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The economics of airport noise: how to manage markets for noise licenses

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**The economics of airport noise:
how to manage markets for noise licenses**

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Abstract

Noise-induced pollution constitutes a hot and topical societal problem for all major airports. This paper discusses various issues in the implementation of a market for noise licenses as a solution to solve the noise externality between the residents located around airports and the aircrafts moving in and to airports.

Keywords: airport, environment, noise, licenses.

JEL Classification: Q5, R4, D4, D6, D78, D82, L5, L93

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1 Introduction

It is hardly disputable that one of the most salient environmental and societal impacts of airport activity is noise pollution. For most airports noise pollution constitutes a crucial management and political problem. Regarding the airport, the problem is how to cope with local residents' resistance. Regarding the public authority, the problem is how to implement a fair and efficient regulation of aircraft activity. A key issue, in particular, is the spreading of aircraft movements over different geographical zones (the choice of routes). One key component of the problem is the absence of residents' revealed preferences about noise pollution. Basically, current noise regulations use command-and-control approaches and they are disconnected from local residents' subjective damages. Most of the discussion focuses on technological improvements (quieter airplanes, alternative land-off and kick-off procedures) or on the definition of noise standards. The question of residents' disutility is never addressed (see Janic, 1999; Brueckner, 2003). Recently, Brueckner and Girvin (2009) discuss the optimal taxation of aircraft given a fixed global quota of noise emissions, but they do not consider the social cost of residents' noise exposure.

In a recent paper we have proposed a novel solution for noise regulation around airports ("The price of silence: markets for noise licenses and airports." *International Economic Review* 51(4), 1097-1125, 2010). It consists in allowing residents to sell tradable noise licenses to airlines companies. By doing so, residents reveal their preferences, and the market for noise licenses, when well-designed by the regulator, implements an efficient flight activity and spreading over the routes. Furthermore, because the rights are given to residents, local acceptability is also met. Finally, the market provides the airline companies with an incentive to adopt quieter aircrafts.

The theoretical properties of a market for noise licenses have been discussed in the just mentioned paper. The purpose of the current paper is to further explore some practical issues related to the implementation of such a market. We complement the theoretical paper by analyzing additional issues about noise licenses markets. Our aim is to help practitioners to consider this economic instrument in the management of airport noise.

The paper is organized as follows. Section 2 explains how markets for noise licenses work and stresses the main features presented in Bréchet and Picard (2010). The two following sections address practical issues. Section 3 discusses how the characteristics of airports and aircraft affect the design and the equilibrium of the market. Section 4 discusses the impact of residents characteristics. Section 6 presents the conclusion.[1]

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[1] An extensive literature review is available in Bréchet and Picard (2010).

2 A market for noise licenses

A major issue for many airports today is the management of noise pollution of inhabited neighbourhoods. As airport activities locate in places with high demand for aircraft transport, airports are naturally built within or close to the suburbs of cities where residential density is generally high.

The starting point of the discussion about airport noise licenses lies in several observations about residents, airlines and airport spatial structure. First, residents incur a disutility from aircraft noise which positively affects their preferences for a residential location away from airports. This has been reflected in both surveys (Van Praag, 2004) and hedonic price models of property values (Nelson, 2004). Second, airports host a bunch of airline companies that offer air connections between city pairs with various level of profitability. Some city pair connections are very profitable while others have a low profitability. In equilibrium the least profitable air connection has zero profit. Third, airports may operate aircraft on one or several runways and each runway can be associated with several aircraft routes. Air traffic is organized along several routes that airplanes may take when they land and take off. Landing and take-off routes are determined by exogenous technical characteristic, for instance, by the direction of wind. Yet, within the same set of technical parameters, there may exist several route possibilities. An aircraft route includes the path, the altitude and the engine power taken by an aircraft for takeoff or landing. As shown in Figure 1, a West runway may for example direct the planes to a South-West, West or North-West route some miles after takeoff. Figure 2 displays no less than six actual routes and three additional proposed routes from the South West runway of Brussels airport.

Each aircraft therefore gives rise to noise disutility $\delta(t)$ that harms the residents living on the ground at the distance t from the airport below a chosen route. The intensity of the noise disutility varies with the altitude and the engine power of each aircraft, which depends on the aircraft position on its route. As shown in Figure 3, the total disutility hence depends on this noise intensity and the number of residents harmed by the noise and is different on each point of the aircraft route.

To easily explain the main economic properties of noise licenses, we make the three following simplifying assumptions in this section. First, we assume that only one type of aircraft operates in the airport, so that the residents have the same noise disutility for every aircraft flight. Second, to emphasize spatial design issues, we suppose that residents are homogenous with respect to their disutility for noise pollution, but they differ according to their distance t from the airport. Finally, there is only one relevant time period, say 8:00-20:00, during which aircrafts operate. Those assumptions will be relaxed and discussed in the next sections.
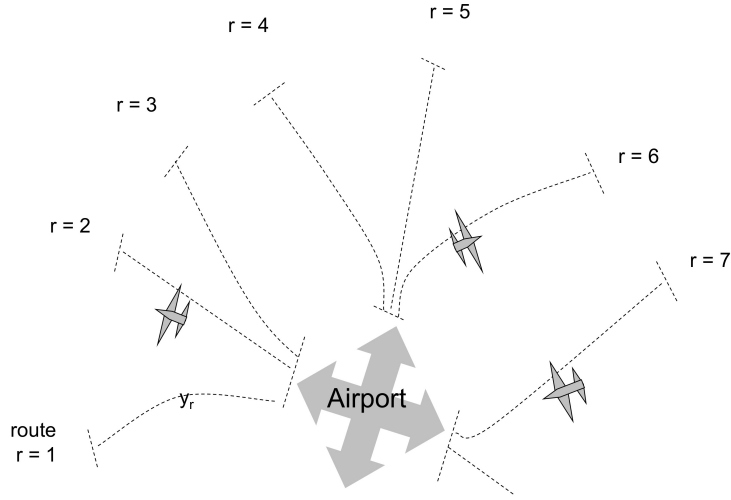
Figure 1: Feasible routes from an airport

The purpose of this section is to explain how markets for noise licenses work. For pedagogical purposes we first begin with the simple case of a single route. Then we generalize to several routes and several zones.

