports" case and, obviously, highest for the "global surplus" case. What is less obvious is that the biggest increase in the total surplus occurs in the transition from "local surplus" to "global surplus". To interpret this, note that the key differences between the "private" and "local" surplus cases are whether prices are set by the private operator or the public authority and, related to this, the treatment of port profits; they are maximized in setting prices in the "private" case, they are taken into account as part of the objective function in the "local surplus" case. The key difference between the "local surplus" and the "global surplus" case lies in the absence or presence of regional coordination and the inclusion of shippers' surplus in the objective function. The numerical results therefore suggest that regional coordination and taking account of shippers' surplus leads to a larger welfare gain than bringing port prices under local control.

Related to this, we observe from Table 3 that the composition of the total surplus differs across scenarios. The biggest change is the increase, in absolute and relative terms, of shippers' surplus in the "global surplus" case. This result is reminiscent of De Borger et al. (2005), where it is found that global surplus maximization leads to large surplus gains, in particular for through-traffic; the same holds for shippers' surplus on the throughput X which passes through the port. Further, note that in moving from the "private" case to the "local surplus" case, both local surplus and port profits increase (these components get the same weight in the objective function).

It may seem counterintuitive that profits are higher in the local surplus case than in the private port case. The results in Table 3 suggest that it is a combination of two factors. First, the discussion in section 3.1 indicated that, for given capacity levels, publicly operated ports may actually charge higher prices than private ports because, if tolls are below marginal external cost, they take full account of the beneficial downward effect of higher port prices on hinterland congestion. Second, investment behaviour differs between the two regimes as well. In the "private" case, the local government takes account of the effect of capacity investments on prices by private ports operators; it does not directly controls port prices. In the "local surplus" case, it does. This induces the local government to invest less in port and hinterland capacity when prices are privately determined, because in this case capacity increases reduce the prices set by the private ports, and hence port profit. The latter is part of the local government welfare function.

Figures in Table 3 confirm this intuitive story. Port prices are higher in the local surplus case than in the case of private ports; at the same time, both port and hinterland capacities are larger in the first case as well. There is a bit more local hinterland travel (where the time cost has decreased due to investment), leading to a higher local surplus. Most interestingly, however, note that the combination of lower time costs and higher port prices in the local surplus case only slightly restrains port demand, so that port profits rise. Paradoxically, then, the port may be better off by giving up price control (but retaining rights to port revenues), since this leads to more port capacity and to higher profits.

Finally, note that port prices are lower in the case of global surplus maximizing behaviour. Taking account of shippers' surplus reduces port prices substantially.[14]

5.3 Sensitivity analysis

We briefly report on the results of a series of sensitivity analyses with respect to important parameters of the problem: the slope and position of the inverse demand functions, the slope of the congestion functions, changing road tolls, and deviating from symmetry. Table 4 summarizes some results.

A first exercise is to tilt the inverse demand functions for both local and shipping traffic, approximately around the equilibrium point of the private port solution described in Table 3, by increasing the absolute value of the slope of the demand functions and adapting intercepts accordingly. The change implies that shipping demand becomes less responsive to price changes. Results in Table 4 show that this raises port prices under all regimes; implications for capacity investment are very small. Shippers' surplus of course strongly rises[15].

Second, we also explored the sensitivity of results to the slope of congestion functions; results are not included in the table for the sake of brevity. Changing the slope of both the port and road congestion functions, making them very small, reduces congestibility in the system as a whole. Since congestion drives many results in the model, its virtual absence reduces the differences among the three scenarios. If ports alone become less congestion-prone, we found that capacity expenditures on ports decline.

Third, in all previous scenarios, the road toll is equal to zero. We now briefly look at the impact of setting positive tolls. In the lower part of Table 4, we report results for tolls equal to 0 (the base case), 2.5 and 5. Aggregate surplus rises when

[14] Observe that port time costs and marginal external costs at the port are the same in the local and global surplus cases. This is an artefact of the setup of the model; it is a consequence of the linearity of port congestion functions in volume-capacity ratios.

[15] Tilting the inverse demand functions by keeping their intercept at the initial value but doubling their slope (not shown in the table) increases market power and this leads to bigger mark-ups, resulting mainly in higher profits and lower capacity levels.

moving from a zero toll to a toll equal to 2.5, but then declines again if the toll is exogenously further increased to 5. This just reflects the fact that this high toll exceeds the first best level, equal to marginal external congestion costs. All components of the surplus decline as tolls rise, except toll revenues. Note that higher hinterland road tolls indeed reduce optimal port prices under all regimes, as suggested in the theoretical sections. In the global surplus scenario, investments in capacity are lower when the toll is higher, because less capacity is required to reduce time costs at the lower levels of demand. But under private port pricing, capacity investments increase as tolls rise, as an indirect way for government to moderate generalized prices, especially for port users.

Finally, we looked at the implications of asymmetric ports in the sense of having different congestibility. For example, it is well known that Rotterdam has much easier access (less congestibility) than the port of Antwerp. This is the case even after deepening of the Scheldt, the river connecting the port to the sea. Technically, differences like this are approximated by assuming that the slope of the congestion function in A is much higher than in B. The results are reported in the upper right part of Table 4. We find that demand in the more congestible port is much smaller, time costs are higher, and optimal port investments are higher. Interestingly, however, port prices at the more congestible port are lower under all three scenarios. In all cases, lower congestibility attracts more traffic through the port. Note that the price difference is most pronounced for the case of private port pricing. Part of the reason is that the elasticity-related markup that a port charges depends on the congestion level at the competing port (see the term θ_B in expression (5)). Not surprisingly, in the case of global surplus maximizing behavior a very large share of all investment in capacity is drawn to the low-congestibility region B. Since no markups are charged in the global case, the resulting price differences at the port are more modest.

