International Journal of Industrial Organization 62 (2019) 4–27

Contents lists available at ScienceDirect

International Journal of Industrial Organization

www.elsevier.com/locate/ijio

Effects of asymmetric information on airport congestion management mechanisms

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ARTICLE INFO

Article history:
Available online 7 August 2018

JEL classification:
D62
L50
L93
R41
R48

Keywords:
Airport congestion
Pigouvian tolls
Airport slots
Asymmetric information

ABSTRACT

We study and compare three different mechanisms for capacity (slot) allocation in a congested airport when airlines have one-dimensional private information: direct allocation of slots, differentiated tolls and slot auctions. With perfect information, direct allocation is a first best policy which can be implemented through Pigouvian taxes or slot auctions; the mechanisms are equivalent in terms of social welfare. With the introduction of asymmetric information this equivalence is lost: direct allocation is always ex-post inefficient and, in some cases, tolls and subsequent quantity delegation is a better alternative social welfare wise. Auctions may be superior or inferior to tolls. We further show that naïve application of Pigouvian tolls is sub-optimal when imperfect information exists.

1. Introduction

In the last decades, the air transport industry has experienced an important growth of demand that has not been accompanied by a similar expansion of airport infrastructure,

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https://doi.org/10.1016/j.ijindorg.2018.07.007

transforming runaways in a scarce, and therefore congested, resource. An observable consequence is delayed flights that affect passengers and airlines. See e.g. Gillen et al. (2016) for facts and figures.

There are two different kinds of measures that can be implemented by a regulator or benevolent decision maker in order to face congestion problems in airports: (i) increase the infrastructure supply or (ii) manage the demand for that supply. The former – investing in runway capacity – might be too costly, too slow and even unfeasible for space reasons; it might also be politically hard to proceed if there is a suspicion of inefficient use of the existing capacity. For the latter, the regulator could influence the demand in order to use the existing capacity more efficiently.

One alternative for the regulator would be to take administrative measures, that is, to dictate new capacity allocations, based on its best judgement of what is optimal in some sense. This has been, in a nutshell, the approach of the operations research literature (see Gillen et al., 2016; Pellegrini et al., 2017). The economics literature, on the other hand, has looked at tools that can decentralize the desired optimal outcome, focusing mainly on two mechanisms: slot auctions, that is, auctioning a fixed number of permits that allow a firm to use the runaway for a period of time (see Brueckner, 2009; Verhoef, 2010; Basso and Zhang, 2010; Pertuiset and Santos, 2014), and Pigouvian tolls – which may be uniform, differentiated per firm and/or changing over time – and which attempt to dampen or flatten the airlines demand for runways (see Czerny and Zhang, 2012 for a review). To this date, most research in this area has been made under the assumption that all the relevant information is common knowledge to the airlines, the airport and the regulator. With this assumption, any whished assignment of landing rights – including the first best – can be reached either by direct allocation, or using enough economic instruments, such as an auction or an adequate set of (differentiated) tolls. In other words, with perfect and complete information, the efforts have focused on looking for mechanism(s) that could induce the "optimal" allocation (such as the welfare first best), concluding that, if different mechanisms implement this optimal allocation, then they are equivalent. Which one to use should then be decided on grounds other than efficiency, such as political feasibility.

Nevertheless, it seems clear that, in reality, airport authorities have imperfect knowledge about the costs and/or the demand of the airlines and there is no obvious reason why airlines would have incentives to truthfully reveal any of this information. Indeed, most of the modern economic regulation literature considers asymmetric information as a basic ingredient of the modelling, starting with the pioneering work on mechanism design by Baron and Myerson (1982) and Lewis and Sappington (1988); see e.g. Armstrong and Sappington (2007) for a review. Moreover, this imperfect knowledge of information is probably also true between airlines: one airline does not know with certainty the type of opponent it faces.

The key question addressed in this paper is the performance of congestion management mechanisms under asymmetric information; how does the outcome of each mechanism change? How does the information setting affect the decision about which is the best mechanism? We study and compare how asymmetric information changes what we know about three congestion management mechanisms to allocate congestible (and scarce) infrastructure when the agents, i.e., the airlines, are non-atomistic: direct allocation, pricing, and slot auctions.

In our models, one or two airlines use the airport's capacity, producing externalities to the exterior if there is only one airline, or between them if there are two; the single airline case is developed mainly because it helps to build intuition and provide results which are building blocks for the proofs of the duopoly case. The airlines are non-atomistic and offer non-substitute products (flights to different cities) but, for most of the paper, face perfectly elastic demands in terms of their full-prices, which are the sum of fares plus congestion delays; since passengers dislike airport congestion, the actual fares that the airlines charge must be discounted below these fixed full prices. Not having downward sloping demands in terms of the full-prices allows us to focus the research questions because, under perfect information and absence of market power thus defined, both auctions and tolls implement the first-best (Brueckner, 2009). We do discuss the market power case (i.e. downward sloping inverse demands in terms of full prices) in the final sections of the paper. Airlines have private information about their costs and, therefore, the duopoly plays a Bayesian game according to the rules that the regulator, with his imperfect knowledge, defines while seeking to maximize expected social welfare.

Our results show that, with asymmetric information, direct allocation never reproduces the perfect information optimum; it is ex-post inefficient. Nevertheless, the pricing mechanism does reach the perfect information first best when the optimal unit toll (in a perfect information sense) is constant, i.e. does not depend on the production level, something that may occur for a lone airline causing a linear (in output) total external cost. In this case, a direct allocation is obviously an inferior policy than pricing, since the latter elicits the agents' private information, expressed through their demand. If optimal (in a perfect information sense) tolls depend on production levels, pricing does not reach an efficient ex-post outcome either. This may occur for a lone airline causing a non-linear total external cost and/or exerting market power, but also, and more importantly, when two non-atomistic airlines impose an externality to each other, even if the total external congestion cost caused by one airline on the rival is linear in the airline's output and they have no market power. However, for the relevant case of the duopoly, we show that if the congestion costs per flight increase linearly with total traffic and market power is absent, congestion tolls always perform better than the direct allocation ex-ante, that is to say, in expectation, tolls are a superior mechanism. In more general terms, what all this imply is that the idea of implementing the first-best allocation through tolls is lost; use of tolls may be superior than direct allocation to the planner. We also show that (i) a naïve application of Pigouvian tolls – a toll equal to the marginal external cost evaluated at quantities that maximize expected social welfare – is sub-optimal, that is, there are prices that induce higher expected social welfare; (ii) slot auctions also fail to implement the first-best and its behavior may be ex-ante and ex-post superior or inferior to congestion tolls (iii) manipulable congestion tolls (explained below) cannot circumvent the asymmetric information problem either.

1.1. Related literature

In order to help the reader to place our paper within the relevant literature we provide here an overview of related papers. We divide this in two parts: first, on papers that focus on the airport problem but that consider a perfect and complete information setting, as opposed to ours. Second, we review papers that have compared the performance of quantity and price mechanisms considering more complex information structures.