2.1 The case of a single route

It is rather easy to understand how markets for noise licenses work when there exists only one route. In this case, a noise license is defined as the right for one aircraft to fly over the route and emit noise. This right is given to the residents. As a consequence, noise licenses must be purchased by each aircraft flying over the route. The demand for noise licenses is given by the profitability of city pair connections. If each city pair connection x makes a profit $\pi(x)$ and the price of the noise license to flight the route is denoted by P, then the demand for noise license is equal to $y^D(P) = \#\{x : \pi(x) - P \geq 0\}$ (see $y^D(P)$ in Figure 3). At a positive noise license price, the lowest profitable connection is no longer viable and must close. On the other hand, noise licenses are granted by the representative of the residents under the unique route. This representative organizes the compensation for aircraft noise. If the latter is utilitarian, she will consider the aggregate disutility over the route, $d(y)$, which depends on the number of flights and on a measure of aggregate disutility $B = \int_0^T n(t)\delta(t) \ dt$, where $n(t)$ is the number of residents at a distance t from the
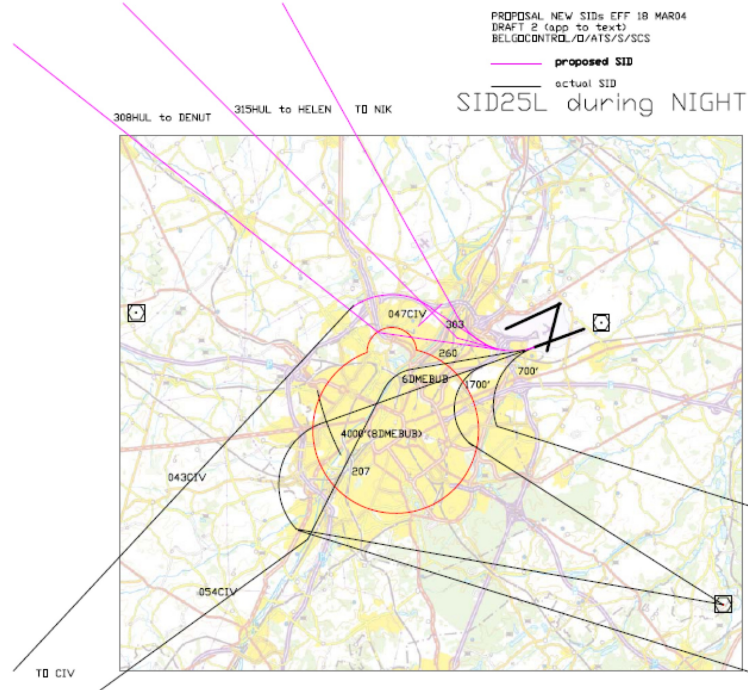
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Figure 2: Actual and proposed routes from Brussels airport (source: Belgocontrol)

airport on the route, and $\delta(t)$ is the intensity of the noise disutility as *perceived* by the residents at distance t. It is to be noted that $\delta(t)$ measures the resident's noise perception and disutility and is not a technical measure of noise exposure such as the dBA index. The key of noise license markets is to allow residents to reveal their true disutility. The representative issues noise licenses and permits aircraft to fly over the route until the aggregate marginal disutility from noise exceeds the revenue for noise licences. The supply curve for noise licenses will be upward sloping and will have a zero intercept under the assumption that the noise of the first flight during the time period implies no noise disutility (see $y^S(P)$ in Figure 4). When there exists only one route and many independent airline companies, the representative will exert monopsony power and set the number of noise licences that maximizes the aggregate utility of the residents located under the route. The residents proceeds are equal to $Py^S(P)$ and their marginal revenues to $(Py^S(P))'$. Then, the equilibrium is given by the equality between marginal revenues and demand: $(Py^S(P))' = y^D(P)$. The residents below the route constrain the number of flights to y^M. Because the number of flights is equal to $y^o > y^M$ in the absence of noise licenses, the requirement

Noise disutility $\delta_r(t)$

0

Population $n_r(t)$

0

Noise*population

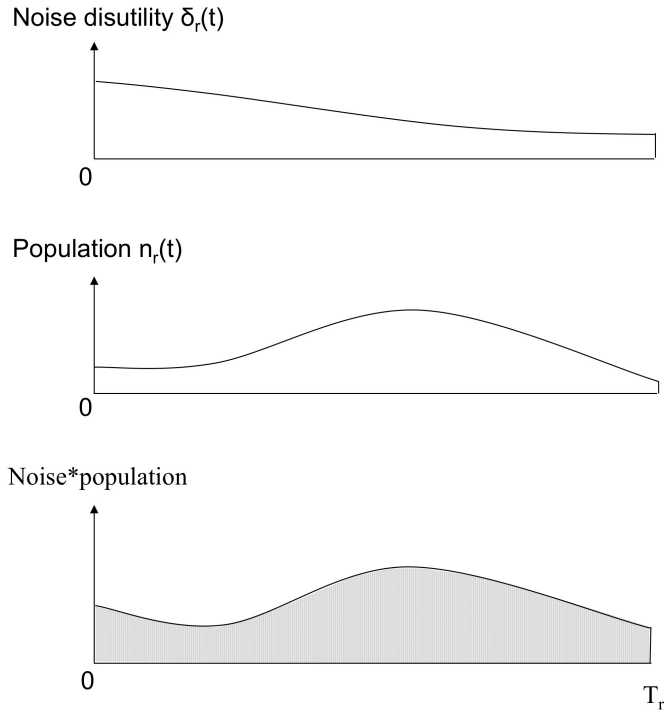0 T_r

Figure 3: Distribution of noise disutility on a route

to purchase noise licenses from residents reduces the airport activity by eliminating the least profitable flights.

Residents do collect a share of the airline activity rents to compensate for their noise disutility. Because of their monopsony power they collect more than what would be necessary to accept the noise related to the flight activity. Nevertheless, it is important to note that residents do not eliminate the airport activity as it is sometimes feared by airport advocates. Indeed, airline companies face a situation similar to the one the manufacturing firms face with union monopsonies: the latter constrains the firms' activities and profits but do not call for their shutdown. To sum up, the main point of this exercise is to show that noise licenses allow residents to reveal their preferences about their noise disutility below the route and allow airline companies to reveal their willingness to pay to operate from the aiport. This is typically what Coase (1960) would advocate: to give property rights over noise either to local victims (the residents) or to polluters (the aircraft companies). Since the residents are victims of aircraft noise pollution, this naturally implies that property rights on noise (or quietness) are granted to those residents. They are then free to
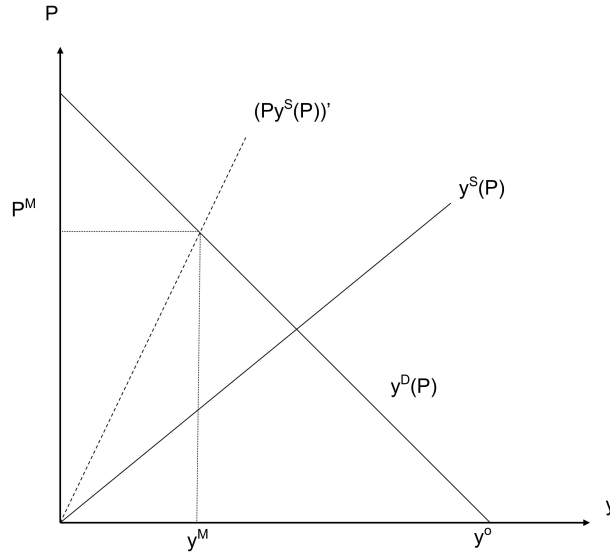
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Figure 4: Market equilibrium on a monopsony route

transfer those rights to aircraft companies by the means of *noise licenses*. Hence, the regulator does not need to arbitrage between residents and airline companies for the noise externality.

2.2 The case of several routes

More realistic is the case where the air traffic controllers can direct flights over several routes. In this case, a noise license is defined as the right for one aircraft to fly and emit noise over a specific route. There are as many types of noise licenses as there are routes. As the reader will understand, the main feature of a market for noise licenses is now its spatial dimension. Residents are distributed over the space under aircraft routes and airline companies are required to buy the licenses to take a route. In addition, each route is associated with an independent representative who is responsible to issue noise licences in exchange for a monetary compensation. Each representative i infers her supply of noise licenses y_i^S from the aggregate noise disutility of the residents dwelling under her route. The representative is in charge of redistributing the compensation to each individual according to the local noise conditions.