6. Conclusions and policy implications

In this paper we studied duopolistic pricing by ports that are congestible and that share a downstream, congestible transport network with other users on their respective hinterlands. Local (country) governments decide on port capacity as well as on investment in the hinterland network. Within this setting we obtained a number of interesting results.

A first general finding is that private ports will, to the extent that it affects their customers, internalize hinterland congestion in the prices they charge for the use of their services. Interestingly, we also showed that, if the country governments directly controlled prices of the port within their jurisdiction, they may actually charge even higher prices than private operators. The reason is that this allows them to take into account un-priced congestion effects on users of the hinterland network. A second general finding is that investments in port capacity reduce port prices. However, additional investments in hinterland capacity in a given country increase the user prices at the local port; they reduce prices at the competing port. A third result was the role of hinterland congestion in judging investments. We found that the main benefits for a country of expanding capacity of the local port, viz. the increase in port activities and profits, may be strongly reduced by an extra cost, viz. the impact of induced port traffic on hinterland congestion. For investment in hinterland capacity, the main benefits are the reduced local user costs and the induced port activities; these benefits dominate the negative effects of the induced port traffic on hinterland congestion. Finally, imposing congestion tolls on the hinterland network contributes to higher capacity investments in ports as well as to higher investments in hinterland capacity.

The models and numerical illustrations presented in this paper offer some modest guidance to judge pricing and investment policies. One observation is related to the fact that the EC advocates the use of marginal cost pricing for all transport services, including sea ports (see the Green Paper on Seaports and Maritime Infrastructure (European Commission, 1997) and the so-called Port Package (European Commission, 2001)). The results of this paper suggest that marginal (private plus external) cost pricing of port services is only globally optimal, provided that port hinterlands are appropriately taxed at marginal external cost as well. Not surprisingly, if no tolls are charged on the hinterland to control for congestion, then it is optimal to charge more for port services to signal the contribution of port users to hinterland congestion.

Another comment follows from the observation that current port pricing is apparently not guided by the proposed EU-principles. Indeed, surveys show that European ports are aware of the high substitution possibilities between ports for unitized goods (containers); they compete in prices as well as through product differentiation and overall quality. These observations are consistent with the results of this paper. They suggest that oligopolistic competition between ports facing congestion at the facility and on the hinterland is likely to yield much higher port prices than marginal social cost. Ports charge a substantial markup over marginal external cost.

Finally, we have argued that country governments have an incentive to raise port capacity to stimulate activities and profits of the local port. Moreover, the numerical results suggested that this will be even more the case in countries where port prices are largely controlled by the government. Overall, in the presence of market power for ports, the market predicts too low capacities. These observations are not consistent with the widespread feeling among transport economists that European port capacity is on ‘the high side’. Of course, there may be other contributing factors to relatively high investments levels. They could also partially be due to ‘common pool’ incentives for port operators and efficient lobbying for large public investments to improve their profits.

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Appendix 1: Reduced form demand characteristics

We here derive the partial effects of taxes and capacities on demands. We start from the system:

$$\begin{aligned}
p^X(X_A+X_B) &= p_A + f_A(X_A,K_A^f) + h_A(X_A+Y_A,K_A^h) + \bar{t}_A \\
p^X(X_A+X_B) &= p_B + f_B(X_B,K_B^f) + h_B(X_B+Y_B,K_B^h) + \bar{t}_B \\
p_A^Y(Y_A) &= g_A + h_A(X_A+Y_A,K_A^h) + \bar{t}_A \\
p_B^Y(Y_B) &= g_B + h_B(X_B+Y_B,K_B^h) + \bar{t}_B
\end{aligned} \qquad \text{(A1.1)}$$

First we solve the two last equations for local road demand as a function of the hinterland capacity and toll levels, and of transit demand:

$$Y_A = z_A(X_A,K_A^h,\bar{t}_A), \quad Y_B = z_B(X_B,K_B^h,\bar{t}_B) \qquad \text{(A1.2)}$$

Partials with respect to capacity and port-related traffic X_A are given by:

$$\frac{\partial z_A}{\partial X_A} = \frac{\dfrac{\partial h_A}{\partial V_A}}{\dfrac{\partial p_A^Y}{\partial Y_A} - \dfrac{\partial h_A}{\partial V_A}} < 0, \qquad \frac{\partial z_A}{\partial K_A^h} = -\frac{\dfrac{\partial h_A}{\partial K_A^h}}{\dfrac{\partial p_A^Y}{\partial Y_A} - \dfrac{\partial h_A}{\partial V_A}} > 0 \qquad \text{(A1.3)}$$

More facility use in A raises hinterland transport demand and reduces local demand because of higher congestion; more road capacity raises local transport demand. Similarly for B.