In terms of the economics of airports, the first analysis of the problem with non-atomistic agents is provided by Brueckner (2002), who showed that in a congested airport and under Cournot competition between airlines, each of them internalize the costs they impose on their own flights, but not the costs they impose on other airlines; airlines would self-internalize part of the congestion yet there still exists an externality, which means that airports are over-utilized. In a nutshell, if the regulator could directly allocate runway slots, he would allocate a smaller number to each airline than what actually happens. As clearly shown by Brueckner, this social optimum can be implemented with a price system by charging a set of differentiated Pigouvian tolls, which are decreasing with an airline's market share. The reason is simple: an airline with larger market share internalizes more of the extra congestion costs caused by an additional flight than one with a smaller market share, because when it decides whether to offer or not an additional flight, it considers the costs that this particular flight imposes on its own other flights. These differentiated charges, equal to marginal external costs and therefore well in the Pigouvian tradition, are obviously very hard to sell politically and, therefore, they might be difficult to implement. Pels and Verhoef (2004) complement Bruckner's analysis with the assumption of airline market power, showing that it decreases the optimal tolls: a firm that exerts market power restricts output and therefore, ceteris paribus, it needs to be subsidized in the first-best in order to artificially decrease its marginal cost thus inducing allocative efficiency (Basso, 2008). With homogenous Cournot (as in Pels and Verhoef, 2004), the mark-up and the market shares are positively related (and both inversely related to marginal cost) and, therefore, it follows that both the market power effect and the self-internalization effect induces the price to a large airline to be smaller than that of a small airline. Later Brueckner and Verhoef (2010) argue that it may be implausible that non-atomistic airlines take the toll as given. Instead, they may display strategic behavior over the tolls size. They show that it is possible to implement the first best allocation using a system of toll *rules* that are designed to be manipulated by the airlines.

Because of the fact that optimal tolls seem impossible to implement, Brueckner (2009) and Verhoef (2010) study slot auctions. Brueckner (2009) demonstrates that under the assumptions of perfect information and absence of market power the first best can be reached with any of the following policies: differentiated tolls, slot auctioning or slot trading, where slots are given for free to the airlines and then they are allowed to trade freely. The two last options require computing the optimal total numbers of slots which is easy given the perfect information assumption. In others words, auction and pricing are equivalents, but the former would be easier to implement. Basso and Silva (2015) show that if market power is included, pricing and auction are no longer equivalents and, in fact, auctioning slots might be a worse policy than uniform (non-differentiated) tolls. Basso and Zhang (2010) show that the equivalence is also lost (under perfect information) if the airport profits matter (either because it is privately owned or because it has to self-finance).

We now move to papers that have compared the performance of quantity and price mechanisms considering more complex information structures. Our goal here is to be precise regarding what distinguish this paper from others that bear similarities. Certainly, it all started with the seminal paper by Weitzman (1974). In his classic contribution, he asked whether it was better to control the behavior of a regulated private firm by setting the price it receives for its output and letting it choose profit-maximizing quantities, or by directly setting the quantity to be produced by the firm. The difference with our setting here is that Weitzman's price mechanism directly controls the output price of the firm while here, the regulator sets a tax to be paid by the firm. In that sense, papers that compare mechanisms for pollution control come closer to what we do. A quite complete survey that encompasses many different industry structures can be found in Requate (2005) yet, in the models and papers reviewed, there is no informational gap between firms and the regulator.

Heuson (2010) revisits Weitzman insights in order to compare emission standards (our direct allocation mechanism) and emission taxes (our congestion tolls) in the context of a polluting oligopoly, and when the regulator has an informational gap regarding firms' costs. While some of our results will have a similar flavour to some of Heuson's results, particularly those for monopoly in Section 3, key differences between models remain. First, Heuson considers a homogenous Cournot setting with homogeneous products, while here we have a duopoly producing different products (flights to different places). Second, in Heuson (2010) the externality is caused by firms to the 'exterior' while here, one airline causes the externality to the other airline, in that it increases both its rival's operational costs and consumers' costs. Third, in Heuson's setting firms may decrease the amount of emissions by either reducing output or by incurring abatement costs. In our model, the possibility of abatement by airlines is not considered.[1] Fourth, and more importantly, in Heuson's setting, all firms have perfect knowledge of own and rivals' cost and only the regulator suffers from incomplete information. In our model, each airline has its own piece of private information which is unknown to both the regulator and the rival. In other

[1] In this industry, it seems much more possible that the airport, rather than the airlines, may take action to abate congestion costs. The simplest way to think of this is the airport investing in capacity expansions, which will decrease the marginal external cost of an additional flight. Basso (2008), in a context of perfect information, derives optimal airport tolls and capacity investments for an airline oligopoly. Lin and Zhang (2017) do the same for a network of airports.

words, our oligopoly game is Cournot–Bayes while in Heuson it is simply Cournot: the effect of asymmetric information through strategic interaction that we have is missing. This renders the Weitzman approach to compare mechanisms unfeasible.

Two final points regarding the literature are worthwhile. First, as far as we know, Czerny (2010) is the only airport paper that looks at the comparison between tolls and direct allocation considering an imperfect information structure. His model, though, assumes that consumer benefits are uncertain and that airlines compete such that they reach zero profit. Hence, there is no asymmetric information (but randomness) nor strategic interactions. Second, for information structures as the one we consider, the mechanism design literature provides approaches to elicit the private information of firms. We do not follow this approach here because the implementation of optimal truth-telling direct mechanism (the result of a mechanism design approach) probably leads, in practice, to mechanisms which may be impossible to apply when more than one firm is involved.[2]

The structure of the paper is as follows: in Section 2 we present the perfect information benchmark. We then analyze in Section 3 a situation where a single airline produces an external damage; this is done mainly for intuition purposes and because it provides with a building blocks which is necessary for proofs down the road. In Section 4 we consider the Cournot–Bayes duopoly competition and perform ex-ante and ex-post comparisons between direct allocation and tolls. Section 5 discusses slot auctions and its comparison to the toll mechanism, the efficiency of manipulable congestion tolls in the asymmetric information setting and the market power case. Finally, Section 6 offers conclusions and discussions.

2. Benchmark: perfect information model

To simplify the presentation, we consider only two airlines who offer non-related products (such as flights to different destinations) but who compete for airport infrastructure. Decision variables are q_i and q_j, the number of flights of airlines i and airline j. We have mentioned before that the main characteristics of airport congestion are market power and non-atomistic agents. Our goal is to study the introduction of imperfect information in airport models thus, to avoid distraction, we first assume – as in Brueckner and Van Dender (2008) and Brueckner (2009) – that airlines do not have market power over the demand they face in the sense that passengers are willing to pay fixed “full prices”, which are the sum of fares plus congestion delays. This allows us to better focus the research questions because, under perfect information and absence of market power, both auctions and tolls implement the first-best.