From the air controllers' viewpoint, routes are generally good substitutes. For instance, under good weather conditions, routing an aircraft to West or North-

West route a couple of miles after takeoff does not present technical and safety challenges. Figure 1.b offers a good example of a handful of routes from Brussels airport. Because routes are substitutes, aircraft are enticed to choose the routes offering the noise licenses with the lowest price. In equilibrium, the noise license prices of all routes must equalize and the equilibrium number of flights, y^R, is given by the aggregation of each route's supply, $y^S(P) = \sum_i y_i^S(P)$, and the total demand for noise licenses, $y^D(P)$. This is shown in Figure 5.
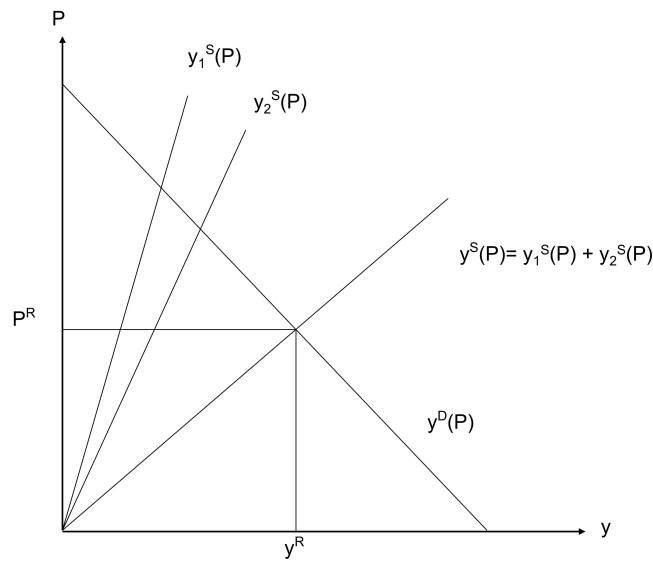

Figure 5: Market equilibrium with two routes

As above, the residents' possibility to sell noise licenses entices them to reveal their preferences about noise. The intervention of the regulator is not needed after the setup of a noise license market. In addition, dividing the space surrounding the airport into several routes has two important properties. First it permits the noise disutility to be spread over more individuals. When individuals are increasingly harmed by additional noise events, they are less hurt by an aircraft noise event at low traffic levels than at high levels. As a consequence, it is more efficient to rebalance flight activity from routes with high flight activity to ones with low activity. The market for noise licenses achieves this dispersion property. Second, by setting up several routes, the routes' representatives lose market power over aircraft and get lower rents. The existence of rents is no surprise as rents are features of any markets with heterogenous buyers and sellers. The market is here used to re-

veal the preferences of both residents and airline companies about the aircraft noise emissions.

Using markets for pollution licenses to regulate pollution is typical in the environmental economics literature. Montgomery (1972) indeed inspired the use of tradeable permits or licenses as policy instruments for environmental issues. Since the 1990s, many examples of markets for tradable permits have been successfully implemented, most notably for sulfur dioxide pollution in the US power industry (Ellerman *et al.*, 2000) and for carbon dioxide in the European Union (see Ellerman *et al.*, 2010). All these markets, nevertheless, are cap-and-trade systems in the sense where the global supply of pollution permits is set by the regulator (this is the cap on pollution), and polluters are then allowed to trade these permits among themselves. In our setting, the supply of licenses is endogenous, and it is based on residents' preferences. By contrast to cap-and-trade systems, our market allows to reveal preferences on both sides of the market.[2]

2.3 The case of several zones, with one route

We can finally consider the last case where aircrafts must follow a unique route, but where this route is divided into several contiguous *zones*. A zone is defined as a land strip below a route where residents are represented by a single representative. So, there may be many zones and representatives below the same route. Figure 6 depicts a situation where the route is divided into two zones. In this case, a noise license is defined as the right for one aircraft to fly over one zone and to emit noise there. So, to fly the entire route an aircraft must purchase a noise license for every zone. The licenses supplied by different zones' representatives are perfect complements for airline companies. Noise pollution is therefore a complementary bad for all zones on a single route. Typically, this may lead to a *tragedy of the anticommons* where the agents do not internalize the global effect of their decisions on the route traffic. The "tragedy of the commons" (Hardin, 1968) explains why people overuse shared resources: it happens when too many owners can have a privilege to use a given resource and no one has a right to exclude another. The "tragedy of the anticommons" (Heller and Eisengerg, 1998) happens when a resource is prone to underuse because too many owners can block each other and no one has an effective privilege of use. In our context, each residents' representative owns the right to issue noise licenses and does not internalize the benefits that other zones bear. One may conjecture that the number of licenses and flights is inefficient. Another way to see this is to observe that noise licenses offered by different zones on a same route are complementary goods. Therefore the market for noise licenses may be

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[2]See Ellerman (2005) for a broad introduction to markets for tradable pollution permits.

suspected to be subject to under-provision of complementary goods. Independent suppliers of complementary goods would set inefficiently low output levels because they would not internalize the effect of the benefit of a larger supply of their goods on the other suppliers. Bréchet and Picard (2010) show that those effects exist but are nevertheless under the control of the market designer.
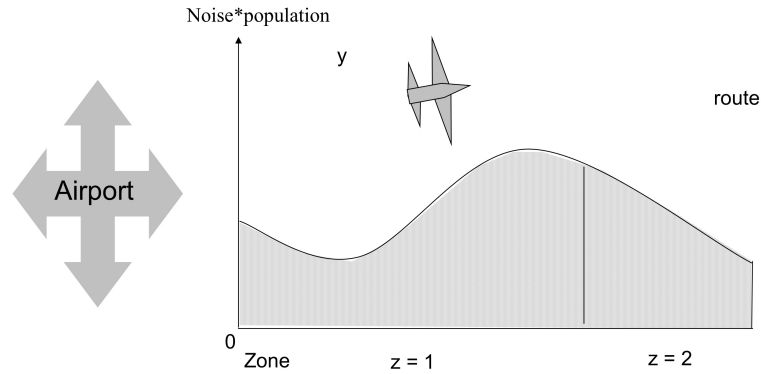

Figure 6: Designing a route with two zones

Bréchet and Picard (2010) propose to organize the market with a neutral auctioneer who collects the noise license price bids supplied by the zone representatives and who sell to each aircraft the bundles of noise licenses on all zones at a price equal to maximum bid price times the number of zones. This means that the zone offering the bid with the highest noise license prices receives exactly what it bids. This zone is called *the critical zone* because it determines the price to fly over the whole route. The other zones receive more than what they bid. Such a situation corresponds to a standard market equilibrium where the marginal transaction gives no rent to the marginal supplier but inframarginal transactions grant some positive rents to inframarginal suppliers. In this context, the equilibrium in the noise license market can be represented as in Figure 7. Let $d_i(y_i)$ be the aggregate noise disutility over the zone i for a traffic intensity y_i over the zone. This is the disutility that zone i's representative considers in deciding its price bid for a noise licence. The bid price of a zone i's representative is then determined by her marginal disutility $d'_i(y_i)$. The market auctioneer picks the largest bid price $\max_i d'_i(y_i)$ and sets