Substituting (A1.2) into the first two equations of (A1.1) for port-related traffic yields:

$$\begin{aligned}
p^X(X_A+X_B) &= p_A + f_A(X_A,K_A^f) + h_A\left[X_A + z_A(X_A,K_A^h;\bar{t}_A),K_A^h\right] \\
p^X(X_A+X_B) &= p_B + f_B(X_B,K_B^f) + h_B\left[X_B + z_B(X_B,K_B^h;\bar{t}_B),K_B^h\right]
\end{aligned}$$

Differentiating and solving by Cramer's rule yields the following partial effects of prices and capacities on reduced-form demands for port use:

$$\begin{aligned}
\frac{\partial X_A^r}{\partial p_A} &= \frac{1}{\Delta} M_B < 0 & \frac{\partial X_A^r}{\partial p_B} &= -\frac{1}{\Delta}\frac{\partial p^X}{\partial X} > 0 \\
\frac{\partial X_A^r}{\partial K_A^f} &= -\frac{1}{\Delta}\left[\frac{\partial f_A}{\partial K_A^f}\right] M_B > 0 & \frac{\partial X_A^r}{\partial K_B^f} &= \frac{1}{\Delta}\frac{\partial p^X}{\partial X}\frac{\partial f_B}{\partial K_B^f} < 0 \\
\frac{\partial X_A^r}{\partial K_A^h} &= -\frac{1}{\Delta}\left[\frac{dh_A}{dK_A^h}\right] M_B > 0 & \frac{\partial X_A^r}{\partial K_B^h} &= \frac{1}{\Delta}\frac{\partial p^X}{\partial X}\frac{dh_B}{dK_B^h} < 0
\end{aligned} \qquad \text{(A1.4)}$$

where $M_i = \frac{\partial p^X(X)}{\partial X} + \frac{\partial f_i}{\partial X_i} + \frac{\partial h_i}{\partial V_i}\left(1 + \frac{\partial z_i}{\partial X_i}\right) < 0$ (A1.5)

$$\frac{dh_i}{dK_i^h} = \frac{\partial h_i}{\partial K_i^h} + \frac{\partial h_i}{\partial V_i}\frac{\partial z_i}{\partial K_i^h} < 0 \qquad \text{(A1.6)}$$

$$\Delta = M_A M_B - \left(\frac{\partial p^X(X)}{\partial X}\right)^2 > 0 \qquad \text{(A1.7)}$$

The signs of (A1.5) and (A1.6) directly follow from using (A1.3). Moreover, the positive sign of Δ directly follows from substituting (A1.5) into (A1.7).

Interpretation of (A1.4) is easy. Higher port prices at A reduce demand at A and raise it at port B. Increases in port capacity in port A raise demand at A, and lower demand at B. Finally, better hinterland capacity at A also raises demand in A and reduces it in B.

Finally, the effects on local hinterland transport are easily derived as well. We find, using (A1.2)-(A1.4) and some algebra[16]:

$$\begin{aligned} &\frac{\partial Y_A^r}{\partial p_A} > 0, \frac{\partial Y_A^r}{\partial p_B} < 0 \\ &\frac{\partial Y_A^r}{\partial K_A^f} < 0, \frac{\partial Y_A^r}{\partial K_B^f} > 0 \\ &\frac{\partial Y_A^r}{\partial K_A^h} > 0, \frac{\partial Y_A^r}{\partial K_B^h} > 0 \end{aligned} \qquad \text{(A1.8)}$$

Higher port prices in A raise local demand on A's hinterland road network because they reduce congestion of port-related traffic. The opposite hold for a price increase at port B. Port capacity in A reduces hinterland local traffic and raises it at B, again due to congestion effects of port-related traffic. Finally, more hinterland capacity in A raises hinterland local demand at A and at B: the shift in port traffic from B to A reduces congestion on the hinterland in B as well.

[16] To be more precise, all signs immediately follow from differentiating (A1.2) and using the signs reported in (A1.4). However, there is one exception. Since differentiating $z_A(X_A, K_A^h; \overline{t}_A)$ with respect to hinterland capacity yields two effects of opposite sign, viz. a positive direct effect and a negative indirect effect via port-related traffic, one needs to use the definition of the M_i and Δ to show that $\frac{\partial Y_A^r}{\partial K_A^h} > 0$. The formal proof is available from the authors.

Appendix 2: Price setting behavior of private port facilities

Consider facility A. It solves:

$$\underset{p_A}{Max}\ \pi_A = p_A X_A^r(p_A, p_B, K_A^f, K_B^f, K_A^h, K_B^h) \quad C_A(X_A^r(.))$$

The first-order condition implies:

$$p_A = MPC_A \quad \frac{X_A^r}{\dfrac{\partial X_A^r}{\partial p_A}}$$

where $MPC_A = \dfrac{\partial C_A(.)}{\partial X_A^r}$ is the marginal production cost at facility A. Using the expression for the impact of facility price on demand, see (A1.4), we can rearrange this to yield:

$$p_A = MPC_A \quad \frac{X_A^r(\Delta)}{[\,]M_B}$$

Using the definition of Δ and the $M_i, i = A, B$ (see (A1.5) and (A1.7)), we find after simple algebra:

$$p_A = MPC_A \quad MEC_A^f \quad X_A^r\left[\frac{\partial p^X}{\partial X} \quad \frac{\partial h_A}{X_A}(1 \quad \frac{z_A}{X_A})\right] \quad \frac{X_A^r\left(\dfrac{\partial p^X}{X}\right)^2}{[\,]M_B}$$

In this expression we defined:

$$MEC_A^f = \frac{\partial f_A}{\partial X_A} X_A^r$$

as the marginal external cost at facility A. Finally, again using the definition of M_B this can be reformulated as:

$$p_A = MPC_A \quad MEC_A^f \quad \frac{X_A}{V_A} MEC_A^h(1 \quad \frac{\partial z_A}{\partial X_A}) \quad X_A \frac{\partial p^X}{X}(\,)\theta_B$$

where $MEC_A^h = V_A \dfrac{\partial h_A}{\partial V_A}$ is the marginal external congestion cost of a traffic increase on the hinterland road network. Finally, θ_B is given by: $\theta_B = \dfrac{\left[\dfrac{\partial p^X}{\partial X} - M_B\right]}{[\,]M_B}$. Simple algebra shows that this implies that $-1 < \theta_B \quad 0$.