Suppose that these full prices are a for airline i and b for airline j. Since passengers dislike airport congestion, because it imposes additional time costs, the actual fares that the airlines charge must be discounted below these full prices. The discount on price will

[2] Glachant (1998) and Heuson (2010) also recognize this point. For a prices versus quantities comparison using a mechanism design approach see Basso et al. (2017). Importantly, their focus lies in the regulation of a single monopoly firm.

depend on the total traffic $Q = q_i + q_j$ through a time cost function $f(Q)$. This implies that the fares each airline my charge are given by $p_i = a - f(Q)$ and $p_j = b - f(Q)$ showing that, in terms of price as a function of quantity, the inverse demands are indeed downward sloping. Assuming that each flight seats S people, revenues for airline i are given by $q_i S(a - f(Q))$ and its profits are then, $\pi_i(q_i, Q) = q_i S(a - f(Q)) - C_i(q_i, Q)$, where C represents costs and depends on Q because congestion also affects airlines; there are production externalities . Note that the profit function may be re-organized as:

$$\pi_i(q_i, Q) = aSq_i - \underbrace{[C_i(q_i, Q) + f(Q)Sq_i]}_{\widetilde{C}_i(q_i, Q)}$$

This shows that, without loss of generality, passengers' congestions costs may be lumped together with the airline cost function, and that S may be set equal to 1.

We consider an airport authority that attempts to maximize social welfare. Because demands are perfectly elastic with respect to the full price (but recall that inverse demands in terms of prices as a function of quantity are downward sloping), social welfare is simply the sum of the airline's profits. Therefore

$$SW(q_i, q_j) = \pi_i(q_i, Q) + \pi_j(q_j, Q) \tag{1}$$

Under perfect information, the social optimum or first-best is attained by maximizing (1) over quantities. Differentiation with respect to q_i and q_j yields the following first-order conditions (we assume second order conditions are satisfied):

$$\frac{\partial \pi_i}{\partial q_i} + \frac{\partial \pi_i}{\partial Q} + \frac{\partial \pi_j}{\partial Q} = 0 \tag{2}$$

$$\frac{\partial \pi_j}{\partial q_j} + \frac{\partial \pi_j}{\partial Q} + \frac{\partial \pi_i}{\partial Q} = 0 \tag{3}$$

Under perfect information, the social optimum can be reached with differentiated tolls (Brueckner, 2002) as we now show. The regulator acts as a Stackelberg leader who takes into account that there is downstream Cournot competition between airlines and, therefore, takes the airlines best response to its set of tolls into account. For airlines to participate in this market, they need to end up with positive profits, something that happens always in equilibrium. We solve the game using backward induction, solving first the problem that an airline faces. Let τ_i be the toll per flight that the airport charges to the airline. Then:

$$\begin{aligned} Max_{q_i} \quad & \pi_i(q_i, Q) - \tau_i q_i \\ \Rightarrow \quad & \frac{d\pi_i}{dq_i} = \frac{\partial \pi_i}{\partial q_i} + \frac{\partial \pi_i}{\partial Q} - \tau_i = 0 \end{aligned} \tag{4}$$

From (4) we observe that an airline internalizes a part of the congestion it creates: when the airline decides about operating an extra flight, it considers the extra cost imposed on its own other flights, effect which is captured by the term $\partial \pi_i / \partial Q$ in (4).

The airline does not consider, however, the congestion cost (and therefore lost profits) that an extra flight imposes on its rival: that is term $\partial\pi_j/\partial Q$ in (2), which is missing in (4). These observations make clear that if the airport authority chooses tolls according to:

$$\tau_i = -\frac{\partial \pi_j}{\partial Q} = \frac{\partial \widetilde{C_j}(q_j, Q)}{\partial Q} \qquad \tau_j = -\frac{\partial \pi_i}{\partial Q} = \frac{\partial \widetilde{C_i}(q_i, Q)}{\partial Q} \tag{5}$$

the airport authority can implement the first-best allocation calculated in (2). Therefore, the optimal tolls are equal to the marginal external congestion costs imposed by one airline upon the other airline, evaluated at the optimal allocation. This is then, a classic Pigouvian tolls.

We now consider a specific example, adapted from Brueckner (2009), which will be useful for the rest of the paper. Consider quadratic operational costs and congestion costs per flight that increase linearly with total traffic (recall that this includes costs for both passengers and airlines). Demands are, as maintained, perfectly elastic with respect to the full price; the maximum full prices that passengers are willing to incur are a for airline i and b for airline j. Thus, the social welfare is the sum of the airlines' profits:

$$SW = \underbrace{aq_i - \theta_i q_i^2 - \alpha(q_i + q_j)q_i}_{\pi_i} + \underbrace{bq_j - \theta_j q_j^2 - \alpha(q_i + q_j)q_j}_{\pi_j} \tag{6}$$

Congestion affects in the same way both airlines and their passengers and its associated cost per flight is represented by the term $\alpha(q_i + q_j)$. Note that the total external congestion cost caused by one airline on the rival is linear in the airline's output, conditional on the rival's traffic. For example, the total external cost imposed by airline i is $(\alpha q_j)q_i$, implying that the marginal external cost is constant conditional on the rival's output (αq_j). The social optimum under perfect information is obtained by maximizing (6) and the result is as follows:

$$q_i^* = \frac{a(\alpha + \theta_j) - b\alpha}{2(\theta_i\theta_j + \alpha(\theta_i + \theta_j))} \qquad q_j^* = \frac{b(\alpha + \theta_i) - a\alpha}{2(\theta_i\theta_j + \alpha(\theta_i + \theta_j))} \tag{7}$$

On the other hand, the tolls that allow reaching the first best, with perfect information, are equal to the marginal external congestion costs imposed by one airline upon the other airline, evaluated at the optimal allocation:

$$\tau_i^* = \alpha q_j^* \qquad \tau_j^* = \alpha q_i^* \tag{8}$$

Each toll is proportional to the competitor's market size because so is the damage caused by an additional flight. Tolls are therefore increasing with the market size of the other airline (Brueckner, 2002).

3. Asymmetric information – single firm case

We introduce now information asymmetries using a parameter of the firm's profit: θ. It can represent the marginal operation cost or marginal congestion effects, and is only known privately. The competitor and regulator only know this parameter imperfectly, something captured by a probability density function over θ.

As explained in the introduction, we build intuition into our results progressively. Here we start with a single airline that imposes an external cost to the society (and not to another airline); this could be for example, emissions or noise pollution. Although not identical, this Section and it results resembles what Heuson (2010) results show for its homogenous Cournot game when the number of firms is equal to one.

3.1. Single firm and constant marginal external cost

Suppose first that the airline produces a total external cost which is linear in the airline's output, implying that the marginal external cost is constant. The social welfare is:

$$SW = \underbrace{aq_i - \theta_i q_i^2}_{\pi_i} - Kq_i \tag{9}$$

The first term represents the airline's revenue, the second its operational costs and the third is the total external cost; K is then the marginal external cost. Under perfect information, that is, if θ_i was known to the regulator, the social optimum is easily obtained by maximizing SW:

$$q_i^* = \frac{a-K}{2\theta_i} \tag{10}$$

Now, consider instead that θ_i represents the airline's private information, with the regulator only knowing that its takes values according to a probability density function. If the regulator uses a direct allocation mechanism, he solves:

$$\begin{aligned} &\max_{q_i} E_{\theta_i}\left[aq_i - \theta_i q_i^2 - Kq_i\right] \\ &\Rightarrow q_i^A = \frac{a-K}{2E[\theta_i]} \end{aligned} \tag{11}$$

The quantity that maximizes expected social welfare in (11) cannot directly depend on θ_i, since it is unknown, but only on an expectation involving θ_i; in this case its expected value. It follows that the direct allocation mechanism cannot reach the perfect information first-best: it is inefficient ex-post. Graphically what happens is shown in Fig. 1. Under imperfect information the regulator will choose q_i^A, however if the real value of θ_i is higher than its expected value, the optimal ex-post quantity is q_i^* to the left of q_i^A and generates an efficiency loss given by the area with horizontal lines. The area with vertical lines represents the efficiency loss if the real value of the variable is below $E[\theta_i]$.