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the price of the route $P^Z = 2 \max_i d_i'(y_i)$. The resulting number of flights is then given by the aircraft demand to fly on the route $y^Z = y^D(P^Z)$. The zone i with the lowest marginal disutility gets a rent equal to $y^Z * \left[\max_i d_i'(y_i) - d_j'(y_j) \right]$. Note that the market designer can tune the level of this rent by altering zones' spatial design. Indeed, if she reduces the size of the critical zone, aircraft noise will affect fewer residents in this zone and will therefore reduce the aggregate disutility and the marginal disutility over this zone, which in turn reduces the critical zone's bid price and therefore the rents given to other zones. The important point is that the tragedy of the anticommons can be significantly reduced in this setup by an appropriate design of the zones on the routes.
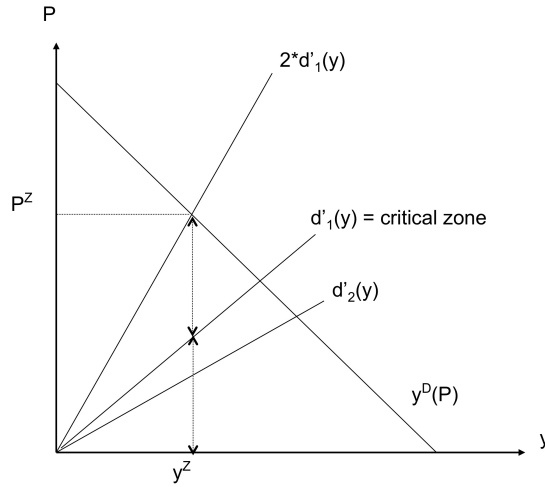

Figure 7: Market equilibrium with two zones

To sum up, the combination of noise licenses given to residents with an appropriate spatial design of aircraft activity around airports is an appealing solution for the management of noise pollution around airports. The market for noise licenses yields an efficient allocation of flights across routes, a solution that airport charges on aircraft movements cannot achieve. By increasing the number of routes the market designer can spread the noise disutility where it has the lowest social cost and she can reduce the residents' rents in eliciting their information about noise disutility. By creating appropriate zones the market designer can delegate the revelation of noise disutility to smaller spatial groups of residents and limit the problem of the tragedy of anticommons.

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The above model is definitively an over-simplification of a complex reality. We now extend our discussion to issues related to airport and aircraft characteristics.

3 Taking aircraft and airport characteristics into account

In this section we focus on the impact of aircraft and airport characteristics on noise licenses and airport traffic. For simplicity we assume that the market designer has set up several routes so that the residents' representatives are price takers. As a result, their supply of noise licences can be aggregated in a unique supply function $y^S(P)$. We sequentially address the issues of aircraft noise heterogeneity, wind contingencies, time schedules and capacity constraints, hubs and airport extensions.

3.1 Aircrafts heterogeneity

Our earlier focus was on the management of noise pollution across space, not the management of the aircraft fleet. We therefore abstracted from possible noise heterogeneity across aircraft types by assuming that aircraft noise is homogenous. In practice, aircraft vary in size, weight, power, age, and other parameters that affect their noise impact on the ground.

Noise licenses can easily be differentiated according to the aircraft types and their noise pollution. A noise license could be issued for each type of aircraft on a given route or zone. Zones' representatives would therefore reveal their preferences for each type of aircraft by offering a price bid for each of them. In particular, they would set higher noise license prices for noisy aircraft types. The representatives and their residents would hence make the trade off between more and less noisy aircraft types by setting high and low prices to fly over their routes. Price differentials would in turn give incentives to airline companies to choose the socially efficient aircraft type. Indeed, airline companies internalize residents' noise disutility through the purchase of noise licenses for each of their aircraft; it can readily be shown that, as in Coase (1960), those companies ultimately maximize the sum of their profits and the noise disutility they generate. As a result, differentiated noise licenses would not only solve the information revelation problem about noise disutility but it would also induce more efficient compositions of aircraft fleets.

Although compelling, this solution suffers from the drawback of complexity. There indeed exist too many aircraft types, and each aircraft can undertake technical improvements for noise reduction, which should also be taken into account. So, it appears unrealistic to ask residents' representatives to offer a bid for each

movement of aircraft. A more realistic solution is then to deal noise heterogeneity across aircraft types with a Quota Count system. As explained in detail by Ollerhead and Hopewell (2002), the Quota Count (QC) System was introduced as part of a new night restrictions regime for Heathrow, Gatwick and Stansted in 1993. Each aircraft movement is given a specific noise quota for each airport according to the QC classification. The QC classification is intended to reflect the contribution made by an aircraft to the total noise impact around an airport. QC classifications measure noise in relative terms: a QC/2 aircraft is deemed to have twice the impact of a QC/1 aircraft, a QC/4 aircraft has four times the impact, and so on. The QC classifications of aircraft are determined from their certificated noise levels. Two options are available to the market designer. On the one hand, she can categorize aircraft types into a small number of QC ranges and require residents to offer noise license bids for each range, for instance, for the four ranges QC/1, QC/2, QC/3 and above. The price for each range will reflect residents disutility for each noise range. This solution allows the market to elicit the value of the noise disutility but may still seem too complex. On the other hand, the market designer can organize a market for QC licences; that is, a market for one type of noise range, for instance QC/1. The market designer must then set conversion rates on the price paid for aircrafts with other QCs. Here conversion rates are no longer endogenous and may no reflect the disutility differences between noise events. However, equivalences between noise experiences have been investigated[3] and the resulting conversion figures could be judged as fair approximations. In this matter, the balance is between complexity and accuracy.

3.2   Wind contingencies

Strong winds can force the air traffic control management to direct taking-off flights to the routes opposite to the winds. In most of airports, winds flow from the West 80% of the time and weather forecast agencies provide a good annual prediction of expected wind directions. Wind contingencies raise two issues, before and after the purchase of noise licences by airline companies.

Consider on the one hand that wind contingencies arise after the purchase of noise licences. Airline companies purchase their books of noise licences at the beginning of the time period during which licenses are valid. At the end of the time period, airline companies must clear their license books so that the number of flights must not exceed the number of purchased noise licenses on routes and zones. However, it may be that wind contingencies force airline companies to put a larger than expected

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[3]See, *e.g.*, Miedeman and Oudshoorn (2001).

number of flights on some routes. There should be some possibilities to adjust the realization to the expectation of the use of routes.

Our above discussion focuses on a *primary market* between residents and airline companies. This market is supposed to clear on a regular basis, say quarterly. To solve the present issue, a secondary market may coexist with the primary one. It would consist in trading licenses among airline companies. As in the case of EU Emission Trading Scheme on CO_2, the *secondary market* can be informally organized as a set of bilateral trades between airline companies, or it can be organized formally in a set of continuous markets (one for each route and flight time period; *e.g.* North-West 7:00-20:00). Stochastic features can alter the day-to-day demand of licenses, for example because of weather conditions or changes in travel demands. If at some time period an airline company needs more (or less) licenses for a route than it owns, then it can buy (or sell) them on the secondary market. Naturally, the total number of licenses for each zone is given for the time-span covered (resulting from the primary market clearing), but the flexibility provided by the secondary market would allow absorption of transitional stochastic shocks. The assumption behind this design is that expectations are not biased. Since the number of licenses on each route is fixed during the quarter, it will always fit the optimal one that resulted from market clearing in the primary market.

There may however be discrepancies between the expected aggregate supply of route and the actual demand for routes. For instance, weather forecasts are not realized perfectly. Airline companies can then become short on certain routes and long on others. Then, airline companies will manage noise licenses according to a *portfolio* approach, taking into account the risk of becoming short on licenses. They will minimize this risk by buying a portfolio of noise licenses that match more than their need for the different routes. They will indeed make a precautionary savings of licenses to cope with such uncertainty. The price of licenses will incorporate an option premium for route availability.