Appendix 3. Locally optimal policies: the government directly controls port prices and capacity investment decisions

Suppose the government of each region controls all instruments, including port prices. Conditional on prices and capacities at the competing region, the government of region A:

$$\underset{p_A, K_A^f, K_A^h}{Max} \int_o^{Y_A} p_A^Y(y)dy - g_A Y_A^r + \left[p_A X_A^r \quad C_A(X_A^r) \quad k_A^f K_A^f \quad k_A^h K_A^h \right. \quad \bar{t}_A (X_A^r \quad Y_A^r)$$

The first-order conditions are:

$$-Y_A^r \frac{dh_A}{dp_A} = (p_A \quad MPC_A) \frac{\partial X_A^r}{\partial p_A} \quad X_A \quad \bar{t}_A \left(\frac{X_A^r}{p_A} \quad \frac{Y_A^r}{p_A} \right) \quad 0$$

$$-Y_A^r \frac{dh_A}{dK_A^f} \quad (p_A \quad MPC_A) \frac{\partial X_A^r}{\partial K_A^f} \quad \bar{t}_A \left(\frac{X_A^r}{K_A^f} \quad \frac{Y_A^r}{K_A^f} \right) \quad k_A^f$$

$$-Y_A^r \frac{dh_A}{dK_A^h} \quad (p_A \quad MPC_A) \frac{\partial X_A^r}{\partial K_A^h} \quad \bar{t}_A \left(\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h} \right) \quad k_A^h$$

where,

$$\frac{dh_A}{dp_A} = \frac{\partial h_A}{\partial V_A} \left[\frac{X_A^r}{p_A} \quad \frac{Y_A^r}{p_A} \right] \quad 0$$

$$\frac{dh_A}{dK_A^f} = \frac{\partial h_A}{\partial V_A} \left[\frac{X_A^r}{K_A^f} \quad \frac{Y_A^r}{K_A^f} \right] > 0$$

$$\frac{dh_A}{dK_A^h} = \frac{\partial h_A}{\partial K_A^h} \quad \frac{h_A}{V_A} \left[\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h} \right] < 0$$

Substituting these expressions, we obtain:

$$(p_A - MPC_A) \frac{\partial X_A^r}{\partial p_A} \left(\bar{t}_A \quad Y_A^r \frac{h_A}{V_A} \right) \left(\frac{X_A^r}{p_A} \quad \frac{Y_A^r}{p_A} \right) \quad X_A \quad 0$$

$$(p_A - MPC_A) \frac{\partial X_A^r}{\partial K_A^f} \left(\bar{t}_A \quad Y_A^r \frac{h_A}{V_A} \right) \left(\frac{X_A^r}{K_A^f} \quad \frac{Y_A^r}{K_A^f} \right) \quad k_A^f$$

$$(p_A - MPC_A) \frac{\partial X_A^r}{\partial K_A^h} Y_A^r \frac{h_A}{K_A^h} \quad \left(\bar{t}_A \quad Y_A^r \frac{h_A}{V_A} \right) \left(\frac{X_A^r}{K_A^h} \quad \frac{Y_A^r}{K_A^h} \right) \quad k_A^h$$

The capacity rules are obviously the same as in the case with exogenous port prices analyzed before, see (13a)-(13b) in section 3.1. Working out the pricing rule, carefully following the steps explained in Appendix 2, yields after simple algebra:

$$p_A = MPC_A + MEC_A^f \left(1-\theta_A\right) + MEC_A^h \left(1 + \frac{\partial t_A}{\partial X_A} X_A^r \frac{p^X}{X}\right)\theta_B$$

This basically says that the government would use the same pricing rule as a profit maximizing private port with one exception. It would internalize the full marginal external congestion cost of hinterland use, including the time losses on local traffic, in port prices. A private port only charges for the external cost to the extent that it affects their customers. It also implies that port prices under public control structurally exceed those under private control.

Appendix 4: First-best pricing and investment rules

Suppose one government operates the complete system of ports and hinterland networks. How would it decide on port pricing and investment rules for port and hinterland capacity, assuming that it cares for shippers as well as hinterland users of the network? First-best pricing and investment rules are the solution to the following problem:

$$\begin{aligned}\underset{p_A,p_B,K_A^f,K_A^h,K_B^f,K_B^h}{Max}\; & \int_o^{Y_A} p_A^Y(y)dy - g_A Y_A^r + \int_o^{Y_B} p_B^Y(y)dy - g_B Y_B^r \\ & + \int_o^{X} p^X(x)dx - C_A(X_A) - f_A X_A^r - g_A X_A^r - C_B(X_B) - f_B X_B^r - g_B X_B^r \\ & \quad - k_A^f K_A^f - k_A^h K_A^h - k_B^f K_B^f - k_B^h K_B^h - \bar{t}_A(X_A^r + Y_A^r) - \bar{t}_B(X_B^r + Y_B^r)\end{aligned}$$

(A3.1)

The first line of the objective function captures the net benefits to local users of the hinterland network in both regions A and B. The net benefits equal the surplus of local users minus generalized costs. The second line captures the total net benefits of port users. The first integral term is the total willingness to pay of all port users (i.e., all users of ports A and B) for the complete trip (port use plus hinterland use). Net benefits are obtained by subtracting monetary port costs, the time costs in the ports and, finally, the time cost on the hinterland. The third line captures all capacity costs and the tax revenues on the hinterland.