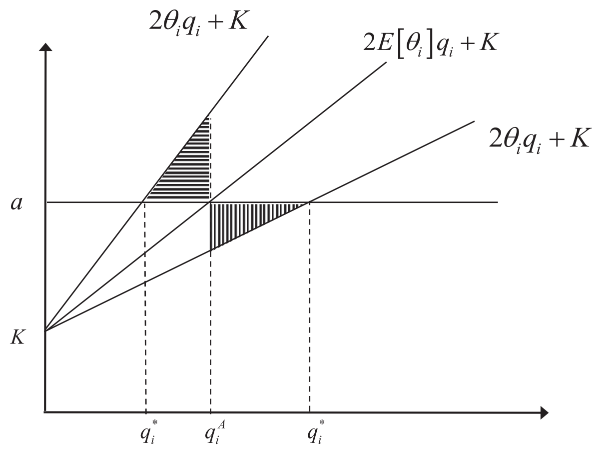

Fig. 1. Ex-post efficiency loss given by direct assignment.

Suppose now that instead of using a direct allocation policy, the regulator implements a toll system. In choosing the toll, the airport acts as a Stackelberg leader, moving first. If the airport charges a toll given by τ_i, the airline will then choose the quantity that maximizes its profits:

$$q_i(\theta_i) = \frac{a - \tau_i}{2\theta_i} \tag{12}$$

The regulator does not know the real value of θ_i, but anticipates the airline best response as a function of the variable θ_i. The problem that the airport solves, then, is:

$$\max_{\tau_i} E_{\theta_i}[SW] = E_{\theta_i}\left[aq_i - \theta_i q_i^2 - Kq_i\right]$$
$$s.t. \quad q_i(\theta_i) = \frac{a - \tau_i}{2\theta_i}$$

First order condition for the above problem leads to:

$$\tau_i^* = K \tag{13}$$

Replacing (13) in (12) we observe that the final quantity is identical to (10), in other words, despite the asymmetric information, the toll system reproduces the first best under perfect information, thus reaching the maximum social welfare possible ex-post. Therefore, when the total external cost is linear, i.e. the marginal external cost is constant, the toll mechanism is ex-post efficient, and therefore better than direct allocation. Delegating to the firm production decisions is preferable, since the firm will adjust its production to its actual costs. A toll is a way to delegate the decision to the informed party, inducing better (in this case optimal) results.

The previous result, however, is not general, since it relies on the constant marginal external cost, which led to a toll independent of the production level (note that production cost is quadratic). While delegation to the better informed party entails some gains, it has also a potential pitfall, since the firm's objective (profits) is imperfectly aligned with the planner's objective (social welfare). In the previous case, the linear nature of the total externality, plus the linearity of marginal costs, allow for ex-post optimality: tolls, which are linear instruments, are enough to align firm's profits and social welfare. However, as we show next, if the optimal (perfect information) toll depends on the level of production, then the regulator's toll will not be ex-post optimal and, therefore, delegation of production decisions to the firm will no longer lead to the full information first-best.

An optimal, perfect information, toll depending on production levels can occur because of three reasons: first, the marginal external cost might not be constant. Secondly, and probably more importantly for the case of airports, the marginal external cost might depend on another airlines' production level, even if the total external congestion costs were to rise linearly with an airline's traffic. Third, airlines may possess market power. We analyze in this section non-constant marginal external cost for the case of monopoly, differing the central case of multiple (two firms) for Section 4. Market power is discussed in Section 5.

3.2. Single firm and non-constant marginal external cost

To show how tolls may also fail to reach the full information first best, we now consider a non-linear (quadratic to illustrate the point) total external cost. The social welfare function is:

$$SW = \underbrace{aq_i - \theta_i q_i^2}_{\pi_i} - Kq_i^2$$

Ex-post efficiency (i.e. the perfect information social optimum) requires:

$$q_i^* = \frac{a}{2(K + \theta_i)} \tag{14}$$

If the regulator wishes to implement this first-best through a price system, it is easy to demonstrate that the toll is equivalent to the marginal external cost evaluated at the optimal production level, that is, a classical Pigouvian toll:

$$\tau_i^* = 2q_i^* K \tag{15}$$

Under imperfect information and a direct allocation mechanism, the regulator solves:

$$E_{\theta_i}[SW] = \max_{q_i} \; aq_i - E[\theta_i]q_i^2 - Kq_i^2$$

And the resulting mandated production is:

$$q_i^A = \frac{a - K}{2(K + E[\theta_i])} \tag{16}$$

If, on the other hand, the airport charges a toll τ_i to the airline, the airline will subsequently choose the level production that maximizes her profit, which is no different than before, i.e. $q_i(\theta_i) = (a - \tau_i)/(2\theta_i)$. So, under imperfect information the problem of the airport now is:

$$\max_{\tau_i} E_{\theta_i}[SW] = E_{\theta_i}\left[aq_i - \theta_i q_i^2 - Kq_i^2\right]$$
$$s.t. \quad q_i(\theta_i) = \frac{a - \tau_i}{2\theta_i}$$

First order condition for the above problem leads to:

$$\tau_i^* = a - \frac{a - 1/2}{K} E\left[\frac{1}{\theta_i^2}\right] \tag{17}$$

The final (ex-post) quantity produced by the airline, as a function of θ_i is:

$$q_i^{final}(\theta_i) = \frac{a - 1/2}{2K\theta_i} E\left[\frac{1}{\theta_i^2}\right] E\left[\frac{1}{\theta_i}\right] \tag{18}$$

Unlike with constant marginal external cost, the final output differs from the optimum under perfect information. Hence, in this case, none of the mechanisms are ex-post efficient. But, in terms of expected social welfare, is one preferable? The answer is no: a number of simulations showed that in terms of ex-post social welfare, there are parameter constellations that make one or the other mechanism better; this result has a similar flavor than results in Heuson (2010).

Eq. (15) is the optimal (Pigouvian) toll under perfect information and helps us to understand the phenomenon behind asymmetric information. The optimal toll depends on the production level because the marginal external cost increases with the quantity produced by the airline. For this reason, unlike with linear total external cost, the regulator can never implement the efficient toll, as this requires that she correctly guesses the actual optimal production level, not just the production rule that the airlines follows conditional on the toll. More importantly, note that the toll under imperfect information in (17) does not correspond to a naïve reinterpretation of the perfect information Pigouvian toll, namely, just replacing the prescribed firm's output under direct allocation into the marginal external cost expression or, in other words, replacing the unknown parameter by its expectation. Under this naïve – yet wrong – assumption, the toll would be equal to $\widetilde{\tau}_i = 2Kq_i^A$ where q_i^A is given by (16). Replacing the value of q_i^A we obtain:

$$\tilde{\tau}_i = \frac{Ka}{K + E[\theta_i]} \tag{19}$$

Note that (19) is evidently different from the imperfect information optimal toll because $\widetilde{\tau}_i$ only depends on the expected value of θ_i, and the imperfect information optimal toll depends on the variance and expected value of $1/\theta_i$. In other words, the optimal toll is not calculated to reproduce or implement some allocation obtained before: naïve application of Pigouvian tolls generates further social welfare loss.