One way for the regulator to minimize this precautionary savings is to allows for the *banking* of licenses. Banking would allow an airline company to keep some licenses for use in the next period. If we consider that licenses are valid only for one time period (say again a quarter), then banking would allow the firm to save some licenses for the next quarter. Banking should be restricted in time (not more than one quarter) and in amount (not more than a given proportion of the quantity purchased each period) to avoid the phenomenon of hot spots or congestion. Alternatively, the regulator may use a *penalty* (per flight) paid by the companies that do not comply *ex post* with the noise licenses quota established in the primary market. The penalty will be returned to residents, because the actual number of flights exceeds the one resulting from the primary market clearing.

Consider on the other hand that wind contingencies arise before the purchase of noise licences so that wind directions are on average biased toward a particular route r (typically a Western route). Air traffic control must then force aircraft to demand noise licenses more often on route r. Such wind contingencies then determine a minimal share of the noise licenses $y_r^{\min}$ demanded on this route. As shown in the left hand panel of Figure 8, the noise license demand is infinitely inelastic at $y_r^{\min}$ and then becomes elastic for larger number of flights. It is straightforward to see that the equilibrium price is unaltered as long as wind contingencies do not constrain too much the genuine demand of noise licences. Because the marginal aircraft using route r can substitute with another route, the price of noise permits should then be equal across routes and the allocation of flights over routes follows from the market equilibrium. By contrast, if wind conditions strongly constrain the demand on route r, as shown in the right hand panel of Figure 8, the noise license price is higher and the traffic on the route is larger compared to a situation were wind conditions are ignored. In particular, the equilibrium price on that route is given by the market clearing between supply $y_r^S(P)$ and minimum demand $y_r^{\min}$. Because the marginal aircraft using route r is unable to substitute with another route, the noise license price on route r is also higher than on other routes. The equilibrium on other routes is determined as before by their residents' supplies and by the residual demand $(y^D(P) - y_r^{\min})$.
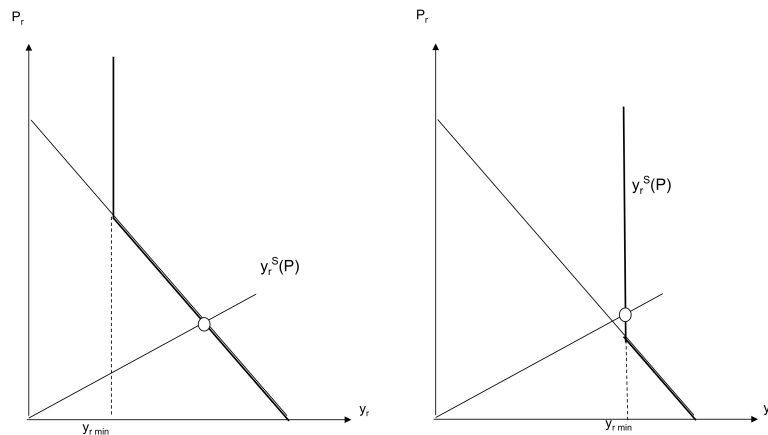

Figure 8: Market equilibrium with wind contingencies

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3.3 Time schedules and capacity constraints

Air traffic has to conform to various time schedule contingencies. Most of the latter are imposed by the behavior of air transport consumers and connectivity. In particular, business consumers are usually bound to day work schedules so that trips must be organized in the beginning and the end of the work day. Also, connectivity entices airline companies to organize their flights from and to hub airports where passenger transit occurs within particular hour ranges. This results in peak-time movements during which congestion may occur. In many airports, peak time traffic leads to the congestion of runway(s) which reaches their limit capacity.

To understand this issue, we propose the four following examples. The peak and off-peak demands for noise licenses are given by $y_{peak}^D(P)$ and $y_{off}^D(P)$ and the noise license total supply by $y^S(P)$. In the first example we suppose that the number of flights is not limited to the runway's capacity. We also suppose that on-peak air traffic can move to off-peak time schedules without cost and that noise licenses are not differentiated according to the peak and off-peak time periods. This can proxy tourist traffic where tourists are not constrained by tight schedules. This also means for instance that noise licenses are issued for a time period between 8:00 and 22:00 which includes the 8:00-10:00 and 16:00-18:00 peak hours. Figure 9 shows how the equilibrium can be constructed. First, the first and second panels display the peak demand y_{peak}^D and the off-peak demand y_{off}^D. The third panel shows the aggregation of the two demands. Since the noise licenses are homogenous, the noise license market aggregates the demands on both markets, which includes a total demand of $y_{peak}^D + y_{off}^D$ flights. The equilibrium price P^* results from the intersection of the noise license supply and total demand. Since noise licences are homogenous they have the same price. Note that if the noise disutility is relatively strong, the license supply can become so steep that the noise license price is higher than the intercept of the off-peak demand. The noise market can therefore imply the exit of off-peak flights.

In the above example, aircraft activity and noise is concentrated on peak times. It might be that residents are dissatisfied by such an outcome and wish to differentiate between the time periods. The market designer can achieve a more efficient solution by setting two types of noise licences, one for peak and one for off-peak time period. This second example is shown in Figure 10. In equilibrium, the noise license price is higher during peak time, which gives incentives to airline companies to shift some flight activity to off-peak time periods. This example shows that more differentiation of noise licenses implies a more efficient allocation of flights and noise. As mentioned before, this nevertheless comes at the cost of a more complex system of licenses.

An additional discussion can be offered when we consider capacity constraints.
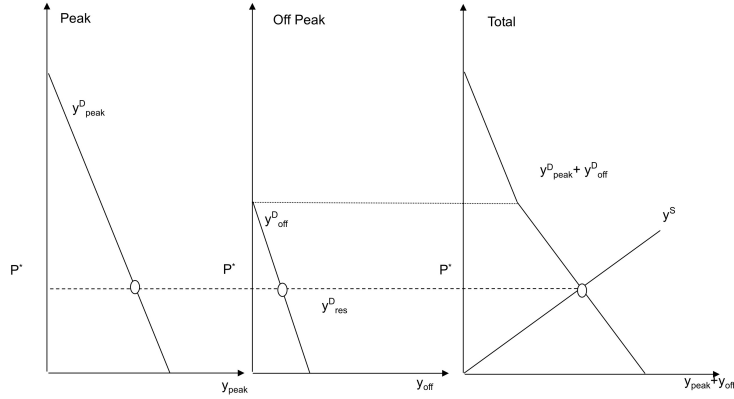
Figure 9: Peak/off-peak and one noise license

In the following third example, we use the first case where on-peak air traffic can be shifted to off-peak time schedules without cost and noise licenses are not differentiated according to the peak and off-peak time periods. In addition, we assume that the number of flights is limited to the runway(s) capacity K. Figure 11 shows how the equilibrium is constructed. First, on can observe in the first panel that, for low enough noise license prices, the peak demand y_{peak}^D is not completely served. The unserved peak demand $y_{peak}^D - K$ is moved to the off-peak demand y_{off}^D to result in a off-peak residual demand $y_{res}^D = y_{off}^D + y_{peak}^D - K$ in the second panel. The third panel shows the aggregation of demand functions. Since the noise licenses are homogenous, the noise license market aggregates the demands on both markets, which includes a total demand of $y_{peak}^D + y_{off}^D$ flights at high enough prices. For small prices, the total demand is the same since the peak demand is equal to K and the off-peak is equal to y_{res}^D, which sums to $y_{peak}^D + y_{off}^D$. The equilibrium price P^* results from the intersection of the noise license supply and total demand. Hence the capacity constraint in peak time periods does not impact the noise licence price. However, the noise license partly substitutes for the fee A that the airport could have extracted from an auction on the peak time slots without noise licenses.