We first focus on the port pricing problem for given capacities. The first-order condition for optimal pricing at port A can be written as, using equality of generalized price and generalized cost of hinterland transport:

$$-Y_A^r\frac{dh_A}{dp_A} - Y_B^r\frac{dh_B}{dp_A} + p^X(X)\left[\frac{\partial X_A^r}{\partial p_A}+\frac{\partial X_B^r}{\partial p_A}\right] - \left[MPC_A + f_A + h_A - \bar{t}_A\right]\frac{\partial X_A^r}{\partial p_A} - X_A^r\left[\frac{df_A}{dp_A}+\frac{dh_A}{dp_A}\right]$$
$$-\left[MPC_B + f_B + h_B - \bar{t}_B\right]\frac{\partial X_B^r}{\partial p_A} - X_B^r\left[\frac{df_B}{dp_A}+\frac{dh_B}{dp_A}\right]$$
$$+\bar{t}_A\left(\frac{\partial X_A^r}{\partial p_A}+\frac{\partial Y_A^r}{\partial p_A}\right)+\bar{t}_B\left(\frac{\partial X_B^r}{\partial p_A}+\frac{\partial Y_B^r}{\partial p_A}\right)=0$$

where,

$$\frac{dh_A}{dp_A} = \frac{\partial h_A}{\partial V_A}\left[\frac{\partial X_A^r}{\partial p_A}+\frac{\partial Y_A^r}{\partial p_A}\right] - \frac{h_A}{V_A}\frac{\partial X_A^r}{\partial p_A}\left(1-\frac{\partial z_A}{\partial X_A}\right) < 0$$

$$\frac{dh_B}{dp_A} = \frac{\partial h_B}{\partial V_B}\left[\frac{\partial X_B^r}{\partial p_A}+\frac{\partial Y_B^r}{\partial p_A}\right] - \frac{h_B}{V_B}\frac{\partial X_B^r}{\partial p_A}\left(1-\frac{\partial z_B}{\partial X_B}\right) > 0$$

$$\frac{df_A}{dp_A} = \frac{\partial f_A}{\partial X_A}\frac{\partial X_A^r}{\partial p_A} < 0$$

$$\frac{df_B}{dp_A} = \frac{\partial f_B}{\partial X_B}\frac{\partial X_B^r}{\partial p_A} > 0$$

Substituting these expressions in the first-order condition, we obtain, using the definitions of the marginal congestion costs in port and hinterland :

$$\left\{p^X(X) - MPC_A - f_A - h_A + \bar{t}_A - MEC_A^f - MEC_A^h\left(1-\frac{\partial z_A}{\partial X_A}\right)\right\}\frac{\partial X_A^r}{\partial p_A}$$
$$+\left\{p^X(X) - MPC_B - f_B - h_B + \bar{t}_B - MEC_B^f - MEC_B^h\left(1-\frac{\partial z_B}{\partial X_B}\right)\right\}\frac{\partial X_B^r}{\partial p_A}$$
$$+\bar{t}_A\left(\frac{\partial X_A^r}{\partial p_A}+\frac{\partial Y_A^r}{\partial p_A}\right)+\bar{t}_B\left(\frac{\partial X_B^r}{\partial p_A}+\frac{\partial Y_B^r}{\partial p_A}\right)=0$$

Noting that, for i=A,B:

$$\frac{\partial X_i^r}{\partial p_A} = \frac{Y_i^r}{p_A}\left(1 \quad \frac{z_i}{X_i^r} \quad \frac{X_i^r}{p_A}\right)$$

and rearranging, we have

$$\left\{p^X(X) - MPC_A - f_A \quad h_A \quad \bar{t}_A \quad MEC_A^f \quad (\,)\bar{t}_A \quad MEC_A^h \left(1 \quad \frac{\partial z_A}{\partial X_A}\right) \quad \frac{X_A^r}{p_A}\right\}$$

$$+\left\{p^X(X) - MPC_B \quad f_B \quad h_B \quad \bar{t}_B \quad MEC_B^f \quad (\,)\bar{t}_B \quad MEC_B^h \left(1 \quad \frac{\partial z_B}{\partial X_B}\right) \quad \frac{X_B^r}{p_A}\right\} \quad 0$$

We develop the first-order condition for the price of port B in a completely analogous fashion. Then note that the equality between the generalized price and the generalized cost of port-related transport (port plus hinterland cost) implies that $p^X(X) = p_A + f_A \quad h_A \quad \bar{t}_A$ (see (1)), and similarly for B. Solving the first-order conditions we then immediately see that optimal prices are given by:

$$p_A = MPC_A \quad MEC_A^f \quad (\,)\bar{t}_A \quad MEC_A^h \left[1 \quad \frac{\partial z_A}{\partial X_A}\right]$$

$$p_B = MPC_B \quad MEC_B^f \quad (\,)\bar{t}_B \quad MEC_B^h \left[1 \quad \frac{\partial z_B}{\partial X_B}\right]$$

Next, consider optimal investment rules. The first-order conditions of problem (A3.1) for the various capacities all have the same structure. Take the one for port capacity in A as an example. It reads:

$$-Y_A^r \frac{dh_A}{dK_A^f} + Y_B^r \frac{dh_B}{dK_A^f} \quad p^X(X)\left[\frac{\partial X_A^r}{\partial K_A^f} \quad \frac{X_B^r}{K_A^f}\right] \quad [\,]MPC_A \quad f_A \quad h_A \quad \bar{t}_A \quad \frac{X_A^r}{K_A^f} \quad X_A^r \quad \frac{df_A}{dK_A^f} \quad \frac{dh_A}{dK_A^f}$$

$$-[\,]MPC_B \quad f_B \quad h_B \quad \bar{t}_B \quad \frac{\partial X_B^r}{\partial K_A^f} \quad X_B^r\left[\frac{df_B}{dK_A^f} \quad \frac{dh_B}{dK_A^f}\right]$$

