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1. INTRODUCTION

This paper investigates the rivalry between two congestible facilities –such as airports and seaports– and its effect on facility charges, capacities and congestion delays. A number of authors have studied duopolistic interactions between congestible facilities: Braid (1986) and Van Dender (2005) examined competition between fixed-capacity facilities, whereas De Palma and Leruth (1989), Baake and Mitusch (2004) and De Borger and Van Dender (2006) examined the rivalry between facilities that are able to adjust capacities. All of these studies have considered the facilities as service providers to final consumers. In particular, De Borger and Van Dender (2006), hereafter DBVD, studied duopolistic interaction between congestible facilities that first decide on capacities and then on prices. They found, among other results, that (i) the duopolists offer lower prices but longer congestion delays –i.e., lower service quality– than the monopolist; (ii) conditional on facility charges, the monopolist has the same rules for capacity investment as a central planner who maximizes social welfare; and (iii) the monopolist offers the same service quality as in the social optimum.

DBVD indicated that their analysis may apply to seaports, airports, internet access providers and roads. Whilst roads and internet access providers may provide services directly to final consumers, seaports and airports are input providers that reach final consumers only through carriers: these facilities are in an intermediate market and not in the final market. In this paper we extend the existing literature, especially the analysis of DBVD, by considering a 'vertical structure' setting: Each facility is an upstream firm that provides input service to downstream firms ('carriers' hereafter), which in turn produce output for final consumers.[1] We shall allow that these carriers may possess market power in the output market: as argued by Brueckner (2002), Pels and Verhoef (2004) and others, airlines at congested airports usually are not atomistic and hence they are not price-takers.

We find that (i) the duopoly facilities have lower prices than the monopolist (as in DBVD), but they offer lower service quality only if the facilities first decide on capacities and then on prices. When the capacity and price decisions are made simultaneously, the duopolists will provide the same service quality as the monopolist. (ii) Conditional on facility charges, the monopolist will have the same capacity investment rules as the central planner if and only if the downstream carrier markets are perfectly competitive at both facilities. If there is (at least) one downstream market that is imperfectly competitive, the monopoly capacity rules will be different from the socially optimal capacity rules. (iii) At a facility, the monopolist will offer the same service quality as the central planner if the carrier market (at that facility) is perfectly competitive. Otherwise, the monopolist provides a higher service level than the central planner.

Importantly, since we have explicitly considered the carriers' market, this allows us to see how the equilibrium prices change with characteristics of this intermediate market. We find that for given capacities, (a) the duopolists' equilibrium prices increase with both the consumers' value of time and the carriers' cost sensitivity to delays; (b) entrance of a new carrier to *any* of the

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[1] As to be elaborated in the text, two other major departures from DBVD are: First, while DBVD considered that facilities supply perfect substitutes in the eyes of final consumers, we shall consider that competing facilities provide differentiated services, with homogeneous facilities being a special case. Second, while DBVD looked at a closed-loop duopoly game where capacities are decided prior to prices, we investigate both the closed-loop game and the open-loop game (in which capacities and input prices are decided simultaneously) and compare their results.

facilities depresses the prices charged by *both* facilities; and (c) lower marginal cost of the carriers at one facility induces a lower price at that facility but a higher price at the other facility. Finally, our analysis shows that when the monopolist vertically integrates with the carriers at its facilities, it would provide the same service level as the central planner. Nevertheless, this service level is not socially optimal in a second-best sense; in effect, in the fully ex-ante symmetric case, it is too low with respect to the second best.

Incorporating the 'vertical structure' into the analysis of airport congestion, congestion pricing and capacity investment has been done by several recent papers. These papers examine either the case of a single airport (e.g., Brueckner, 2002; Zhang and Zhang, 2006) or the case of non-competing airports. For the latter, Pels and Verhoef (2004), Brueckner (2005) and Basso (2005) considered multiple airports but these airports are complementary to each other: passengers travel from one airport to another (and back) so the airports produce complements, not substitutes; moreover, only Basso (2005) looked at the case of private airports. In general, very few papers in the airport literature have examined the case of competing airports analytically.[2] This is understandable given the local monopoly nature of an airport. The situation is changing, however. The world has experienced a rapid growth in air transport demand since the 1970s, and many airports have been built or expanded as a result. This has led to a number of multi-airport regions such as greater London and the San Francisco Bay Area, within which airports may compete for air travelers.[3] At the same time, the dramatic growth of low cost carriers (e.g., Southwest Airlines and Jet Blue in the United States) has enabled some smaller and peripheral airports to cut into the catchment areas of large airports. Taken together, these two developments have significantly increased the degree of competition between certain airports. Furthermore, airports susceptible to competition are usually prime candidates for congestion. In the U.S., for example, the three multi-airport markets –Chicago, New York, and Washington metropolitan areas– contain the four airports that are officially designated by the Federal Aviation Administration (FAA) as 'slot controlled.' The description also applies to several of the 23 airports identified by the FAA as 'delay-problem airports' –these airports are in the metropolitan areas containing one or more other airports with airline service (e.g., Dallas, Detroit, Huston, Los Angeles, and San Francisco). In this context, our paper intends to extend the recent airport congestion pricing literature that incorporates the vertical airport-airline structure to an environment of competing airports, and compare the results with those of the single-airport case. The competing-facilities case is also highly relevant in the study of ports, as there are many multi-seaport regions around the world.

The paper is organized as follows. Section 2 sets up the model. Section 3 examines rivalry between the two facilities, each of which chooses its capacity and price to maximize profit. Section 4 investigates the monopoly case and the social optimum, and compares them with the duopoly case. Section 5 examines the case in which the monopolist vertically integrates with the carriers at its facilities, and Section 6 contains concluding remarks.

[2] One exception is Gillen and Morrison (2003), who examined two competing airports in the context of a full-service carrier and a low cost carrier. But they did not address the issue of congestion and capacity decisions, nor airline competition within each airport.

[3] De Neufville (1995) identified 26 multi-airport regions in different parts of the world as of the early 1990s. These multi-airport regions cover large territorial size, with some spanning over 100 kilometres, and have high passenger generating capacity (10 million or more annual originating air passengers).

2. THE MODEL

We consider an infinite linear city, where potential consumers are distributed uniformly with a density of one consumer per unit of length. There are two congestible facilities located at 0 and 1 with, respectively, N_0 and N_1 carriers offering services (Figure 1). The locations of the facilities, the number of carriers and the facility from which they produce are exogenous. At each facility, carriers are ex-ante symmetric and offer a homogenous good/service, which is to be referred to as a 'product' hereafter. We will use the term 'fare' to indicate the price of the final product, reserving the terms 'price' and 'charge' for the facilities' price. Given the homogeneity and symmetry, the fare at a given facility will, in equilibrium, be the same for every carrier.

The vertical structure of facility-carrier behavior is represented by a multistage game: (i) the facilities choose their capacities and prices for the input to be used by carriers; (ii) given the facilities' decisions, carriers compete with one another in the output market; and (iii) final consumers decide whether to consume the product and if so, which facility to go.

We investigate the subgame perfect Nash equilibrium of this facility-rivalry game. For this purpose, we first specify and solve the consumers' problem. Potential consumers have unit demands for the product, and they care for its 'full fare.' The full fare faced by a consumer located at $0 \le z \le 1$, and who goes to facility 0, is given by:

$$f_0 + \alpha D(Q_0, K_0) + (t/4)z,$$

where f_0 is the (equilibrium) fare at facility 0, D is its congestion delay time –which depends on total carriers' production at the facility, Q_0, and its capacity K_0–, α is the consumers' value of time, and $t/4$ is a parameter capturing consumers' transportation cost.[4] Thus the full fare is the sum of fare, facility congestion cost, and travel cost to the facility. If the product is consumed, the consumer derives a net benefit (utility):

$$U_0 = V - f_0 - \alpha D(Q_0, K_0) - (t/4)z,$$

with V denoting a gross benefit. Similarly, if the consumer goes to facility 1, then she derives a net benefit:

$$U_1 = V - f_1 - \alpha D(Q_1, K_1) - (t/4)(1-z).$$

This is an 'address model' with linear transportation costs, and the differentiation of the two facilities is captured by consumer transportation cost (i.e., positive t). Within a multi-airport region, for example, passengers may not necessarily choose an airport with cheaper fare, but may go to an airport that is nearer and has shorter total travel time. Indeed, the access time has been shown empirically to be one of the main determinants of airport choice (e.g., Pels, et al., 2001; Ishii, et al., 2005; Fournier, et al., 2006). Our 'differentiated facilities' formulation extends the

[4] The parameter $t/4$ is chosen for it will simplify most of the equations in the paper (see, e.g., equations (4)).