4. Asymmetric information – duopoly case

4.1. Direct allocation and tolls: the general case

Consider now two firms, as in Section 2 – and the direct allocation mechanism. Here, the regulator directly mandates the number of slots to be used by each of the airlines, which are not allowed to trade afterwards. The regulator maximizes expected social welfare, since it does not know the firms' private information. The problem and the ensuing first order conditions are:

$$Max_{q_i,q_j}\ E_\theta[SW] = \ E_\theta[\pi_i(q_i,\theta_i,Q)+\pi_j(q_j,\theta_j,Q)]$$

Leading to

$$E_{\theta_j}\left[\frac{\partial\pi_i}{\partial q_i}+\frac{\partial\pi_i}{\partial Q}\right]+E_{\theta_j}\left[\frac{\partial\pi_j}{\partial Q}\right]=0 \tag{20}$$

$$E_{\theta_i}\left[\frac{\partial\pi_j}{\partial q_j}+\frac{\partial\pi_j}{\partial Q}\right]+E_{\theta_i}\left[\frac{\partial\pi_i}{\partial Q}\right]=0 \tag{21}$$

where θ_i represents firm *i*'s private information. Expressions (20) and (21) are to be compared to expressions (2) and (3). Now, the regulator assigns slots according to the *expected* marginal profits and external costs, immediately indicating that the result cannot match the ex-post efficient benchmark. Still, in this mechanism, the regulator knows exactly the total numbers of flights ex-post, as she will command them, and, therefore, she knows the final congestion level, despite that it will be ex-post inefficient.

In the (differentiated) toll mechanism, the regulator is a Stackelberg leader under imperfect information as well, and anticipates Cournot–Bayes competition between airlines downstream. A major difference with the perfect information benchmark is that, here, the final congestion level is unknown because the production of each firm depends on their private information about θ_i and therefore, the regulator does not know with certainty the number of flights that there will be in the end. However, this mechanism has the property of delegating the production decision to the better informed agent, the airlines. The problem is:

$$\begin{gathered} Max_{\tau_i,\tau_j}\qquad E_\theta[SW] = \ E_\theta[\pi_i(q_i,\theta_i,Q)+\pi_j(q_j,\theta_j,Q)] \\ \text{s.t.} \\ E_{\theta_j}\left[\frac{\partial\pi_i}{\partial q_i}+\frac{\partial\pi_i}{\partial Q}\right]-\tau_i=0 \\ E_{\theta_i}\left[\frac{\partial\pi_j}{\partial q_j}+\frac{\partial\pi_j}{\partial Q}\right]-\tau_j=0 \end{gathered}$$

Where the constraints represent the Cournot–Bayes equilibrium between airlines.[3]

We compare both mechanisms in terms of expected social welfare. Since this is complex in general, to push the analysis further we use specific functional forms according to (6), analyzing separately the case of private information on one or both firms.

4.2. One sided asymmetric information

We focus on the functional form adapted from Brueckner (2009), where congestion costs per flight increase linearly with total traffic. Repeating Eq. (6) to help the reader:

$$SW = \underbrace{aq_i - \theta_i q_i^2 - \alpha(q_i + q_j)q_i}_{\pi_i} + \underbrace{bq_j - \theta_j q_j^2 - \alpha(q_i + q_j)q_j}_{\pi_j}$$

Since each firm is non-atomistic, and contributes sizably to the congestion, there is a quadratic effect for each firm that is fully internalized, αq_i^2, while the marginal external cost is constant conditional on the rival's output, αq_j (leading to a linear in own traffic total external cost).

The informational structure is as follows. Airline i knows perfectly her and the opponent profit functions: θ_j is common knowledge. Nevertheless, firm j and the regulator only know a probability density function for θ_i: asymmetric information is one sided. There are two reasons to include one-sided asymmetric information as part of the analysis. The first is that it corresponds to a quite natural situation, with an incumbent and a new entrant. Incumbents' costs are much better known than the entrant ones, and a natural approximation is to consider a model where only the entrant has private information. The second reason is technical. The setting is really helpful to highlight the role of asymmetric information on the performance of a regulatory tool. Crucially, it shows how the response to a linear tax would depend on the cost structure of the firm, which is unknown to the regulator but well known to the firm

Under these conditions, the direct allocation mechanism solves:

$$\begin{aligned} Max_{q_i,q_j} \quad E_{\theta_i}[SW] = {} & E_{\theta_i}\left[aq_i - \theta_i q_i^2 - \alpha(q_i + q_j)q_i + bq_j - \theta_j q_j^2 - \alpha(q_i + q_j)q_j\right] \\ & = aq_i - E[\theta_i]q_i^2 - \alpha(q_i + q_j)q_i + bq_j - \theta_j q_j^2 - \alpha(q_i + q_j)q_j \end{aligned}$$

[3] Note that each airline best responds to its rival taking expectation over the rival's private parameter, while with perfect information the constraints do not have the expectation operators. This is the main and central difference with the literature on pollution control mechanisms. As discussed in the introduction, Heuson (2010) assumes that the parameter unknown to the regulator is common knowledge to all producing firms. Therefore, while the expectation operator would remain in the objective function, it would not appear in the constraints. This implies that, unless simplifying assumptions are made regarding the distribution of the private parameter, the downstream game cannot be solved explicitly. Weitzman and Heuson approach was, indeed, to solve the firms game explicitly, in order to replace the equilibrium values in the welfare function, and then calculate an explicit expression for expected welfare. That allowed direct comparison against the expected welfare of the quantity mechanism.

leading to

$$q_i^A = \frac{a(\alpha+\theta_j) - b\alpha}{2(E[\theta_i]\theta_j + \alpha(E[\theta_i]+\theta_j))} \qquad q_j^A = \frac{b(\alpha+E[\theta_i]) - a\alpha}{2(\theta_i\theta_j + \alpha(E[\theta_i]+\theta_j))} \tag{22}$$

Under the differentiated tolls mechanism, the airport solves:

$$\begin{aligned} Max_{\tau_i,\tau_j} \quad E_{\theta_i}[SW] = \; & E_\theta\left[aq_i - \theta_i q_i^2 - \alpha(q_i+q_j)q_i + bq_j - \theta_j q_j^2 - \alpha(q_i+q_j)q_j\right] \\ s.t. \quad q_i(q_j) = \; & \frac{a - \alpha q_j - \tau_i}{2(\theta_i+\alpha)} \qquad q_j = \frac{b - \alpha E[q_i] - \tau_j}{2(\theta_j+\alpha)} \end{aligned}$$

Where the quantity of flights produced by each airline has to be those arising from downstream Cournot–Bayes competition between firms, as indicated by the constraints.