$$+\bar{t}_A\left[\frac{\partial X_A^r}{\partial K_A^f}\right] \quad \frac{Y_B^r}{K_A^f} \quad \bar{t}_B \quad \frac{X_B^r}{K_A^f} \quad \frac{Y_B^r}{K_A^f} \quad k_A^f$$

where,

$$\frac{dh_A}{dK_A^f} = \frac{\partial h_A}{\partial V_A}\left[\frac{\partial X_A^r}{\partial K_A^f} \quad \frac{Y_A^r}{K_A^f}\right] \quad \frac{h_A}{V_A}\frac{X_A^r}{K_A^f}\left|1 \quad \frac{z_A}{X_A}\right| \quad 0$$

$$\frac{dh_B}{dK_A^f} = \frac{\partial h_B}{\partial V_B}\left[\frac{\partial X_B^r}{\partial K_A^f} \quad \frac{Y_B^r}{K_A^f}\right] \quad \frac{h_B}{V_B}\frac{X_B^r}{K_A^f}\left|1 \quad \frac{z_B}{X_B}\right| \quad 0$$

$$\frac{df_A}{dK_A^f} = \frac{\partial f_A}{\partial K_A^f} + \frac{\partial f_A}{\partial X_A}\frac{\partial X_A^r}{\partial K_A^f} < 0$$

$$\frac{df_B}{dK_A^f} = \frac{\partial f_B}{\partial X_B}\frac{\partial X_B^r}{\partial K_A^f} < 0$$

Substituting these expressions in the first-order condition, noting that $p^X(X) = p_A + f_A + h_A + \overline{t}_A$, and using the optimal pricing rules (A3.2)-(A3.3), we immediately find the following rule:

$$-X_A \frac{\partial f_A}{\partial K_A^f} = k_A^f$$

This just says that the marginal capacity cost should equal the marginal benefit of capacity investment. The latter is just the direct reduction of the time cost of port use.

In a similar fashion we find for hinterland investment:

$$-(X_A + Y_A)\frac{\partial h_A}{\partial K_A^h} = k_A^h$$

This states that the capacity cost of hinterland investment should equal the reduction in hinterland time costs enjoyed by all hinterland users.

These findings have an interesting implication. They suggest that a supranational authority responsible for port prices as well as investment decisions would correct for its inability to charge the appropriate hinterland tolls by adjusting port prices, but that investment rules would be first-best.

<u>Appendix 5. The Nash equilibrium in prices with linear demands and linear congestion functions</u>

To study the effect of capacities on Nash equilibrium port prices, we start by noting that the port's first-order condition for optimal pricing

$$\left(p_A - \frac{\partial C_A(.)}{\partial X_A^r}\right)\frac{\partial X_A^r}{\partial p_A} + X_A^r = 0$$

implicitly defines the reaction function $p_A^R(p_B; K_A^f, K_B^f, K_A^h, K_B^h, \overline{t}_A, \overline{t}_B)$. The implicit function theorem then leads to:

$$\frac{\partial p_A^R}{\partial p_B} = -\frac{\dfrac{\partial X_A^r}{\partial p_A}\dfrac{\partial X_A^r}{\partial p_B} - X_A \dfrac{\partial^2 X_A^r}{\partial p_A \partial p_B}}{2\left(\dfrac{\partial X_A^r}{\partial p_A}\right)^2 - X_A \dfrac{\partial^2 X_A^r}{\partial p_A^2}}$$

where the denominator can be shown to be positive by the second-order condition for optimal pricing. The effects of the various capacities are derived in an analogous manner. For example, the effect of an increase in port capacity on prices at A, holding port prices at B constant, is given by:

$$\frac{\partial p_A^R}{\partial K_A^f} = -\frac{\dfrac{\partial X_A^r}{\partial p_A}\dfrac{\partial X_A^r}{\partial K_A^f} - X_A \dfrac{\partial^2 X_A^r}{\partial p_A \partial K_A^f}}{2\left(\dfrac{\partial X_A^r}{\partial p_A}\right)^2 - X_A \dfrac{\partial^2 X_A^r}{\partial p_A^2}}$$

The Nash equilibrium can further be defined as the solution to the two reaction function. By Cramer's rule, we then find that the impact of capacity changes on the Nash equilibrium prices is given by:

$$\frac{\partial p_A^{NE}}{\partial K_A^f} = \frac{\dfrac{\partial p_A^R}{\partial K_A^f} + \dfrac{\partial p_B^R}{\partial K_A^f}\dfrac{\partial p_A^R}{\partial p_B}}{1 - \dfrac{\partial p_A^R}{\partial p_B}\dfrac{\partial p_B^R}{\partial p_A}} \qquad \frac{\partial p_A^{NE}}{\partial K_B^f} = \frac{\dfrac{\partial p_A^R}{\partial K_B^f} + \dfrac{\partial p_B^R}{\partial K_B^f}\dfrac{\partial p_A^R}{\partial p_B}}{1 - \dfrac{\partial p_A^R}{\partial p_B}\dfrac{\partial p_B^R}{\partial p_A}}$$

$$\frac{\partial p_A^{NE}}{\partial K_A^h} = \frac{\dfrac{\partial p_A^R}{\partial K_A^h} + \dfrac{\partial p_B^R}{\partial K_A^h}\dfrac{\partial p_A^R}{\partial p_B}}{1 - \dfrac{\partial p_A^R}{\partial p_B}\dfrac{\partial p_B^R}{\partial p_A}} \qquad \frac{\partial p_A^{NE}}{\partial K_B^h} = \frac{\dfrac{\partial p_A^R}{\partial K_B^h} + \dfrac{\partial p_B^R}{\partial K_B^h}\dfrac{\partial p_A^R}{\partial p_B}}{1 - \dfrac{\partial p_A^R}{\partial p_B}\dfrac{\partial p_B^R}{\partial p_A}}$$