'homogenous facilities' formulation in DBVD, noting that by setting t to zero we get the homogenous case.[5]

Assuming that everyone in the [0,1] interval consumes and both facilities receive consumers from [0,1],[6] then the indifferent consumer $\tilde{z} \in (0,1)$ is determined by $U_0 = U_1$, or

$$\tilde{z} = \frac{1}{2} + \frac{f_1 + \alpha D(Q_1, K_1) - f_0 - \alpha D(Q_0, K_0)}{t/2}. \qquad (1)$$

Thus, the number of [0,1] consumers going to facility 0 (rather than facility 1) increases in $f_1 + \alpha D(Q_1, K_1)$ and decreases in $f_0 + \alpha D(Q_0, K_0)$. Since facility 0 also captures the consumers at its immediate left side, define z^l as the last consumer on the left side of the city, who consumes and goes to facility 0. Similarly, define z^r as the last consumer on the right side of the city, who consumes and goes to facility 1. With the uniformity and unit density of consumers, z^l and z^r can be obtained as:

$$z^l = -\frac{V - f_0 - \alpha D(Q_0, K_0)}{t/4}, \qquad z^r = 1 + \frac{V - f_1 - \alpha D(Q_1, K_1)}{t/4}. \qquad (2)$$

These points, along with $\tilde{z}$, also define the catchment areas of each facility as shown in Figure 1.

Hence, the consumer demands are given by $Q_0 = \tilde{z} + \left|z^l\right|$ and $Q_1 = (1-\tilde{z}) + (z^r - 1)$. Replacing $\tilde{z}$ from (1) and z^l, z^r from (2) then yields:

$$\begin{aligned} Q_0 &= \frac{(t/4) + 2V}{t/2} + \frac{f_1 + \alpha D_1 - 3(f_0 + \alpha D_0)}{t/4} \\ Q_1 &= \frac{(t/4) + 2V}{t/2} + \frac{f_0 + \alpha D_0 - 3(f_1 + \alpha D_1)}{t/2} \end{aligned} \qquad (3)$$

where $D_h \equiv D(Q_h, K_h)$. It is clear that the consumer demands depend not only on the fares, but also on the delays at the two facilities. Notice that in order to have both facilities receiving consumers from [0,1], we need $\left|f_1 + \alpha D_1 - f_0 - \alpha D_0\right| < t/4$, whereas in order to have everyone in the [0,1] interval consuming, we need $2V \geq f_1 + \alpha D_1 + f_0 + \alpha D_0 + (t/4)$, both of which are our maintained assumptions.

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[5] In addition to distance, other aspects of facility differentiation may be captured by extending the present formulation. For instance, Pels, et al. (2000, 2001, 2003) have shown, using a hypothetical example and later the San Francisco Bay Area case study, that ground accessibility of an airport is the most important factor in affecting airport choices in a multi-airport market. We could further address the differential ground access costs by introducing a parameter to the net-benefit function such that $U_1 = V - f_1 - \alpha D(Q_1, K_1) - t\lambda_1(1-z)/4$, where $\lambda_1 > 1$ ($0 < \lambda_1 < 1$, respectively) if facility 1 has a higher (lower, respectively) access cost for consumers than facility 0.

[6] For the conditions for both assumptions to hold, see the analysis below.

In the output market we assume Cournot behavior in modeling carrier competition.[7] Inverting the demand system (3) in (f_0, f_1), we obtain the inverse demand functions that carriers at each facility face:

$$\begin{aligned} f_0(Q_0, Q_1, K_0) &= 2t + V - 3tQ_0 - tQ_1 - \alpha D_0(Q_0, K_0) \\ f_1(Q_0, Q_1, K_1) &= 2t + V - 3tQ_1 - tQ_0 - \alpha D_1(Q_1, K_1) \end{aligned} \tag{4}$$

Thus, in the output market, although any given carrier faces direct competition from the other carries at the same facility, it would also take into account what happens at the other facility: the demands depend on both Q_0 and Q_1. From (4) it may also seem that carries would care about the congestion only at their own facility, but this is not the case. Recall that in the direct demand system (3), the demands depend on the delays at both facilities.

Since we consider ex-ante symmetric carriers at each facility, the cost function of carrier i at facility h is given by:

$$C^{ih}(Q_h^i, \mathbf{Q}_h^{-i}) = \left(c_h + P_h + \beta_h D(Q_h, K_h)\right)Q_h^i, \quad h = 0,1 \tag{5}$$

where c_h is the (constant) marginal operating cost, P_h is the facility charge (an input price), and β_h is the (positive) delay cost parameter for carriers at facility h. Thus, congestion at a facility affects not only its final consumers as discussed above, but its carriers as well. Further, the cost function C^{ih} depends not only on its own output level Q_h^i, but also on the output of other carriers at the facility, $\mathbf{Q}_h^{-i}$, through the congestion term and $Q_h = \sum_i Q_h^i$. It does not depend on the output of carriers at the other facility, however.

Having specified demand and cost functions, we now turn to the delay function. We shall use the same delay function as the one in De Borger and Van Dender (2006):

$$D(Q, K) = a(Q / K), \tag{6}$$

where a is a positive parameter. Use of this linear delay function may nevertheless lead to the problem of the first-order condition approach prescribing a solution in which capacity is exceeded, something that does not happen when delay functions are convex enough (e.g., when $D(Q, K) = Q[K(K-Q)]^{-1}$, delays approach infinity when output approaches capacity). There are two ways around this problem: (i) we can assume an interior solution and later find conditions for this to be true; or (ii) we can impose *a priori* a capacity-rationing rule for the case in which capacity is reached. In this paper we shall take the first approach.

With these specifications, the profit for carrier i at facility 0 is:

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[7] Earlier studies that have incorporated imperfect competition of carriers at a congestible airport (e.g., Brueckner, 2002, 2005; Pels and Verhoef, 2004; Basso, 2005; Zhang and Zhang, 2006; Basso and Zhang, 2006) have assumed Cournot behavior. Brander and Zhang (1990, 1993), for example, find some empirical evidence that rivalry between duopoly airlines is consistent with Cournot behaviour.

$$\phi^{i0}(Q_0^i, \mathbf{Q}_0^{-i}, Q_1, K_0) = f_0(Q_0, Q_1, K_0)Q_0^i - \left(c_0 + P_0 + \beta_0 D(Q_0, K_0)\right)Q_0^i, \qquad i=1,\ldots,N_0 \quad (7)$$

and the carrier profits at facility 1 can be similarly written. As can be seen from (7), these profit functions depend on the outputs of carriers at both facilities.[8] The Cournot equilibrium is characterized by first-order conditions,

$$\partial \phi^{ih} / \partial Q_h^i = 0, \qquad i=1,\ldots,N_h, \qquad h=0,1. \qquad (8)$$

Solving (8) we can obtain the *derived* demands for the two facilities. Specifically, the derived demand for facility 0 is:

$$Q_0(\mathbf{P}, \mathbf{K}) = \frac{t(c_1 + P_1 - 2t - V) - g_1(c_0 + P_0 - 2t - V)}{g_0 g_1 - t^2} \qquad (9)$$

where $\mathbf{P} \equiv (P_0, P_1)$, $\mathbf{K} \equiv (K_0, K_1)$, and

$$g_0 = \frac{N_0 + 1}{N_0}\left(3t + a\frac{\alpha + \beta_0}{K_0}\right). \qquad (10)$$

The expressions for facility 1 are analogous.[9] Thus, the demands faced by the facilities depend directly on facility prices and capacities: they are linear in P_0, P_1, but non-linear in K_0, K_1. Notice that g_0 consists of two parts: the first part is related to transportation cost t (which leads to the two facilities being differentiated), and the second part is related to K_0. It depends on the carrier market structure: g_0 is largest with a monopoly carrier ($N_0 = 1$) and smallest with atomistic carriers ($N_0 \to \infty$). It can be easily shown that $g_h > t$ and so the denominator of (9) is positive. Furthermore, g_h increases in α and β_h, and decreases in K_h and N_h.