The contention between the noise licenses and revenues from airport capacity management is confirmed by the last example. To make things simple, we now sup-
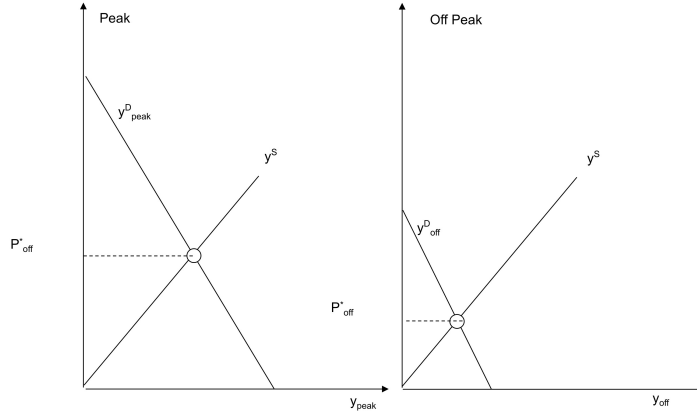
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Figure 10: Peak/off-peak noise licenses with segmentation

pose that on-peak air traffic cannot be reported to off-peak time schedules and that noise licenses are differentiated according to peak and off-peak. This will happen if peak time consumption is mainly for business purposes and off-peak consumption for tourism. For example, an aircraft must purchase separate noise licenses for the 8:00-10:00 and 16:00-18:00 peak hours and for the other off-peak time periods. As shown in Figure 12, two situations can occur according to the steepness of the supply function $y^S(P)$. First, as shown in the right hand panel, if the noise license supply is steep enough, the equilibrium in the noise permit market takes place at P^*_{peak} and reduces the peak traffic below the runway capacity K. The capacity constraint is not binding and has no effect on the noise license market. However it can have an effect on other markets or instruments. For instance, some airports manage the runway capacity by using an auction. Without noise licenses, the auction allows the airport to efficiently allocate flights and to raise a fee equal to A. Because the noise license supply removes the capacity constraint, this fee can no longer be collected. Second, as shown in the left hand panel, if the noise license supply is flat enough, the capacity constraint is binding and the noise license price is equal to P^*_{peak}. This price is lower than the fee A, so that the airport can raise only $A - P^*_{peak}$ per flight in presence of a market for noise licenses whereas it would raise A without it. This analysis shows that noise licenses can therefore directly conflict with the airport
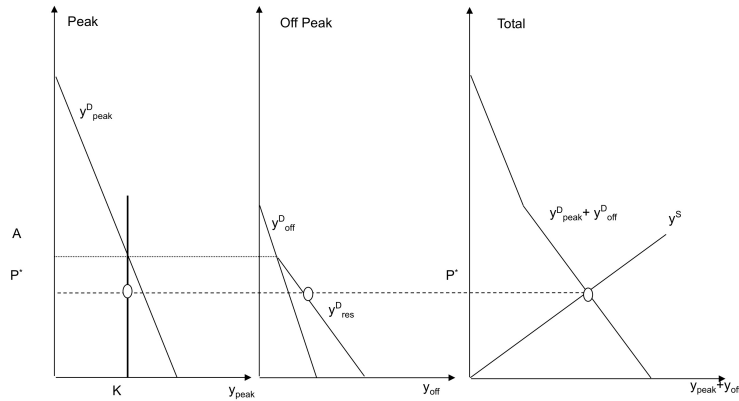
Figure 11: Peak/off-peak with perfect substitution

finances when there exist capacity constraints.

The above discussion suggests that capacity constraints and peak time congestion impact on the price of noise licenses and involve revenue shifts from airport managers to local residents. Such potential loss of airport revenues adds to the revenue loss from air traffic reduction created by noise licenses.

3.4 Hubs and flight connections

Most airline companies use some specific airports as hubs, that is, a connection node for their passengers and flights. By organizing flight connections those companies are able to propose more destinations and cheaper prices to customers. In addition to better connectivity, hubs allow airline companies to save on the costs that are subject to economies of scale and scope such as terminal costs and service costs. Large airline companies are also able to exert stronger negotiation power in dealing with the airport management of the hub airport they use, with a result of smaller prices for ground services. When such a negotiation power is not strong enough, large airline companies tend to integrate their hub airport or to use binding long term contracts. As hubs are an increasingly important feature of current air transport industry, it is important to analyze the impact of noise licenses on them.

The basic feature of flight connectivity and hubs is that flights are organized in
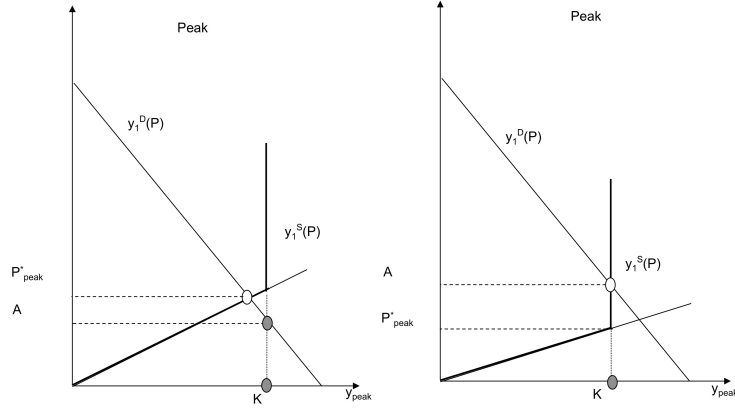
Figure 12: No peak/off-peak substitution

a "star" network and that the profitability of connected flights are interdependent. The simplest way to understand the impact of noise licenses is to consider the example of a hub airport with a single airline company that has a fixed cost of operations F and operates a set of n flights with same profitability $\pi(x) = \pi$. When noise licenses have a price P, the profit of the bundle of connected flights is given by $n(\pi - P) - F$. Hence, if $P < P^B \equiv \pi - F/n$, the bundle of flights is profitable; otherwise the airline must consider stopping its hub activities in the airport. As shown in Figure 13, the demand for noise licenses is now kinked so that $y_1^D(P) = n$ if $P < P^B$ and 0 otherwise. The noise license market equilibrium works as follows. When the noise disutility is not too strong, the noise license supply curve is not to steep so that the market equilibrium take place at a price P^* and for the hub flight activity n. Otherwise, if the noise disutility is too strong and the supply curve too steep, then the equilibrium eliminates this hub activity.