Quantities are given by:

$$q_i(\theta_i) = \alpha\left[\frac{4(\theta_j+\alpha) - 2b - \alpha\tau_i E_{\theta_i}\left[\frac{1}{\theta_i+\alpha}\right] + 2\tau_j}{4(\theta_j+\alpha) - \alpha^2 E_{\theta_i}\left[\frac{1}{\theta_i+\alpha}\right]}\right]\frac{1}{2(\theta_i+\alpha)}$$

$$q_j = \frac{2b - \alpha(\alpha-\tau_i)E_{\theta_i}\left[\frac{1}{\theta_i+\alpha}\right] - 2\tau_j}{4(\theta_j+\alpha) - \alpha^2 E_{\theta_i}\left[\frac{1}{\theta_i+\alpha}\right]}$$

Note that it is impossible to reproduce the first best solution through linear tolls. Moreover, for any set of linear tolls τ_i, τ_j, the chosen quantities have an essentially different structure than the ones obtained in (21) and (22), the direct allocation.

Solving the regulator's problem we obtain τ_i^T and τ_j^T, which will induce a known number of flights of firm j given by q_j^T and a function $q_i^T(\theta_i)$: the regulator perfectly anticipates q_j and delegates q_i to the informed firm. Nevertheless, it is important to emphasize that, again, the naïve application of the Pigouvian tax is suboptimal: $\tau_i^T \neq \alpha q_j^A$ and $\tau_j^T \neq \alpha q_i^A$, where q_j^A and q_i^A are given by (22). Thus, again, the optimal toll is not calculated in order to reproduce a "first-best" allocation obtained before; that idea is lost.

We have considered a congestion technology that has a constant marginal external cost, conditional on the rival's output, but none of the mechanisms reproduces the perfect information social optimum. This is due to the non-atomistic characteristic of the agents that make the optimal toll depend on the production levels and therefore on private information. Ranking the policies *ex-post* is impossible, that is, depending on the particular value that θ_i takes, sometimes direct allocation generates a higher ex-post social welfare and in others a tolls system is better. However, we can demonstrate that using these particular functional forms, the tolls mechanism always generate higher expected social welfare, i.e. it is always better *ex-ante*.

Proposition 1. In the absence of market power in terms of full price, with non-atomistic airlines, congestion costs per flight that increase linearly with total traffic and one sided asymmetric information, differentiated tolls are ex-ante more efficient than direct allocation.

Proof. Consider first a hybrid mechanism that assigns a quantity q_j^A to firm j (the firm with common knowledge costs) and charge a toll $\tau_i^A = \alpha q_j^A$ to firm i. Using the result in Section 3, we conclude that this mechanism is better than direct allocation because, conditional on q_j^A, the airline i's decision is ex-post optimal since the marginal external cost is constant (αq_j^A) and the toll is equal to this value. The previous mechanism can be implemented through two tolls, which fulfill the followings conditions: $\tau_i = \alpha q_j^A$ and $q_j(\tau_i, \tau_j) = q_j^A$, where $q_j(\tau_i, \tau_j)$ is the sub-game equilibrium quantity for firm j. Because these tolls are not optimal, the welfare result is dominated by the one induced by τ_i^T and τ_j^T. □

The intuition behind Proposition 1 is that tolls can replicate any direct allocation. Therefore, an optimal toll (weakly) improves on an optimal allocation. The key is therefore that tolls bring flexibility to the table. This flexibility, which allows the informed party to adjust production based on its costs, makes tolls the superior tool.

4.3. Two firms and bilateral private information

With private information for both firms the direct allocation problem is now as follows:

$$\begin{aligned} Max_{q_i,q_j} \quad E_{\theta_i,\theta_j}[SW] &= E_{\theta_i,\theta_j}\left[aq_i - \theta_i q_i^2 - \alpha(q_i+q_j)q_i + bq_j - \theta_j q_j^2 - \alpha(q_i+q_j)q_j\right] \\ &= aq_i - E[\theta_i]q_i^2 - \alpha(q_i+q_j)q_i + bq_j - E[\theta_j]q_j^2 - \alpha(q_i+q_j)q_j \end{aligned}$$

Using differentiated tolls the problems is:

$$\begin{aligned} Max_{\tau_i,\tau_j} \quad E_{\theta_i,\theta_j}[SW] &= E_{\theta_i,\theta_j}\left[aq_i - \theta_i q_i^2 - \alpha(q_i+q_j)q_i + bq_j - \theta_j q_j^2 - \alpha(q_i+q_j)q_j\right] \\ s.t. \qquad q_i &= \frac{a - \alpha E[q_j] - \tau_i}{2(\theta_i+\alpha)} \qquad q_j = \frac{b - \alpha E[q_i] - \tau_j}{2(\theta_j+\alpha)} \end{aligned}$$

Where the quantity of flights produced by each airline has to be restricted to those arising from the sub game equilibrium, i.e. the downstream Cournot–Bayes competition between the firms, as indicated by the constraints.

Again, neither policy reaches the perfect information optimum. Also, the naïve application of the Pigouvian toll (compute the direct allocation's quantities and then charge the marginal external cost evaluated in those quantities) is suboptimal. Ex-post ranking is again impossible, that is, after the mechanisms are set, and production decisions are taken, either mechanism can be better at times. Yet, we can prove that

Proposition 2. In the absence of market power, with non-atomistic airlines, congestion costs per flight that increase linearly with total traffic and bilateral asymmetric information, differentiated tolls are ex-ante more efficient than direct allocation of slots.

Proof. Like in the proof of Proposition 1, consider first a hybrid mechanism, which sets a production level q_j^A to airline j, according to Eq. (22), and charges a toll equal to $\tau_i^A = \alpha q_j^A$. As explained, this mechanism is better than direct allocation because, conditional on q_j^A, the airline i's decision is ex-post optimal because the toll is equal to the now constant marginal external cost. The difference is that now, one cannot search for a pair of tolls that induce this, because the regulator can never induce j to produce exactly q_j^A, since now j also has private information. What we do then, is go further and look at firm i best response to the hybrid mechanism. Since the hybrid mechanism has a fixed allocation for j, q_j^A, and a known toll $\tau_i^A = \alpha q_j^A$ this is easy to do and leads to:

$$\widetilde{q_i}(\theta_i) = \frac{a - 2\alpha q_j^A}{2(\theta_i + \alpha)} \tag{23}$$

What we have for the moment is a new hybrid mechanism leading to production levels given by (23) and q_j^A, which we know is superior in expected welfare terms to the direct allocation mechanism. What we do next is to improve things by optimizing over j's production this time, considering for a second that this does not change airline i production choice given in (22); we later will make sure that whatever we do, this is the case. Given (23) if the regulator maximizes welfare over j's production, she would like j to produce according to:

$$\widetilde{q_j}(\theta_j) = \frac{b - 2\alpha E[\widetilde{q_i}]}{2(\theta_j + \alpha)} \tag{24}$$

Note that this production rule depends on the expected value of $\widetilde{q_i}$ since the regulator has imperfect information.