Taking the perspective of facility 0, we can characterize the facility demands through the following comparative statics:

$$\frac{\partial Q_0}{\partial P_0} = \frac{\partial Q_0}{\partial c_0} = -\frac{g_1}{g_0 g_1 - t^2} < 0 \qquad (11)$$

$$\frac{\partial Q_0}{\partial P_1} = \frac{\partial Q_0}{\partial c_1} = \frac{t}{g_0 g_1 - t^2} > 0 \qquad (12)$$

[8] Since each consumer in the model consumes one unit of the carriers' products, this would imply, in the airport-airlines case, one flight per person. The simplest way to obtain the real case of many passengers per flight would be through a 'fixed proportions' assumption: let S be the number of consumers in a flight and then assume S is constant and the same across the airlines. The only change in our results would be that a parameter S would be included. The fixed-proportions condition has been assumed in Brueckner (2002, 2005), Pels and Verhoef (2004), Basso (2005), Zhang and Zhang (2006), and Basso and Zhang (2006).

[9] To save notations, in what follows various expressions may be written for facility 0 only, rather than for both facilities 0 and 1. If this is the case, the corresponding expressions for facility 1 will be analogous.

$$\frac{\partial Q_0}{\partial \eta} = -\frac{Q_0\ g_1\ (\partial g_0 / \partial \eta)}{g_0 g_1 - t^2} > 0\,, \quad \text{for } \eta \in \{K_0, N_0 - \beta_0\} \tag{13}$$

$$\frac{\partial Q_0}{\partial \eta} = \frac{Q_1\ t\ (\partial g_1 / \partial \eta)}{g_0 g_1 - t^2} < 0\,, \quad \text{for } \eta \in \{K_1, N_1, -\beta_1\} \tag{14}$$

$$\frac{\partial Q_0}{\partial \alpha} = \frac{Q_1\ t\ (\partial g_1 / \partial \alpha) - Q_0\ g_1\ (\partial g_0 / \partial \alpha)}{g_0 g_1 - t^2}\,. \tag{15}$$

All the signs in (11)-(14) are as expected: e.g., inequality (11) is equivalent to the demand functions being downward sloping, whereas (12) shows that the facilities are 'gross' substitutes. The effects of carriers' marginal costs on the facility demands are the same as those of prices; after all, for the carriers, the facility charge is part of its marginal cost. Further, (13) and (14) indicate that the demand for a facility increases in own capacity, but decreases in the rival's capacity. Moreover, a facility's demand rises the greater the number of carriers it has, and the less its carriers care about congestion (i.e., the lower the value β_h is). Its demand also rises the fewer carriers there are at the other facility, and the more they care about congestion. These comparative-static results are sensible, and will be used in our subsequent analysis.

3. EQUILIBRIA OF DUOPOLY FACILITIES

Having characterized the output-market equilibrium and the facilities' demands, we now analyze the facility market. This section investigates rivalry between the two facilities, each of which chooses its capacity and price to maximize own profit. Following DBVD we shall, initially, investigate a closed-loop game in which capacities are chosen prior to prices. We later compare this case with an open-loop game in which capacities and prices are decided simultaneously.

Assume that the facilities' operational and capacity costs are separable and their marginal costs are constant. Without loss of generality we further set the operational marginal costs to zero, so the profit of facility h can be written as:

$$\pi^h(\mathbf{P}, \mathbf{K}) = Q_h(\mathbf{P}, \mathbf{K}) P_h - m_h K_h\,, \qquad h = 0,1 \tag{16}$$

where m_h denotes the marginal cost of capacity.

3.1 Closed-loop Duopoly

Pricing Stage

The closed-loop game is solved by backward induction, that is, price rivalry is analyzed first. Specifically, given capacities $\mathbf{K} \equiv (K_0, K_1)$, the facilities simultaneously choose their prices P_h

to maximize profit (16). After taking the carriers' competition into account (e.g., equation (11)), the first-order conditions lead to the following pricing rules:

$$P_0 = Q_0 g_0 - (Q_0 t^2 / g_1), \qquad P_1 = Q_1 g_1 - (Q_1 t^2 / g_0). \tag{17}$$

Using (6) and (10) these pricing rules can be further written as, for facility 0:

$$P_0 = (\alpha + \beta_0) D_0 (1 + s_0) + 3t Q_0 (1 + s_0) - (Q_0 t^2 / g_1) \tag{18}$$

where $s_0 = 1/N_0$ is a carrier's market share at facility 0. The first term on the RHS of equation (18) is a congestion toll. But here, the duopoly facilities charge more than just the pure un-internalized congestion of each carrier (which would have been factored by $1 - s_h$, rather than $1 + s_h$): this is caused by the failure of coordination in the vertical structures.[10] The second term in (18) is a mark-up from the exploitation of market power that arises from the locational preferences of consumers and travelling cost (positive t). The third term is a mark-down, owing to facility competition: As the other facility becomes more attractive –i.e., as K_1 rises and hence g_1 falls– the mark-down for facility 0 increases, reducing its price.[11]

Each pricing rule in (18) implicitly defines a 'best reply' function and the pricing equilibrium, denoted $\mathbf{P}^* = (P_0^*, P_1^*)$, is at the intersection of the two best-reply functions. To see how $\mathbf{P}^*$ are affected by both the capacities and features of the consumer demand and the carrier market, we first examine whether $\mathbf{P}^*$ are unique and stable. From (11)-(12) and $g_h > t$, we have

$$\frac{\partial Q_0}{\partial P_0} + \frac{\partial Q_0}{\partial P_1} = -\frac{g_1 - t}{g_0 g_1 - t^2} < 0,$$

that is, own-price effects on demand dominate cross-price effects. This condition is equivalent to the stability condition for $\mathbf{P}^*$ and, together with downward-sloping demands (11), further implies the uniqueness of $\mathbf{P}^*$ (see, e.g., Dixit, 1986). The uniqueness and stability of $\mathbf{P}^*$ then allows us to conduct the comparative statics; the results are reported in Proposition 1.

Proposition 1: In a closed-loop duopoly,

(i) $\partial P_0^* / \partial K_0 < 0$, $\partial P_0^* / \partial K_1 < 0$, i.e., higher capacities imply smaller equilibrium prices;

(ii) For given capacities, (a) the (equilibrium) prices increase with the time costs –either consumers' cost (α) or carriers' cost (β_0, β_1); (b) entrance of a new carrier to *any* of the facilities depresses the prices charged by *both* facilities; and (c) lower marginal cost of the carriers at one facility induces a lower price at that facility but a higher price at the other facility.

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[10] As is to be seen in Sections 4 and 5, this coordination failure is not resolved even if both facilities are owned by a single firm (monopolist), but would be resolved by a vertical integration of facilities and carriers.

[11] This expression has a different flavor than the one obtained in a non-vertical setting –e.g., De Borger and Van Dender (2006, equation (9))– even if we assume away facility differentiation. In the non-vertical case, the third part would be positive, although a less attractive facility 1 would reduce the mark-up.

Proof. See the Appendix .