Not surprisingly, many of the price effects of capacity changes are ambiguous in general. To simplify the analysis, we assume all demand and cost functions to be linear. We use the following specifications:

$$p^X(X) = a - \rho X$$
$$p_A^Y(Y_A) = e_A - d_A Y_A$$
$$p_B^Y(Y_B) = e_B - d_B Y_B$$

$$f_A = \beta_A \left(\frac{X_A}{K_A^f}\right) \qquad f_B = \beta_B \left(\frac{X_B}{K_B^f}\right)$$

$$h_A = \delta_A \left(\frac{X_A + Y_A}{K_A^h}\right) \qquad h_B = \delta_B \left(\frac{X_B + Y_B}{K_B^h}\right)$$

Note that β_i is the slope of the congestion cost function at facility i (handling, processing, waiting); δ_i is the slope of the hinterland congestion cost function. The congestion functions assume that the time cost is proportional to the volume-capacity ratio. Note that we have set all intercepts of the congestion functions equal to zero to save on notation. A final simplification is that we set the marginal private production cost equal to zero.

Under the above assumptions, we obtain after simple but substantial algebra, using the above specifications, expressions (A1.4) and the formulas reported in section 2.3 of the main body of the paper:

$$\frac{\partial p_A^R}{\partial p_B} = -\frac{\rho}{2M_B} > 0$$

$$\frac{\partial p_A^R}{\partial K_A^f} = 0 \qquad \frac{\partial p_A^R}{\partial K_B^f} = \frac{\rho\beta_B(M_B X_B \quad X_A)}{2(M_B K_B)^2} < 0$$

$$\frac{\partial p_A^R}{\partial K_A^h} = \frac{1}{2}\frac{\delta_A d_A c_A}{(d_A K_A^h \quad \delta_A)} > 0 \qquad \frac{\partial p_A^R}{\partial K_B^h} = -\frac{\rho}{2(M_B)^2}\left[M_B \frac{dh_B}{dK_B^h} \quad \rho X_A \frac{\partial M_B}{\partial K_B^h}\right] < 0$$

where

$$M_i = -\rho\left(\frac{\beta_i}{K_i^f} \quad \frac{\delta_i d_i}{d_i K_i^h + \delta_i}\right) < 0$$

$$\frac{\partial M_i}{\partial K_i^h} = \rho\delta_i\left(\frac{d_i}{d_i K_i \quad \delta_i}\right)^2 > 0$$

$$\frac{dh_i}{dK_i^h} = -\frac{d_i\delta_i(c_i + d_i X_i)}{\left(d_i K_i^h + \delta_i\right)^2} < 0$$

It follows, therefore, that:

$$\frac{\partial p_A^R}{\partial p_B} > 0, \quad \frac{\partial p_A^R}{\partial K_A^f} = 0, \quad \frac{\partial p_A^R}{\partial K_B^f} < 0, \quad \frac{\partial p_A^R}{\partial K_A^h} > 0, \quad \frac{\partial p_A^R}{\partial K_B^h} < 0$$

Using these results to evaluate the effect of capacity changes on Nash equilibrium prices, we substitute these findings in the above expressions. For increases in port capacity we immediately find:

$$\frac{\partial p_A^{NE}}{\partial K_A^f} < 0, \qquad \frac{\partial p_A^{NE}}{\partial K_B^f} \quad 0$$

Investment in more port capacity induces both ports to reduce prices. Unfortunately, the effects of hinterland capacity are not completely clear. We can show the following:

$$\frac{\partial p_A^R}{\partial K_A^h} + \frac{p_B^R}{K_A^h}\frac{p_A^R}{p_B}\left[\frac{\delta_A d_A}{4M_A M_B\left(d_A K_A^h+\delta_A\right)^2}\right]\left\{\left[c_A\left(2M_A M_B \quad \rho^2\rho\right) \; 2 \; {}^3 d_A X_B M_A \quad d_A \; {}^2 X_A\right]\right\}$$

$$\frac{\partial p_A^R}{\partial K_B^h} + \frac{p_B^R}{K_B^h}\frac{p_A^R}{p_B} \quad \frac{\rho\rho}{2M_B}\left\{\frac{1}{2}\frac{d_B\delta_B c_B}{\left(d_B K_B+\delta_B\right)^2} \quad \frac{(d_B)^2 \; {}_B X_B}{\left(d_B K_B \quad {}_B\right)^2}\left[\frac{}{M_B}\right] \; 1\right\} \quad 0$$

It follows that the effect of a hinterland capacity in a given region unambiguously reduces port prices at the competing port. This makes sense, because a capacity expansion of A's hinterland reduces both port and hinterland congestion in B. However, the effect of a hinterland capacity increase on port prices in A are ambiguous in general. Since, using the definition of the M_i, the term $\left[c_A\left(2M_A M_B - \rho\rho^2\right) \; 2 \; {}^3 d_A X_B M_A\right]$ is easily shown to be positive, the overall effect is positive, unless X_A is very large. That the impact is plausibly positive is no surprise. Better hinterland connections reduce hinterland congestion but raise port congestion. Unless X_A is very large and makes up a large fraction of hinterland transport, however, the impact on port congestion will dominate and induce the port to raise prices.