The production combination given by (23) and (24) generates a higher expected social welfare than (23) and q_j^A by construction, which in turn was better than the direct allocation productions. The final question is then whether one can find a pair of tolls that generates, given the Cournot–Bayes competition downstream, exactly those production rules. And the answer is yes; best responses in the downstream game are:

$$q_i = \frac{a - \alpha E[q_j] - \tau_i}{2(\theta_i + \alpha)} \qquad q_j = \frac{b - \alpha E[q_i] - \tau_j}{2(\theta_j + \alpha)}$$

Then, $E[\widetilde{q_i}]$ is easily calculated from (23) recalling that q_j^A is a fixed number. This enables calculation of $E[\widetilde{q_j}]$ using (24). With these in hand, if i chooses production according to (23), a toll $\widetilde{\tau_j} = \alpha E[\widetilde{q_i}]$ induces, precisely a production for j given by (24). We then only need a toll that induces i to produce according to (23), and that toll is

$\widetilde{\tau}_i = 2\alpha q_j^A - \alpha E[\widetilde{q_j}]$. Thus, the pair of tolls:

$$\widetilde{\tau}_i = 2\alpha q_j^A - \alpha E[\widetilde{q_j}] \qquad \widetilde{\tau}_j = \alpha E[\widetilde{q_i}]$$

induce airlines to produce according to (23) and (24) and therefore they induce a situation that is better in expected-social welfare terms than direct allocation. And since they are not even the optimal tolls, it follows that ex-ante, the differentiated tolls mechanism is always better than direct allocation. □

Hence, the intuition for Proposition 2 is similar to that of Proposition 1, but through a more involved argument. Here we prove that for any direct allocation (q_i^A, q_j^A), it is possible to find tolls that improve on them. The key, again, is the flexibility provided by tolls, which allow firms to adjust production, reacting to their cost realizations. Most importantly, once again, the idea of implementing some "first-best" allocation through tolls is gone.

4.4. Non-linear congestion costs per flight

Propositions 1 and 2 have shown that, in the absence of market power, with non-atomistic airlines and congestion costs per flight that increase linearly with total traffic, differentiated tolls are ex-ante more efficient than direct allocation of slots when there is asymmetric information. To prove this we used the result that, for monopoly, when the total external cost is linear, i.e. the marginal external cost is constant, the toll mechanism is ex-post efficient, and therefore better than direct allocation. But we also showed for the case of monopoly that when total external cost is not linear, i.e. the marginal external cost is non-constant, the mechanisms cannot be ranked in general ex-ante.

This imply that Propositions 1 and 2 do not hold for non-linear congestion costs per flight. To illustrate this consider now that the congestion cost per flight is of the form αQ^2. Then, if one considers the following values for parameters: $a = 10$, $b = 15$, $\alpha = 1$ and assume that the conjecture all agents have about the private information variables θ_i and θ_j, is that they are normally distributed with support [1,2], then the ex-ante social welfare of the direct allocation mechanism exceeds that of the differentiated tolls.[4]

5. Slot auctions, manipulable congestion tolls, market power and dynamics

Having established that differentiated tolls are better in expected terms than direct allocation when there is asymmetric information, no market power and congestion costs per flight that increase linearly with total traffic, we can now analyze what happens with

[4] Note that a value 0 for θ, makes the profit maximizing problems not concave. Also, as explained in footnote 3, the approach used by Weitzman and Heuson to compare mechanisms in general and find what makes it more likely for one to dominate cannot be applied because the airlines game cannot be easily solved explicitly in this case because of two reasons: the non-linearity of the cost per flight, and because best-response functions are solved in expectation.

two other instruments that have been put forward as means to deal with congestion: slot auctions and manipulable congestion tolls. We also discuss market power and the possibility of learning the private information through repeated (dynamic) interactions.

5.1. Slot auctions

Under perfect information and no-market power, Brueckner (2009) showed that a slot auction implements the first best. The idea goes as follows. Consider a uniform-price multiunit auction, where each airline pays the same amount for each slot they get. The social planner announces the quantity of slots to be auctioned Q^*, airlines submit their bids – a decreasing function of the number of slots – and the auctioneer computes the price that clears the market. Since the airlines have no market power, and there is perfect information, there is no manipulative behavior and the firms bid their true marginal willingness to pay for slots, i.e. they bid their marginal profits function, but now given a fixed level of congestion per flight given by αQ^* . Thus, the bid functions are:

$$b_i(q_i) = b - 2\theta_i q_i - \alpha Q^* \qquad b_j(q_j) = b - 2\theta_j q_j - \alpha Q^* \tag{25}$$

In equilibrium, bids are equalized but note that, this time, there is no externality problem, as an additional slot does not change congestion because the number of slots is fixed. It is then only a matter of defining the number of slots to be auctioned adequately. The optimal allocation is then recovered if $Q^* = q_j^* + q_j^*$, i.e. the sum of the optimal perfect information allocations.

Unfortunately, under imperfect information the regulator cannot set Q^* optimally; the most she can do is make the best guess which, as we saw when analyzing direct allocation under asymmetric information, may not be all that positive since the party making the quantity decision is the uninformed one. What we would need then, is to somehow also delegate the decision of the total number of slots to the informed agents, that is, the number of slots to be auctioned should depend on information provided by the airlines. Is this possible? Mechanism design theory provides us with the first answers: the Vickrey–Clarke–Grooves mechanisms (known as VCG, see e.g., Krishna, 2009) are known to implement perfect information outcomes even when informational asymmetries exists. The problem is that the VCG mechanism is not a real auction and its direct implementation is difficult.[5] Firms must pay according to the externality they impose on others, which leads to asymmetric payments and, in many cases, smaller producers paying higher transfers, which can be perceived as unfair. For this reason, the economics literature has made important efforts to generate simple auctions that help implement VCG mechanisms. The most recent and relevant effort is Montero (2008) but, unfortunately this mechanism does not work under private – or production – externalities,

[5] The VCG auction is not implemented by a generalized second price auction, since the firm's information is needed to even compute the number of slots to auction. It is also not implemented by a uniform price auction, since with differentiated marginal external costs, prices would have to be different.

a phenomenon that occurs when a firm imposes externalities upon another firm and they share production inputs. The problem in that case is, precisely, that there is no simple way to calculate how many units to auction. In fact, Pertuiset and Santos (2014) propose the use of VCG mechanism and indicates how it should be used in practice, yet the number of slots to be auctioned is exogenously given. Here, obtaining a first-best allocation requires, critically, to choose the total amount of slots to be auctioned, precluding the use of the Pertuiset and Santos approach.

A simpler, yet sub-optimal way to proceed, then, is that the regulator chooses, using the available information it has, the number of slots to be auctioned and that it then proceeds with the auction. The best guess for the number of slots is the quantity that maximizes the expected social welfare under direct allocation, i.e. the regulator would define $Q^* = q_j^A + q_j^A$, according to (22). Once that number is defined, a uniform price auction, or Vickrey auction (Vickrey, 1961), would induce airlines to bid according to their true marginal profit functions, thus revealing the private information.

Note the problem: imperfect information can be undone once the number of slots to be auctioned is defined, something good for welfare; but the number of slots is decided by the uninformed party, which is bad for welfare. Indeed, this mixed nature of the mechanism shows in different numerical examples that we calculated: it is not possible to rank in terms of expected social welfare the Vickrey auction and differentiated tolls. It all depends on parameter values.