One implication of Proposition 1 (i) is that the more congestible the system is, the higher the equilibrium prices are. This result was also found in the non-vertical setting of DBVD, which is not surprising because our derived demands for the facilities react to changes in prices and capacities in the same fashion as the demands they assumed in their final market. Another interesting result is that $\partial P_0^* / \partial \alpha > 0$ –part (a) of (ii). From (15), higher time value α will, in a fully symmetric case with respect to both facilities and carriers, reduce the demands for both facilities. However, the demand for a facility may increase with α in asymmetric cases.[12] Despite that the demand for a facility may increase or decrease in α, the equilibrium prices will always increase in α. Just as a more congestible system leads to higher facility prices, a higher consumer time cost also induces higher facility prices.

But perhaps more interesting results from Proposition 1 pertain to the price effects of changes in characteristics of the *intermediate* market such as variables β_h, N_h or c_h, as this is our main departure from the literature. In particular, Proposition 1 suggests that for given capacities, a lower marginal cost of the carriers at a facility would induce a lower price at that facility, but a higher price at the other facility. For example, if we start from a situation in which airlines have the same marginal costs $c_0 = c_1$ and we replace the airlines of one facility by lower marginal-cost carriers, then the airport charge would fall at the airport with low-cost carriers, while the charge at the other airport would rise. This might serve as a testable implication for empirical studies. Note, here, that the number of airlines at each airport does not need to be the same.

Capacity Stage

In the closed-loop game, each facility chooses its capacity taking price equilibrium $\mathbf{P}^*(\mathbf{K})$ into account. The reduced-form profit of each facility is:

$$\Pi^h(\mathbf{K}) = \pi^h\left(\mathbf{P}^*(\mathbf{K}), \mathbf{K}\right), \qquad h = 0,1 \tag{19}$$

where $\pi^h\left(\mathbf{P}, \mathbf{K}\right)$ is given by (16). The capacity equilibrium is characterized by first-order conditions,

$$\Pi_0^0 \equiv \frac{\partial \Pi^0(\mathbf{K})}{\partial K_0} = \frac{\partial \pi^0}{\partial P_0}\frac{\partial P_0^*}{\partial K_0} + \frac{\partial \pi^0}{\partial P_1}\frac{\partial P_1^*}{\partial K_0} + \frac{\partial \pi^0}{\partial K_0} = \frac{\partial \pi^0}{\partial P_1}\frac{\partial P_1^*}{\partial K_0} + \frac{\partial \pi^0}{\partial K_0} = 0 \tag{20}$$

(where the second equality follows from the envelope theorem) and $\Pi_1^1 = 0$. We assume the second-order conditions $\Pi_{hh}^h < 0$ hold for the entire range of interest.

[12] For example, if everything is symmetric except for carriers' marginal costs, and (c_0 – c_1) is large enough, then higher c_0 implies that carriers at facility 0 would have, *ceteris paribus*, higher fares and hence the facility will have a smaller demand but also less congestion. A marginal increase in α would induce a shift by consumers towards the less congested facility, thereby increasing its demand.

Notice that equation (20) can be rewritten as:

$$\underbrace{P_0^*}_{+}\underbrace{\frac{\partial Q_0}{\partial P_1}}_{+}\underbrace{\frac{\partial P_1^*}{\partial K_0}}_{-}+[P_0^*\frac{\partial Q_0}{\partial K_0}-m_0]=0\,. \tag{21}$$

The bracketed term in (21) contains the direct effect of capacity: At cost m_0, a marginal increase in capacity will enhance own demand –recall $\partial Q_0/\partial K_0>0$ by (13)– and hence own revenue. The indirect effect –the first term in (21)– indicates that a marginal increase in own capacity will lead to a reduction in the rival facility's price (recall Proposition 1) which in turn will, by (12), reduce own demand. As indicated, this 'strategic' effect is negative to the facility's profit.

3.2 Open-loop Duopoly and Comparison with Closed-loop Duopoly

In an open-loop game, the problem faced by facility *h* is:

$$\max_{P_h,\,K_h}\pi^h(\mathbf{P},\mathbf{K})$$

where π^h is given by (16). The corresponding first-order conditions will give rise to the pricing and capacity rules. The pricing rules remain the same as those given in (17) or (18), whereas the capacity rules can be derived, using (13), as:

$$K_h^o=\left(\frac{a(\alpha+\beta_h)(N_h+1)}{m_h\,N_h}\right)^{1/2}Q_h^o\,,\qquad h=0,1 \tag{22}$$

where superscript *o* stands for the open-loop game. (22) implies that in equilibrium, the delay time at facility *h* equals:

$$D(Q_h^o,K_h^o)=a\frac{Q_h^o}{K_h^o}=\left(\frac{a\,m_h\,N_h}{(\alpha+\beta_h)(N_h+1)}\right)^{1/2},\qquad h=0,1. \tag{23}$$

At the open-loop equilibrium, therefore, congestion delay at facility *h* increases in N_h and m_h, but decreases in α (consumers' time cost) and β_h (facility *h* carriers' time cost). Equations (23) also define a sufficient condition for an 'interior solution:' that $Q_h\le K_h$ if and only if

$$m_h\le a(\alpha+\beta_h)\,,\qquad h=0,1. \tag{24}$$

Hence, if the capacity costs are *low enough*, or if the time costs are *high enough*, the open-loop game will have an interior solution.

Next, compare the results between the closed- and open-loop games. We first show that the facilities invest less in capacity in the closed-loop game than in the open-loop game. Recall that the closed-loop capacity rule is given by (20), that is, $\Pi_0^0\big|_{K_0^c} = 0$, where superscript c stands for the closed-loop game. Evaluating Π_0^0 at the open-loop capacity yields:

$$\Pi_0^0\Big|_{K_0^o} = \left(\frac{\partial \pi^0}{\partial P_1}\frac{\partial P_1^*}{\partial K_0} + \frac{\partial \pi^0}{\partial K_0}\right)\Bigg|_{K_0^o} = \left(\frac{\partial \pi^0}{\partial P_1}\frac{\partial P_1^*}{\partial K_0}\right)\Bigg|_{K_0^o} = P_0^* \frac{\partial Q_0}{\partial P_1}\frac{\partial P_1^*}{\partial K_0} < 0\,. \tag{25}$$

In (25), the second equality follows from the capacity first-order condition in the open-loop game, whereas the inequality has already been indicated in (21). Then $K_0^c < K_0^o$ and, similarly, $K_1^c < K_1^o$ follow by the concavity of the profit functions.

The intuition behind the above result is clear. In the closed-loop game, according to the nomenclature of Fudenberg and Tirole (1984), the facilities invest less in capacity following ‘puppy dog’ strategies: Investment in capacity would make a facility tough, in that it decreases the facility’s price hurting the rival (recall that prices are higher in more congestible systems). But that would trigger a harsh pricing reaction from the rival facility, since the prices are strategic complements. Hence, the facilities will try to soften the price competition by committing to smaller capacities in the first stage: they want to look small and inoffensive. This also directly leads to higher prices.

However, the fact that capacities are smaller when they are chosen prior to prices does not directly imply that delays will also be longer. This is because, on one hand, capacity levels directly affect demands and, on the other hand, we now have higher prices. Yet, it can be shown that the delays do increase. From (25) and (21) we have, at the closed-loop equilibrium,

$$\left(P_0^* \frac{\partial Q_0}{\partial K_0} - m_0\right)\Bigg|_c > 0\,. \tag{26}$$

Since equation (17) must hold at this equilibrium, we can replace P_0^* in (26) with $Q_0 g_0 - (Q_0 t^2 / g_1)$. Further replacing $\partial Q_0 / \partial K_0$ with (13), calculating $\partial g_0 / \partial K_0$ with (10), and rearranging, (26) becomes:

$$a\frac{Q_0^c}{K_0^c} > \left(\frac{a\, m_0\, N_0}{(\alpha+\beta_0)(N_0+1)}\right)^{1/2} \;\Rightarrow\; D(Q_0^c, K_0^c) > D(Q_0^o, K_0^o) \tag{27}$$

where (23) is used in the second part of (27). The above comparisons thus lead to:

Proposition 2: A closed-loop duopoly invests less in capacity, charges higher facility prices, and has longer congestion delays than an open-loop duopoly.