This example is only illustrative and does not represent a practical airport situation. In practice, the complementarity caused by flight connectivity is not so strong and there exists no unique level of hub activies. Indeed, shutting one connection does not always simultaneously cause losses for all other connections. Flight connections may be clustered in several networks that are not too interdependent as it can be the case for connections to business and touristic places. The demand
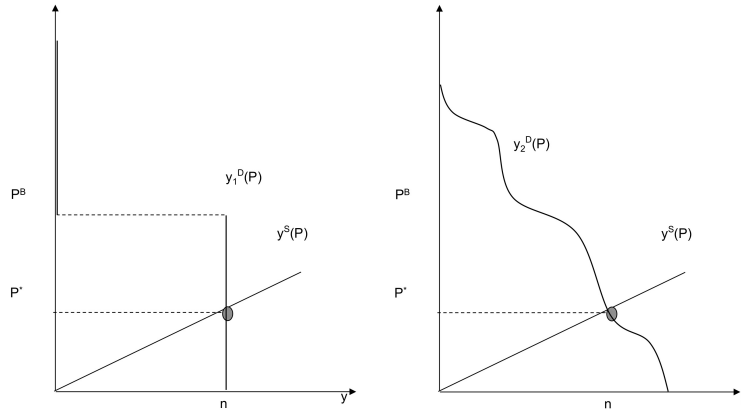
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Figure 13: Hub airports

for noise licenses more likely looks like the smooth curve $y_2^D(P)$ rather than $y_1^D(P)$. As a consequence, the introduction of noise license markets will certainly affect the airport hub activity level and triggers a series of flight connection shutdowns. It is, however, much less certain that it leads to shutting down of a hub airport. Finally, it is worth pointing out that such an effect does not hinge on the existence of noise permits market since a tax on flights yields the same effect.

3.5 Airport planning and extension

Noise licenses can be introduced in a new airport. In the past, noise and environmental issues have usually been dealt with by urban planers and political institutions who have enticed/imposed investors to set the new airport activities away from a dense urban area. New airports have been located away from dense areas (e.g. Mirabel in Quebec) or even on reclaimed land (e.g. Kansai in Japan) partly because of noise considerations. The above discussion about noise licenses directly applies to new airports. In this case, the airport investment decisions can be delegated to public investors as is usual but they can also be delegated to private investors who shall assess the profitability of their airport projects using their anticipation of the noise license market. Because noise licences oblige airlines to internalize the noise externality and reduce their willingness to pay for the airport infrastructure,

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they also oblige public or private investors to consider the noise damage around the airport. If investors anticipate correctly the noise license price, their decisions must correspond to the social optimal ones. In this case, the public and private investors also have incentives to make adequate environmental studies to measure the disutility of residents and the possible compensations. So, such studies can be left to the responsibility of the investors whenever they are public or private entreprises.

Nevertheless, most of the complaints on noise externalities concern airports that extend their activities. The above discussion about noise licenses also applies but brings about new features. To simplify our discussion we assume that an investment for y_1 aircraft movements has been sunk on a first terminal when the air traffic demand was low and that the demand is now high so that an investment K can be now made for a second terminal to expand traffic to y_2. We also assume that airport is non-profit and self-financed so that the investment cost must be covered by an airport tax t that applies to all aircraft movements. Indeed, although the privatization of some airport services has been in the air for two decades, airport infrastructure is usually planned by (local) governments. The same argument would, however, be made about a private investor who is imposed a regulated return-on-investment that caps her airport profits. (See Basso and Zhang, 2007, for a discussion about airports' objective functions). The new terminal investment is equal to $c(y) = K + vc * (y - n_1)$ where K is a fixed cost and vc a variable cost measured in terms of aircraft movements, which is typically the cost of a new gate divided by the total number of flights at this gate during the investment time period. The tax t must therefore be equal to the average investment cost $ac(y) = c(y)/y$ where y is the total number of movements. The fixed cost is usually more important than the variable cost so that ac is generally a decreasing function (which happens if $K > vc\ n_1$) but it can be an increasing function without loss of generality. The profit of each city pair connection y is given by $\pi(y) - P - t$ so that airlines serve city pair connections with profits higher than $\pi(y) > P + ac(y)$ where P is the noise license price. This is shown in Figure 14 where $d'(y)$ is the noise disutility, or the inverse supply of the noise licenses, $y^S(P)$. The equilibrium investment is reached at the capacity level y_2^*. This analysis allows us to make two points.

First, the presence of a noise license market diminishes the size of the airport extension $(y_2^* < y_2^o)$ because the noise licenses augment the cost of each flight and therefore force the least productive one out of the market. It can even block the airport extension if the capacity increase is not large enough. In Figure 14, this occurs when the past investment capacity y_1' is larger than the equilibrium capacity y_2^*. So, when the extension investment and the implementation of a noise license market are bundled, the investor must internalize the noise externality that was previously not considered. Second, the noise license market introduces a rent to
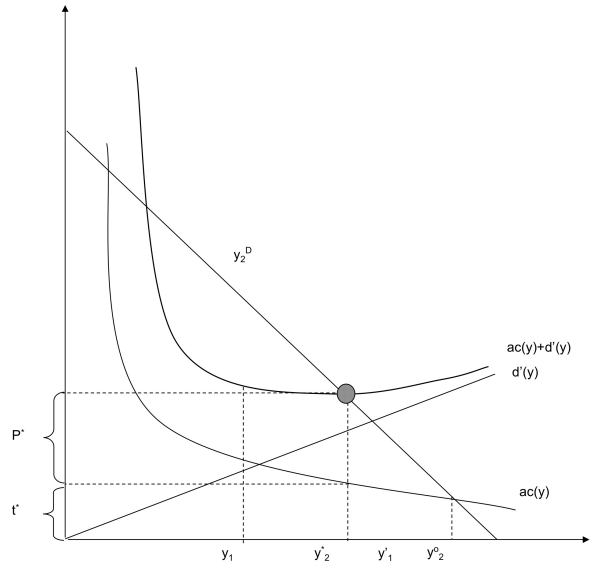
Figure 14: Airport extension

residents, $P^*y_2^*$, that encompasses all past and new aircraft movements. Residents are therefore compensated for a noise disutility that was already present. This could constitute an unfair windfall, in particular when noise disutility has already been incorporated into housing prices and cashed by residents who settled there when the noise was present. It is nevertheless possible to reduce this rent and to keep the properties of the market for noise licenses by restricting the compensation for noise licenses only to the new flights on the routes. This would give a rent to equal to $P^*(y_2^* - y_1^*)$ that would compensate only for their noise disutility caused by the new terminal. This however brings a revenue $P^*y_1^*$ that could be returned to the government, redistributed as lump sum to residents or airlines, or used by the airport facility.

To sum up, noise licenses can be embed in the planning of new airport or extension projects. The introduction of noise licenses generates a rent to residents. In the case of an extension project, this rent can be partly recouped by government or airport management by restricting the compensation for noise licenses to the only new flights. This leads us to the next section.

4 Taking residents characteristics into account

After having discussed how some features related to the airport (the demand side of the market) can be managed with the market for noise licenses, we now turn to some issues related to local residents (the supply side of the market). Three main issues deserve to be discussed: victim activism, the role of local representatives, and the management of the resident's rent associated to the market for noise licenses.

4.1 Victim activism

Under a market for noise licenses, the equilibrium shares the "victim activity" properties presented by Baumol and Oates (1988). In the short run, residents may take inappropriate decisions to increase their compensation from the noise licences. In particular, residents may avoid taking sound proofing measures. In the long run, individuals may prefer to stay in or relocate into noisy areas because of the compensation they can enjoy there. We here show that the argument of victim activism does not apply in the short run whereas it applies in the long run and calls for specific urban control measures.