Quite naturally, though, the auction should reach higher rents for the social planner than tolls. The intuition behind this follows the logic of Basso and Zhang (2010): while differentiated tolls only charge for uninternalized congestion, the VCG auction charges each airline the total harm they impose over its competitor, i.e airline i pays all the revenues that airline j does not receive because i participates in the market.

5.2. Manipulable congestion tolls

Brueckner and Verhoef (2010) argue that it may be implausible that non-atomistic airlines act as Stackelberg followers, taking the toll as given. Instead, they claim that airlines might have an influence on the toll to be charged. In order to prevent this strategic effect, Brueckner and Verhoef comes up with the idea of manipulable tolls. In this case what the regulator chooses are not differentiated tolls but differentiated toll rules, one for each airline, which take the form of $\tau_i = Z_i(q_i, q_j)$. They show that it is possible to implement the first best allocation using a system of optimal toll rules that are designed to be manipulable by the airlines.

Such approach does not disable the asymmetric information problem. The issue is that the optimal toll rule depends on the conjecture that the regulator has on how (q_i, q_j) will be chosen. With perfect information, the regulator is able to calculate perfectly the best respone functions, which he then uses to design the optimal toll rules. But with asymmetric information, she cannot calculate the exact best response functions, she can only calculate the Bayes–Nash reaction functions. The toll rules, then, have to be chosen over expectations, making the rule ex-post inefficient.

5.3. Market power

Up to this point we have only considered cases where the airlines face perfectly elastic demands with respect to the full prices. In order to understand how our results would change if demands were downward sloping in terms of the full price – the market power case – we first analyze the single firm case, but adding a slope to the demand function. If we consider for the monopoly case a demand given by $a - Bq_i$, social welfare is given by

$$SW = aq_i - \frac{1}{2}Bq_i^2 - \theta_i q_i^2 - Kq_i$$

The optimal toll under perfect information is easily derived as

$$a - \tau_i = (a - K)2\frac{B + \theta_i}{B + 2\theta_i}$$

Note that the optimal toll is now different from K, despite the fact the marginal external cost is constant. The optimal toll does depend on private information because, as discussed by Pels and Verhoef (2004) and Basso (2008), the toll now has to tackle two different distortions: the congestion externality distortion, which leads to the positive term equal to the marginal external cost, and the market power distortion which, to be curbed, requires a subsidy to artificially decrease the marginal cost of the airline and thus induce an increase in output. Note how, if $B = 0$, and there is no market power, then the toll becomes independent of θ_i. But when $B > 0$, the market power subsidy does depend on θ_i, because the degree of market power depends on both demand and the marginal cost. It follows, just as in the case of non-constant marginal external cost, that under asymmetric information, the toll for the monopoly case is not better than direct allocation in ex-post or ex-ante terms, result which, as before, carries on two duopoly. Hence, when market power is strong, the mechanisms cannot be ranked in general while with low degrees of market power, tolls will be better ex-ante (by a continuity argument). Mind though, that when market power is strong, the congestion problem becomes weaker and might even not really exist.

5.4. Dynamic interactions

The solution concept used in the paper is static Bayesian Nash equilibrium. Agents know their own costs, know only the distribution of a rivals' cost and simultaneously (or without observation) choose the quantity to produce. Therefore, there are no dynamic considerations here. In particular, firms do not learn, over time, about the cost structure of other firms. A model with learning through repeated interaction would generate dynamics much more complicated that the ones suggested in this comment. If firms could learn (from quantities) something about the cost structure of a different firm, they themselves would modify their strategies, to limit this learning from competitors. This "ratchet effect" (Freixas et al., 1985) completely changes the nature of the analysis. The very equilibrium concept would need to change to Perfect Bayesian, appropriate for dynamic games of incomplete information. Firms will play mixed strategies in order to hide their types, and generate mistakes by the competitor. But would a dynamic setting be more appropriate? Do we thing that airlines randomize dynamically the number of slots they will use? We side with the negative answer: airlines decisions about the number of slots to use and routes to serve do not change often and do not seem to be randomized. Cost structures, on the other hand, can be changing quite often and, therefore learning becomes obsolete before it can be effectively used.

The same applies for regulatory instruments: they do not change often but, rather the regulator commits to regulatory rules for long periods of time. But there is an extra reason here. For a regulator, it is better to have commitment power. Not having it would induce airlines to act sub-optimally in order to protect themselves from future regulatory changes. Whatever a regulator can achieve without commitment power he can obviously replicate with it.

6. Conclusions

We have studied and compared three economics tools that can be used for reducing congestion problems in airports when carriers have private information: direct allocation, tolls and slot auctions.

We first establish a key difference between full and imperfect information models. In the former our "direct allocation" policy represents the first best, and the optimal tolls are a way to implement that allocation. Therefore, using one or another is simply a matter of political feasibility, easiness of implementation, etc. Nevertheless, this equivalence is no longer valid under imperfect information: using a direct allocation mechanism the regulator only uses his imperfect information for choosing quantities that maximizes the expected social welfare. Under a toll mechanism, the airport delegates the production decision to airlines, and therefore the better informed agents choose production levels. This intuition explains why, in some cases tolls (a pricing mechanism) achieve a better result than direct allocation, sometimes in expected value, and in a few cases achieve the full information first-best. Concretely, without strategic interaction, if the toll under perfect information is constant and the total external cost is linear, then pricing under imperfect information will be optimal ex-post, while direct allocation is always inefficient. When strategic interaction is included, as long as congestion costs per flight are linear in total traffic, pricing will be always better than direct allocation in expectation.

Another interesting conclusion is related to the idea of Pigouvian taxes. Under incomplete information, a naïve application of Pigouvian tolls, where the regulator computes the toll as if the private information parameter is equal to its expectation, is suboptimal. There always exists a set of tolls that are better than charging the marginal external cost evaluated at the quantities that maximizes the (expected) social welfare. The optimal toll anticipates that the informed agent will react strategically to it, using his private information, and therefore does not correspond to a simple expected Pigovian tax. This highlights, once again, the difference between uncertainty, where both sides of the relationship are uninformed, and asymmetric information.

Finally, we discuss a third economical tool proposed in the literature. Under perfect information and no-market power, Brueckner (2009) showed that this tool implements the first best. But that requires the regulator to set the total number of slots initially to its optimal level, something easy under perfect information but impossible under asymmetric information, since the regulator does not have the necessary information.

What would be needed in this case is to also delegate the decision of the total number of slots to the informed agents. A VCG mechanism would achieve exactly that, but its direct implementation would require a mechanism that is far from an auction, and almost impossible to achieve in practice. For this reason, the economics literature has made important efforts to generate simple auctions that help implement VCG mechanisms. The most recent and relevant effort is Montero (2008) but, unfortunately this mechanism does not work under private externalities, phenomenon that occurs when a firm imposes externalities upon another firm and they share production inputs. The problem in that case is, precisely, that there is no simple way to calculate how many units to auction. Our current research agenda looks to advance in this direction, because VCG mechanism seems to be a promising approach for solving the congestion problem when regulators are not perfectly informed.

Acknowledgments

We gratefully acknowledge financial support from the Complex Engineering Systems Institute, ISCI, grant CONICYT: FB0816.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijindorg.2018.07.007.

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