Thus, in terms of facility price and service quality, the open-loop duopoly dominates the closed-loop duopoly as it has both lower facility prices and shorter delays.

4. MONOPOLY AND THE SOCIAL OPTIMUM

Having examined the duopoly case, we shall in this section investigate the monopoly case –in which a monopolist owns both facilities– and the social optimum, emphasizing comparisons among the three cases. Note that in both the monopoly case and the social optimum, the results remain the same whether the capacity and price decisions are made simultaneously or sequentially.

4.1 Monopoly

The monopolist's problem is:

$$\max_{\mathbf{P},\mathbf{K}} \pi^0(\mathbf{P},\mathbf{K}) + \pi^1(\mathbf{P},\mathbf{K}) = \max_{\mathbf{P},\mathbf{K}} \sum_h (Q_h(\mathbf{P},\mathbf{K})P_h - m_h K_h) .$$

Taking the first-order conditions for prices, and using (6), (10) and (11), we obtain (superscript M stands for monopoly):

$$P_0^M = (\alpha + \beta_0) D_0 (1 + s_0) + 3tQ_0 (1 + s_0) + Q_1 t . \tag{28}$$

and the expression for facility 1 is analogous. These monopoly pricing rules can be compared to the duopoly pricing rules (18). The first two terms on the RHS of (28) are the same as those in (18), although they are evaluated at different prices (and capacities). The first term is related to the congestion toll, but the monopoly facilities, like the duopolists, charge more than just the pure un-internalized congestion of each carrier (which would have been $1 - s_0$, rather than $1 + s_0$). The second term is the mark-up from the exploitation of market power, which arises from the consumers' locational preferences and their traveling cost. As for the third term in (28), contrary to what happens with the duopoly, the monopoly has a mark-up –rather than a mark-down as in (18)– owing to the absence of facility competition. Here, when raising the price for one facility, the monopolist takes into consideration that it is actually increasing the demand for the other facility, with the resulting profit accruing to itself. In other words, the monopolist has internalized the interrelation of demands, and hence the facility competition.

From (28) and (18) it is not immediate, however, to conclude that monopoly facility charges are higher than duopoly charges. The reasons are two-folds. First, both (28) and (18) are actually a system of fixed points, since Q_0 and Q_1 depend on both P_0 and P_1. Second, perhaps more fundamentally, capacities will likely differ in the two cases; prices and capacities are decided simultaneously. Prices can therefore be compared in two ways (see Spence, 1975; Basso, 2005): (i) compare prices as if capacities were fixed; and (ii) compare actual prices, taking the capacity difference (if any) into consideration. The first one is useful because it may represent a short-term case, but it is also useful in performing the second comparison. In what follows we will, when feasible, perform both comparisons.

Prior to the price comparisons, we first look at the capacity rules under monopoly. Taking the first-order conditions for capacities, and using (10), (13) and (28), we get:

$$K_h^M = \left(\frac{a(\alpha + \beta_h)(N_h + 1)}{m_h \; N_h} \right)^{1/2} Q_h^M \,, \qquad h = 0,1. \tag{29}$$

The monopoly capacity rule (29) is identical to the open-loop duopoly capacity rule (22). Obviously, since their pricing rules are different, the consumption levels, and hence actual capacities, will be different in the two cases. Delay times will be equal however, given the linearity assumption of the delay function. From (29) we have:

$$D(Q_0^M, K_0^M) = a \frac{Q_0^M}{K_0^M} = \left(\frac{a \, m_0 \; N_0}{(\alpha + \beta_0)(N_0 + 1)} \right)^{1/2} = D(Q_0^o, K_0^o)\,, \tag{30}$$

where the last equality follows from (23). Note that the sufficient condition for an interior solution in the monopoly case remains the same as (24). De Borger and Van Dender (2006) found that the duopolists offer lower service quality, in terms of longer delays, than the monopolist. Here we find that this is the case only if capacity decisions are made prior to price decisions (which is the situation analyzed in DBVD). When the capacity and price decisions are made simultaneously, or when capacity investments are not observable prior to price decisions, the duopolists will provide the same service quality as the monopolist.

Next, compare the monopoly and duopoly prices for given capacities. Obtaining monopoly prices for given capacities involves solving system (28), which leads to:

$$P_0^M(\mathbf{K}) = (2t + V - c_0)/2\,, \qquad P_1^M(\mathbf{K}) = (2t + V - c_1)/2\,. \tag{31}$$

Thus, given the capacities, the monopoly prices are, somewhat surprisingly, actually independent of the capacities! This means that the monopolist would charge prices (31) independently of whether it can choose capacities or not (provided, of course, that it leads to an interior solution). A facility’s price decreases with the marginal cost of carriers at that facility, but is independent of the marginal cost of carriers at the other facility. This is in contrast to the duopoly case, where a fall in carriers’ marginal cost at one facility induces a price increase at the other facility. It is noted that this distinction between the duopoly and monopoly pricing might serve as an empirically testable hypothesis.

The result that the monopoly pricing rules do not depend on capacities also allows us to show that the monopoly prices are indeed higher than the actual duopoly prices. The monopoly-duopoly comparisons are reported in Proposition 3:

Proposition 3: For facility h (h = 0,1),

(i) $P_h^o < P_h^c < P_h^M$, i.e., an open-loop duopoly has lower facility prices than a closed-loop duopoly, which in turn has lower facility prices than a monopoly; and

(ii) $D_h^o = D_h^M < D_h^c$, i.e., duopoly facilities offer lower service quality, in terms of longer delays, than the monopolist only if capacity decisions are made prior to price decisions. If the capacity and price decisions are made simultaneously, the duopolists offer the same service level as the monopolist.

Proof. See the Appendix.

Thus, in terms of facility price and service quality, the open-loop duopoly dominates monopoly as it has both lower prices and shorter delays. It is not clear, however, whether the closed-loop duopoly is superior to monopoly: while having lower prices, it has longer delays than monopoly.

4.2 The Social Optimum

The social optimum arises when a central planner chooses facility prices $\mathbf{P}$ and capacities $\mathbf{K}$ to maximize social welfare. Since our setting extends DBVD's by introducing the downstream carriers, we now have the surplus of three types of agents –namely, facilities, carriers, and final consumers– to consider, rather than just two types of agents (facilities and final consumers as in DBVD).[13] This gives rise to the following social-welfare function:

$$SW(\mathbf{P},\mathbf{K}) = CS + (\Phi^0 + \Phi^1) + (\pi^0 + \pi^1) \tag{32}$$

where CS is consumer surplus, $\Phi^h = \sum_i \phi^{ih}$ is the aggregate (equilibrium) profit for carriers at facility h, and π^h is the (equilibrium) profit of facility h.

The first-order conditions with respect to $\mathbf{P}$ give rise to the social pricing rules. The derivation is long but straightforward and hence is given in the Appendix. We obtain:

$$P_0^W = (\alpha + \beta_0)D_0(1 - s_0) - 3tQ_0 s_0, \qquad P_1^W = (\alpha + \beta_1)D_1(1 - s_1) - 3tQ_1 s_1 \tag{33}$$

where superscript W stands for welfare maximization. This pricing rule for each facility is conceptually similar to the ones obtained by Brueckner (2002), Pels and Verhoef (2004), Basso (2005) and Zhang and Zhang (2006). The socially optimal price at a facility consists of a *congestion term* –by which the facility charges each carrier for the un-internalized congestion it produces– and a mark-down, the *market-power term*, by which the facilities 'subsidize' carriers so as to countervail the exploitation of market power by monopoly or oligopoly carriers and induce the allocatively efficient output. One consequence of such subsidy is that the facilities may not recover their costs if the carriers' market power, and hence the market-power term, is large, even though we have constant returns to scale in the provision of capacity and linear delay functions. This is in contrast to DBVD, and earlier studies (e.g., Morrison, 1983; Zhang and Zhang, 1997), that have shown that under the constant returns to scale and linear delay functions, the optimal pricing and optimal provision of capacity lead to exact cost recovery for a congestible facility (e.g., airport). These studies did not consider imperfect competition in the carriers' market.[14]

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[13] As demonstrated by Basso (2005, 2006), this distinction is relevant and important in the derivation of welfare-maximization results. This is also seen from the analysis below.