Summarizing this discussion, we have the following result:

$$\frac{\partial p_A^{NE}}{\partial K_A^h} > 0 \quad (plausibly), \qquad \frac{p_A^{NE}}{K_B^h} \quad 0$$

Tables

Table 1. Summary of port pricing results under different regimes

	Marginal private cost port	**External cost port**	**External cost hinterland**	**Markup**
Private port operators	Yes	Yes	Yes, but only to the extent that it affects port users	Yes
Local public control over port prices	Yes	Yes	Yes, but only to the extent that hinterland tolls are too low	Yes
Supranational control over port prices	Yes	Yes	Yes, but only to the extent that hinterland tolls are too low	No

Table 2: The marginal benefits of investments taken into account under different regimes (note that marginal investment costs are the same under all regimes)

	Induced port profits (at fixed port prices)	**Induced port profits via change in port prices**	**Direct savings of port user costs (at given volumes)**	**Direct savings of hinterland user costs (at given volumes)**	**Costs of induced hinterland traffic (at fixed port prices)**	**Costs of induced hinterland traffic via change in port prices**
PORT INVESTMENT						
Regional government only controls capacities	>0	<0			<0 (if toll too low)	>0 (if toll too low)
Regional government controls capacities and port prices	>0				<0 (if toll too low)	
Global government controls capacities and port prices			>0			
HINTERLAND INVESTMENT						
Regional government only controls capacities	>0	<0		>0	<0 (if toll too low)	>0(if toll too low)
Regional government controls capacities and port prices	>0			>0	<0 (if toll too low)	
Global government controls capacities and port prices				>0		

Table 3 Numerical illustration – Base Scenario

		Private	Local surplus	Global surplus
X	Aggregate shipping demand	31.116	30.964	32.453
	Shipping demand per port	15.558	15.482	16.226
Y	Local demand	17.235	17.286	17.305
f(.)	Port time cost	7.022	6.739	6.739
h(.)	Road time cost	6.913	6.785	6.739
p	Port price	8.274	9.066	5.391
t	Road toll	0	0	0
V	Road volume	32.793	32.768	33.531
Kf	Port capacity	3.861	4.240	4.444
Kh	Road capacity	8.443	8.825	9.183
MECf	External congestion cost port	3.022	2.739	2.739
MECh	External congestion cost road	2.913	2.785	2.739
Surplus measures				
(1) Surplus shippers		1,210.284	1,198.472	1,316.486
(2) Surplus local traffic		371.297	373.511	374.309
(3) Port profits (equal to revenues)		128.731	140.365	87.470
(4) Toll revenues		0	0	0
(5) Capital expenditures ports		38.614	42.399	44.438
(6) Capital expenditures roads		84.429	88.252	91.828
(7) Total surplus = 1+2*(2+3+4)-2*(5+6)		1,964.254	1,964.922	1,967.513

Table 4 Sensitivity analysis

	Base scenario			Tilted demand function			Asymmetrical regions					
	Private	**Local surplus**	**Global surplus**	**Private**	**Local surplus**	**Global surplus**	**Private**		**Local surplus**		**Global surplus**	
Region:	A and B	A and B	A and B	A and B	A and B	A and B	A	B	A	B	A	B
f(.): port time cost	7.022	6.739	6.739	7.016	6.739	6.739	7.2	4.8	6.7	4.7	6.7	4.7
h(.): road time cost	6.913	6.785	6.739	6.885	6.762	6.739	7.0	6.9	6.8	6.8	6.7	6.7
P: port price	8.274	9.066	5.391	8.489	9.279	5.432	5.8	8.4	6.7	8.8	5.3	7.3
KF: port capacity	3.861	4.240	4.444	3.864	4.245	4.351	2.9	1.3	3.4	1.4	0	2.3
KH: road capacity	8.443	8.825	9.183	8.521	8.899	9.081	7.5	9.5	8.0	9.9	4.7	13.6
Surplus shippers	1,210.284	1,198.472	1,316.486	2,414.913	2,402.853	2,524.316	1,279		1,272		1,319	
Surplus local traffic	371.297	373.511	374.309	743.071	745.207	745.603	370	371	373	374	374	374
Port profits	128.731	140.365	87.470	131.924	143.840	86.316	73	163	84	171	0.01	239
Toll revenues	0	0	0	0	0	0	0	0	0	0	0	0
Total surplus	1,964.254	1,964.922	1,967.513	3,917.210	3,918.068	3,919.519	1,957		1,958		1,973	

	Base scenario			Low toll (Toll = 2.5)			High toll (Toll = 5)		
	Private	**Local surplus**	**Global surplus**	**Private**	**Local surplus**	**Global surplus**	**Private**	**Local surplus**	**Global surplus**
Region:	A and B	A and B	A and B	A and B	A and B	A and B	A and B	A and B	A and B
f(.): port time cost	7.022	6.739	6.739	6.552	6.739	6.739	6.182	6.739	6.739
h(.): road time cost	6.913	6.785	6.739	6.648	6.743	6.793	6.393	6.700	6.739
P: port price	8.274	9.066	5.391	7.251	6.623	2.969	6.398	4.182	0.553
KF: port capacity	3.861	4.240	4.444	4.529	4.239	4.439	5.226	4.238	4.435
KH: road capacity	8.443	8.825	9.183	8.992	8.691	8.905	9.605	8.555	8.626
Surplus shippers	1,210.284	1,198.472	1,316.486	1187.318	1198.021	1313.928	1156.011	1197.509	1311.213
Surplus local traffic	371.297	373.511	374.309	333.774	332.232	332.298	298.099	293.379	292.787
Port profits	128.731	140.365	87.470	111.733	102.518	48.137	97.286	64.724	8.959
Toll revenues	0	0	0	79.376	79.455	81.288	153.241	153.979	157.492
Total surplus	1,964.254	1,964.922	1,967.513	1966.659	1967.828	1970.491	1956.634	1965.816	1968.467