[14] The non-cost recovery result has also been obtained by Brueckner (2002), Basso (2005) and Zhang and Zhang (2006) under different model settings. All of these studies have explicitly considered imperfect competition in the carriers' market. The issue of budget adequacy is further discussed by Zhang and Zhang (2006) for the single-airport case and by Basso (2005) in the context two distant airports, but the conclusions there apply to this competing-facilities case as well: two-part tariffs, or cost-recovery two-part tariffs if the carriers do not make enough profits,

Equations (33) also show that when there is a single carrier at a facility ($s_h = 1$), the congestion term at that facility becomes zero. This is because the monopoly carrier perfectly internalizes congestion and consequently there is no need to correct for congestion. On the other hand, with atomistic carriers ($s_h \to 0$) the market-power term at facility h will vanish. These results have already been obtained by Brueckner (2002) and others in the context of non-competing airports. With competing facilities, (33) further shows that absent of any facility differentiation (i.e., t=0) the market-power terms at both facilities will vanish, *irrespective of the carrier market structure at either facility*. This result is related to our Bertrand assumption of facility competition; it also extends the analysis of DBVD who considered Bertrand rivalry between perfectly substitutable facilities: With t=0, the market-power term disappears and so the socially-optimal charges will equal $P_h^W = (\alpha + \beta_h) D_h (1 - s_h)$, i.e., the (un-internalized) congestion tolls. Finally, (33) is easily comparable to both the monopoly pricing equation (28) and the duopoly pricing equation (18).

The first-order conditions with respect to $\mathbf{K}$ give rise to the following social capacity rules (the derivation is given in the Appendix):

$$K_h^W = \left(\frac{a(\alpha + \beta_h)}{m_h} \right)^{1/2} Q_h^W, \qquad h = 0,1. \tag{34}$$

These capacity rules can be compared to the monopoly capacity rules (29), giving rise to:

Proposition 4: Conditional on facility charges, the monopoly capacity rules are the same as the socially-optimal capacity rules if and only if $N_0, N_1 \to \infty$, i.e., the downstream carrier markets are perfectly competitive at both facilities.

Thus, if there is (at least) one downstream market that is imperfectly competitive, the monopoly capacity rules will be different from the social capacity rules. This is in contrast to what was found by DBVD in their analysis without an intermediate carrier market; they found that the monopoly and socially optimal capacity rules are identical. Their result had a precedent in Oum, et al. (2004) who analyzed the price and capacity decisions by a single congestible airport. Since they did not formally derive the airport's demand from the equilibrium of the airline market, their setting is actually quite close to DBVD's, with the exception that DBVD had two facilities with interdependent demands. Proposition 4 shows that, when one takes into consideration that the congestible facilities may be upstream providers of an input, which is the case for airports, seaports, and perhaps railroad tracks or telecommunication networks, the monopoly capacity rules will coincide with the socially optimal rules only when carriers are atomistic.[15]

Both Oum et al. and DBVD correctly pointed out that, since the pricing rules are different, the consumption levels and, hence, actual capacities will be different. However, taking advantage of the assumption of a linear delay function, DBVD showed that, in their case where the facilities

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may resolve the problem. If fixed fees are not feasible for some reason, the less efficient alternative of Ramsey-Boiteaux prices is called for.

[15] See also Basso (2005) and Zhang and Zhang (2006) for a similar result in the context of non-competing airports.

interact directly with final consumers, the monopolist offers exactly the same service quality –i.e., the same level of delays– as welfare-maximizing facilities. In our case, from (34) and (30) it follows that[16]

$$D(Q_h^W, K_h^W) = a\,\frac{Q_h^W}{K_h^W} = \left(\frac{a\,m_h}{\alpha+\beta_h}\right)^{1/2} > \left(\frac{a\,m_h\;N_h}{(\alpha+\beta_h)(N_h+1)}\right)^{1/2} = D(Q_h^M, K_h^M) \qquad (35)$$

and $D(Q_h^W, K_h^W) = D(Q_h^M, K_h^M)$ only if $N_h \to \infty$. Thus, DBVD's result emerges as a special case of our comparison (i.e., when carriers are atomistic). Proposition 5 summarizes the result:

Proposition 5: At a facility, the monopolist will offer the same service quality –in terms of congestion delays– as the central planner if the carrier market at the facility is perfectly competitive. Otherwise, the monopolist offers a higher service level than the central planner.

5. VERTICAL INTEGRATION

Proposition 5 shows that when the facilities are input providers to an imperfectly competitive output market, the monopolist would no longer provide exactly the same service quality as the central planner. However, an important issue is: if the congestion levels were equal, does that mean that the monopolist is providing the *socially optimal* level of service quality? To address the issue, we analyze the case in which the monopolist vertically integrates with the carriers at the facilities: As is to be seen below, in this case the monopolist will have exactly the same service level as the central planner, just as in the case of DBVD. The vertical-integration case is also relevant in the real world. For example, in the case of airports, it has often been argued that strategic collaboration between airports and airlines would solve the incentive and coordination problems regarding capacity and pricing in the vertical structure (see, e.g., Beesley, 1999; Forsyth, 1997; Starkie, 2001; for a more complete list see Basso, 2005).

Under vertical integration, our hyper-monopolist's problem is:

$$\max_{\mathbf{P},\mathbf{K}} \sum_h (\Phi^h + \pi^h)\,.$$

The pricing rules are given by:

$$P_0^{VI} = (\alpha+\beta_0)D_0(1-s_0) + [3tQ_0(1-s_0) + Q_1 t] \qquad (36)$$

where superscript *VI* stands for vertical integration. This pricing equation is conceptually similar to the ones obtained by Basso (2005) for the case of two distant airports that vertically integrate with airlines, and by Basso and Zhang (2006) for the case of peak-period pricing by a vertically integrated airport. It shows that the price consists of a congestion toll –by which the facility

[16] Note that the sufficient condition for an interior solution at the social optimum remains the same as (24), that is, $m_h \le a(\alpha+\beta_h)$.

charges each carrier for the un-internalized congestion it produces– and a mark-up. The congestion toll –represented by the first term on the RHS of (36)– depends on the number of carriers at the facility in the same fashion as in the central-planner case of (33). By the mark-up –which is represented by the bracketed term in (36)– the facility induces the cartel level of output, and hence maximizes the carriers' joint profit, by raising their marginal costs through a higher facility charge. In particular, the mark-up takes into account both the *intra-facility* carrier competition –represented by $3tQ_0(1-s_0)$, which vanishes when there is a single carrier– and the *inter-facility* carrier competition ($Q_1 t$, which vanishes when t=0).

It turns out that the hyper-monopolist's capacity rule is the same as the central-planner rule (34). As a result, the level of service quality (delays) is also the same:

$$D(Q_0^{VI}, K_0^{VI}) = a\,\frac{Q_0^{VI}}{K_0^{VI}} = \left(\frac{a\,m_0}{\alpha+\beta_0}\right)^{1/2} = D(Q_0^{W}, K_0^{W})\,, \tag{37}$$

where the last equality is based on (35). While the level of delays in (37) is optimal *given the socially optimal pricing*, if a *constrained* central planner is forced to price as the hyper-monopolist does, it would choose a different capacity rule and thereby induce a different –in fact, probably superior– service level. We formally state the result in Proposition 6:

Proposition 6: When the monopolist vertically integrates with the carriers at its facilities, it would provide the same service level as the central planner. Nevertheless, the hyper-monopoly service level is not socially optimal in a second-best sense; in effect, in the fully ex-ante symmetric case, it is too low with respect to the second best.

Proof. See the Appendix.

Hence, the service level provided by the hyper-monopolist is not optimal: at the very least, in the fully symmetric case, a central planner who is forced to use the same pricing rule as the hyper-monopolist would choose a higher service level. The congestion delays of the hyper-monopolist are not second best. The intuition is simple: given that the prices will be higher, the constrained central planner will compensate consumers and carriers by providing a higher quality service. More generally, as has been pointed out, capacities and prices are decided jointly so they cannot be analyzed separately. And since service quality is a result of both the level of demands induced and the capacities chosen, it cannot be looked at on its own; just as with capacity, delays must be analyzed together with pricing.

6. CONCLUDING REMARKS

Our main objective in writing this paper is to contribute to the understanding of rivalry between congestible facilities, but for the case in which the facilities provide an input for downstream firms, who sell the final product to consumers. This is the case for airports, seaports, and perhaps railroad tracks or telecommunication networks. By explicitly incorporating the behaviour of oligopolistic downstream carriers and final consumers into the analysis of a duopolistic facility rivalry, we found that for given capacities, (a) the duopolists' equilibrium prices increase with both the consumers' value of time and the carriers' cost sensitivity to congestion delays; (b) entrance of a new carrier to *any* of the facilities depresses the prices charged by *both* facilities; and (c) lower marginal cost of the carriers at one facility induces a lower price at that facility but a higher price at the other facility. As discussed in the text, some of these results might serve as testable implications for empirical studies.

We further found that: (i) although the duopoly facilities have lower prices than the monopolist, they offer lower service quality only if capacity decisions are made prior to the facility pricing decisions (i.e., if the duopoly rivalry is a closed-loop game, as in DBVD). When the capacity and pricing decisions are made simultaneously (i.e., an open-loop game), the duopolists will provide the same service quality as the monopolist. (ii) A closed-loop duopoly invests less in capacity and charges higher facility prices than an open-loop duopoly. Here, the closed-loop duopolists follow a 'puppy dog' strategy: they try to soften the price competition by committing to smaller capacities in the first stage. This directly leads to higher prices. (iii) Conditional on facility charges, the monopolist will have the same capacity rules as the central planner if and only if the downstream carrier markets are perfectly competitive at both facilities. If there is (at least) one downstream market that is imperfectly competitive, the monopoly capacity rules will be different from the socially optimal capacity rules. (iv) At a facility, the monopolist will provide the same service quality as the central planner if the carrier market is perfectly competitive; otherwise, the monopolist provides a higher service level than the central planner. Finally, our analysis showed that when the monopolist vertically integrates with the carriers at its facilities, it would provide the same congestion level as the central planner. Nevertheless, this integrated monopoly service level is not socially optimal in a second-best sense. In effect, in the fully symmetric case, it is too low with respect to the second best.

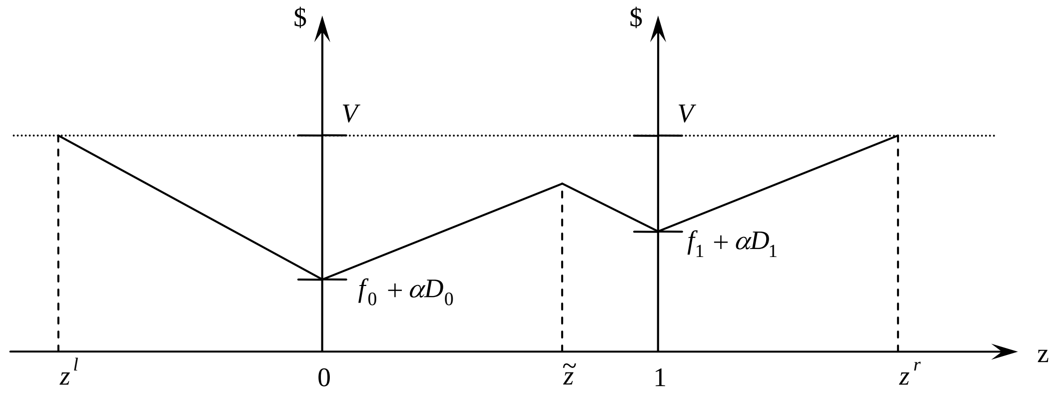

Figure 1. Consumer distribution and facilities' catchment areas

Appendix

***Proof of Proposition 1*:** (i) Solving (17) for $\mathbf{P}^*$ and using of (9) and (10), we find:

$$P_0^*(\mathbf{K};\mathbf{x}) = \frac{g_0 t(c_1 - 2t - V) - (c_0 - 2t - V)(2g_1 g_0 - t^2)}{4g_0 g_1 - t^2}, \tag{A.1}$$

where $\mathbf{x} \equiv (\alpha, \beta_0, \beta_1, N_0, N_1, c_0, c_1)$ is the vector of exogenous parameters. Differentiating P_0^* with respect to K_0, K_1 yields:

$$\frac{\partial P_0^*}{\partial K_0} = \frac{t^2(Q_0 g_0 + Q_1 t)}{g_0(4g_0 g_1 - t^2)}\frac{\partial g_0}{\partial K_0} < 0, \qquad \frac{\partial P_0^*}{\partial K_1} = \frac{2g_0 t(Q_1 g_1 + Q_0 t)}{g_1(4g_0 g_1 - t^2)}\frac{\partial g_1}{\partial K_1} < 0 \tag{A.2}$$

where the inequalities arise from $g_h > t$ and the use of (10).

(ii) From (A.1) we can show, for h=0,1,

$$\frac{\partial P_0^*}{\partial \alpha} > 0, \qquad \frac{\partial P_0^*}{\partial \beta_h} > 0, \qquad \frac{\partial P_0^*}{\partial N_h} < 0$$

which give rise to parts a) and b). Part c) follows from the following inequalities:

$$\frac{dP_0^*}{dc_0} = -\frac{2g_0 g_1 - t^2}{4g_0 g_1 - t^2} < 0, \qquad \frac{dP_0^*}{dc_1} = \frac{g_0 t}{4g_0 g_1 - t^2} > 0. \qquad \textit{Q.E.D.}$$

***Proof of Proposition 3*:** Part (ii) has been proved in the text and by using Proposition 2. For the proof of part (i), it is sufficient, using Proposition 2, to prove $P_0^c < P_0^M$. From (A.1) and (31) we can easily show that for given capacities, the duopoly prices are, as expected, smaller than the monopoly prices:

$$P_0^M(\mathbf{K}) - P_0^*(\mathbf{K}) = \frac{t\left[t(2t + V - c_0) + 2g_0(2t + V - c_1)\right]}{2\left(4g_0 g_1 - t^2\right)} > 0. \tag{A.3}$$

Hence,

$$P_0^c = P_0^*(\mathbf{K}^c) < P_0^M(\mathbf{K}^c) = P_0^M(\mathbf{K}^M) = P_0^M \Rightarrow P_0^c < P_0^M \tag{A.4}$$

where the first inequality follows from (A.3), and the equality $P_0^M(\mathbf{K}^c) = P_0^M(\mathbf{K}^M)$ follows from (31), i.e., the monopoly pricing rules do not depend on capacities. *Q.E.D.*

***Derivations of Social Pricing and Capacity Rules*:** We first specify the welfare function. With consumers being uniformly distributed with density one per unit of length, the consumers' surplus is given by (see Figure 1):

$$CS = \int_0^{|z^l|}\left[V - p_0(Q_0,Q_1) - \alpha D_0 - tz)\right]dz + \int_0^{\tilde{z}}\left[V - p_0(Q_0,Q_1) - \alpha D_0 - tz)\right]dz$$
$$+ \int_0^{1-\tilde{z}}\left[V - p_1(Q_0,Q_1) - \alpha D_1 - tz)\right]dz + \int_0^{z^r - 1}\left[V - p_1(Q_0,Q_1) - \alpha D_1 - tz)\right]dz$$

Note that Q_0 and Q_1 –which are given by (3)– do not depend on z, whereas z^l, z^r and $\tilde{z}$ depend on Q_0 and Q_1. Hence, we will obtain an expression dependent on Q_0 and Q_1. Using (4) to replace p_0 and p_1 both in the integrands and in z^l, z^r and $\tilde{z}$, and solving the integrals we get:

$$CS = t\left(3Q_0^2 + 2Q_0Q_1 + 3Q_1^2 - 4\right)/2\,. \qquad \text{(A.5)}$$

It might seem that *CS* increases in *t*, and it is negative if there is no consumption. However, it is important to recall that both Q_0 and Q_1 are *equilibrium* values, so they depend on the level of congestion and on the value of *t*. Indeed, an examination of (3) reveals that Q_0 and Q_1 will rise as *t* falls, so the overall result is that *CS* actually falls as *t* increases, as expected. Also, recall that the maintained assumption has been that *V* is sufficiently large so that everyone in the [0,1] interval consumes. This implies that the minimum values of Q_0 and Q_1 for which the above *CS* expression is valid are when both are equal to 1 (each facility gets ½ consumer from each side, left and right). Therefore, *CS* is never less than 2*t*.

Regarding the carriers' profit, it is straightforward, from (7), (4) and symmetry, to obtain:

$$\Phi^0(\mathbf{P},\mathbf{K}) = (2t + V - c_0)Q_0 - Q_0P_0 - 3tQ_0^2 - tQ_0Q_1 - (\alpha + \beta_0)Q_0D_0\,. \qquad \text{(A.6)}$$

With *CS*, Φ^h and the facilities' profits by (16), the welfare function (32) can be written as:

$$\begin{aligned} SW(\mathbf{P},\mathbf{K}) &= (2t + V - c_0)Q_0 + (2t + V - c_1)Q_1 - (t/2)(3Q_0^2 + 2Q_0Q_1 + 3Q_1^2) - 2t \\ &\quad - (\alpha + \beta_0)Q_0D_0 - (\alpha + \beta_1)Q_1D_1 - m_0K_0 - m_1K_1 \end{aligned} \qquad \text{(A.7)}$$

Notice that *SW* above is not directly a function of prices; instead, it is a function of Q_0, Q_1 and, through them, a function of P_0, P_1.

The first-order condition with respect to P_0 is,

$$\frac{dSW}{dP_0} = \frac{\partial SW}{\partial Q_0}\frac{\partial Q_0}{\partial P_0} + \frac{\partial SW}{\partial Q_1}\frac{\partial Q_1}{\partial P_0} + \frac{\partial SW}{\partial P_0} = 0\,.$$

Calculating this –noticing $\partial SW/\partial P_0 = 0$ and using (A.7), (A.1), (11) and (12) – we get:

$$\left[P_1 + 3t\frac{Q_1}{N_1} - a(\alpha + \beta_1)\frac{Q_1}{K_1}\left(\frac{N_1 - 1}{N_1}\right)\right]t = \left[P_0 + 3t\frac{Q_0}{N_0} - a(\alpha + \beta_0)\frac{Q_0}{K_0}\left(\frac{N_0 - 1}{N_0}\right)\right]g_0\,. \qquad \text{(A.8)}$$

Similarly, the first-order condition with respect to P_1 leads to:

$$\left[P_1 + 3t\frac{Q_1}{N_1} - a(\alpha + \beta_1)\frac{Q_1}{K_1}\left(\frac{N_1 - 1}{N_1}\right)\right]g_1 = \left[P_0 + 3t\frac{Q_0}{N_0} - a(\alpha + \beta_0)\frac{Q_0}{K_0}\left(\frac{N_0 - 1}{N_0}\right)\right]t\,. \qquad \text{(A.9)}$$

Since the bracketed terms on the LHS of (A.8) and (A.9) are the same, the bracketed terms on the RHS of (A.8) and (A.9) are the same, $g_0, g_1 > t$ and $g_0 \neq g_1$, equations (A.8) and (A.9) hold only if each of the bracketed terms is zero. Using (6), this gives rise to the social pricing rules (33).

To derive the social capacity rules, it is useful to point out that the pricing rules (33) are obtained as if we were maximizing directly in terms of (Q_0, Q_1) rather than (P_0, P_1), because the pricing rules are in fact derived from $\partial SW/\partial Q_h = 0$. Hence:

$$\frac{dSW}{dK_h} = \frac{\partial SW}{\partial Q_0}\frac{\partial Q_0}{\partial K_h} + \frac{\partial SW}{\partial Q_1}\frac{\partial Q_1}{\partial K_h} + \frac{\partial SW}{\partial K_h} = \frac{\partial SW}{\partial K_h} = 0\,. \qquad \text{(A.10)}$$

From (A.10), (A.7), it follows immediately that the social capacity rules are given by (34).

***Proof of Proposition 6*:** The first part of the proposition has been indicated by (37). To prove the remaining parts, consider the fully ex-ante symmetric case, namely, $N_0 = N_1 = N$, $\beta_0 = \beta_1 = \beta$ and $m_0 = m_1 = m$. Let $\tilde{S}W(\mathbf{K}) \equiv SW(\mathbf{P}^{VI}(\mathbf{K}))$ be a second-best social welfare function, where $\mathbf{P}^{VI}(\mathbf{K})$ represents the hyper-monopolist pricing rule. Hence we have:

$$\frac{d\tilde{S}W}{dK_0} = 0 \Leftrightarrow \left.\frac{dSW}{dK_0}\right|_{\mathbf{P}^{VI}(\mathbf{K})} = 0 .$$

Calculating $\frac{dSW}{dK_0} = \frac{\partial SW}{\partial Q_0}\frac{\partial Q_0}{\partial K_0} + \frac{\partial SW}{\partial Q_1}\frac{\partial Q_1}{\partial K_0} + \frac{\partial SW}{\partial K_0}$ from (A.7), we get:

$$\left[P_0 + 3t\frac{Q_0}{N_0} - a(\alpha+\beta_0)\frac{Q_0}{K_0}\left(\frac{N_0 - 1}{N_0}\right)\right]\frac{\partial Q_0}{\partial K_0} + \left[P_1 + 3t\frac{Q_1}{N_1} - a(\alpha+\beta_1)\frac{Q_1}{K_1}\left(\frac{N_1 - 1}{N_1}\right)\right]\frac{\partial Q_1}{\partial K_0}$$
$$+ a(\alpha+\beta_0)\left(\frac{Q_0}{K_0}\right)^2 - m_0 = 0.$$

Evaluating this at $\mathbf{P}^{VI}(\mathbf{K})$, which is given by (36) an its counterpart for facility 1, yields:

$$\left.\frac{dSW}{dK_0}\right|_{\mathbf{P}^{VI}(\mathbf{K})} = \left[3tQ_0 + tQ_1\right]\frac{\partial Q_0}{\partial K_0} + \left[3tQ_1 + tQ_0\right]\frac{\partial Q_1}{\partial K_0} + a(\alpha+\beta_0)\left(\frac{Q_0}{K_0}\right)^2 - m_0 = 0 . \qquad \text{(A.11)}$$

From (13) and (14) it follows that:

$$\frac{\partial Q_0}{\partial K_0} = \frac{g_1\,(N_0+1)\,a(\alpha+\beta_0)\,Q_0}{N_0(g_0 g_1 - t^2)K_0{}^2}, \qquad \frac{\partial Q_0}{\partial K_0} = -\frac{t\,(N_0+1)\,a(\alpha+\beta_0)\,Q_0}{N_0(g_0 g_1 - t^2)K_0{}^2} .$$

Replacing these in (A.11) and then looking into the symmetric-capacities solution for the fully symmetric case, we obtain:

$$a(\alpha+\beta)\frac{Q^2}{K^2}\left[\underbrace{\frac{(N+1)4t}{N(g+t)}}_{\Psi} + 1\right] - m = 0 .$$

Since Ψ>0, we can conclude that:

$$D(\tilde{Q}^W, \tilde{K}^W) = a\frac{\tilde{Q}^W}{\tilde{K}^W} = \left(\frac{a\,m}{(\alpha+\beta)(1+\Psi)}\right)^{1/2} < D(Q^W, K^W) = D(Q^{VI}, K^{VI}) . \qquad \text{(A.12)}$$

Q.E.D.

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