It can be argued that noise licenses introduce some victim activism that diminishes incentives to invest in sound proofing measures. Accordingly, residents would increase the noise damage to collect additional compensation. This does not prove to be correct as the following simple model shows. Suppose that routes are represented by utilitarian representatives and that individuals could reduce the noise disutility by investing in noise protection measures. Each resident's disutility is given by $d_r(x, a, t)$ where x is the number of aircraft events, a is the soundproofing protection investment and t is the resident's distance on the route r. The disutility is assumed to increase in x and decrease in a while the marginal disutility of an additional flight on the route decreases with soundproofing $d_{xa} < 0$. The cost of the investment is assumed to be the increasing and convex function $c(a)$. Each city pair connection $x \in \Re$ brings a profit equal to $\pi(x)$. A utilitarian planner finds the number of flights y and soundproof protection $a(t)$ that maximizes

$$W = \int_0^y \pi(x)dx - \sum_r \int_0^T [d_r(x_r, a, t) + c(a)]\mathrm{d}t$$

subject to $y = \sum_r x_r$. This yields the first order conditions

$$d'_{rx}(x_r, a, t) = \pi(y) \quad \text{and} \quad d'_{ra}(x_r, a(t), t) = -c'(a(t))$$

Consider now a noise license market where route representatives decide about the soundproofing protection of each resident at location t. Let the noise license price be

P. At the equilibrium, the demand for noise license is given by $\pi(y) = P^*$. The objective of the route r's representative is $U(x_r, a(\cdot)) = -\int_0^T [d_r(x_r, a(t), t) + c(a(t))]\, \mathrm{d}t + Px_r$. At the equilibrium price P^*, they supply a number of noise licenses that satisfies $d'_{rx}(x_r, a, t) = P^*$ whereas they impose the soundproofing protection $a_r^*(t)$ at each location t such that $-d'_{ra}(x_r, a_r^*(t), t) = c(a_r^*(t))$. It is readily shown that this equilibrium replicates the socially optimal solution. The market equilibrium does not differ from the planner's if the representatives delegate the soundproofing decision to the residents. In this case, each resident i would set a^i such that $d'_{ra}(x_r, a^i, t) = -c'(a^i)$, which yields the same equilibrium.

By contrast, a noise license market does generate victim activity in the long run. Accordingly, any compensation scheme gives the wrong incentives to victims as they prefer to stay in or relocate into polluted areas because of the rents they can enjoy there. In the long run, this rent is capitalized in higher land prices and can entice land owners to divide their land plot in smaller parcels and invite new residents to live and collect a rent below a route. Picard and Bréchet (2010) present a long run equilibrium spatial model to highlight the negative long term effects of new residents' entry and landlords' choice of lot size or housing structure. They show that "victim activity" exists and needs to be addressed either by land planning restrictions and/or by fixing the number of individuals who are entitled to a compensation.

There nevertheless are several differences between the present setup and the traditional discussion about enviromental economics instilled by Baumol and Oates (1988). First, this traditional discussion focuses on Pareto optimality and does not consider agents' participation in the environmental program. In the case of airport noise pollution, the residents' agreement for the economic activity cannot be obtained without some form of compensation. In essence, environmental economics supposes some redistribution through lump sum transfers to residents before any environmental tax is implemented. To make residents participate the government must know the disutility profile of individuals along the routes, which raises issues about information collection and local politics (which we claim to avoid) as well as issues of victim activity. Second, traditional environmental economists derive and discuss extensively the value of the environmental tax but remain silent about how information about the benefit and damage of the polluting activity is collected and aggregated in a tax rate. Noise licenses attempt to correct this weakness. Compensation to victims is here unavoidable because it is a piece of the information revelation process. Third, many discussions about victim activism do not consider the entry of polluters in the area. In this model of noise licenses, airlines enter as long as city-pair connection flights are profitable.

4.2 Local institutions and representatives

A market for noise licenses is not exactly about giving the rights for quietness to residents, but it is about giving those rights to some local institutions that represent them along the routes that aircrafts take.

Those institutions first solve the problems of resident heterogeneity with respect to noise sensitivity. Noise sensibility depends not only on individuals' idiosyncratic physical and psychological characteristics, but also on housing characteristics and family status. For example, van Praag (2004) shows that adults raising children and living in houses attached with gardens are more sensitive to aircraft noise. The role of the representative is to aggregate individuals preferences and to arrive with reasonable bids for compensation. In the process of aggregating, the representative mitigates the extreme preferences for quietness. The representative can also distribute the compensation according to physical characteristics like the noise exposure, house characteristics, and perhaps family composition. Although this function can be performed by a central government, public economic theory suggests to delegate it to more local authorities or associations because of their better knowledge of local conditions. An additional political economic argument also suggests to delegate this function to local institutions because the local population may not be large enough to have electoral power on the central government and because the airport and airlines are less likely to lobby and to exert pressure on local institutions.

It is important to discuss the form of the local institutions representing the residents. Ideally, residents should be represented by a local planner minimizing the local aggregate noise disutility. In democratic countries, local institutions already exist as city councils, residents associations, communities, etc. When residents are able to elect their representative, the representative is more likely to behave according to the preferences of the median voter. In this case, the noise license market will deviate from the efficient result to the extent that the median noise disutility differs from the mean noise disutitlity. In particular, if a zone or a route includes a minority of population that is very much harmed by noise, its representative will accept more flights and noise events than would a utilitarian representative.

Finally, in a market for noise licenses, critical zones are the only binding zones so that they may have market power. Although the existence of several routes put the competitive zones in competitive environment, their small number may entice their representatives to collude and reach a different market outcome. However, the analysis of collusion among critical zones is similar to residents' monopsony analysis performed in Section 3 and explained in Figure 3. Collusion reduces the flight activity and augments the rents to residents living in the critical zones. In turn other zones also benefit from higher rents. An interesting question is about

how the dispersion of flight across routes is affected by this collusion. For the sake of the argument we can make the following simple analysis when *all* critical zones collude. For simplicity, let us suppose that the market design sets the same number of zone Z on each route and that the noise disutility is a quadratic function. Under collusion, all critical zones are represented by a single representative who maximizes the aggregate disutility of all critical zones

$$\sum_r U_{r\bar{z}} = \sum_r \left[\frac{Py_r}{Z} - d_{r\bar{z}}(y_r) \right] = \sum_r \left[\frac{Py_r}{Z} - \overline{\alpha}_r \frac{y_r^2}{2} \right]$$

subject to the demand for noise licences given by $\pi(P) = \sum_r y_r$. In this expression, $\overline{\alpha}_r$ expresses the aggregate disutility within the critical zone of route r. We can compute that under collusion the distribution of flights is given by

$$\frac{y_r^M}{y^M} = \frac{(Z\overline{\alpha}_r)^{-1}}{\sum_s (Z\overline{\alpha}_s)^{-1}}$$

which is the same as in the competitive equilibrium reported in equation (4) in Bréchet and Picard (2010). So, in this example there is no inefficiency in the route allocation.

4.3   Reducing residents' rents

With no market for noise licenses residents are simply harmed by noise pollution. By constrast, with such a market, residents are able to obtain a rent. The rent level can nevertheless be reduced by using other forms of market institutions like an auction. In particular, an institution that would allow airline companies to discriminate among the zones would diminish the rents to residents and would therefore allow a larger number of flights. We here briefly discuss this idea, which faces some difficulties. First, the auction should not only be discriminatory but also combinatory. Indeed, airlines companies must buy noise licenses over several zones by 'blocks'. Although such a feature is usual in electricity markets, it complicates a lot the implementation of a market and therefore reduces transparency and acceptability, in particular in the eyes of residents and their representatives. Second, the standard auction theory is developed for the sales of a fixed number of items. By contrast, the main focus of our paper is about endogenizing the number of noise licenses offered by residents. It is precisely the residents' ability to choose the number of noise licenses over their zones that creates their rents. The benefit of this ability is the revelation of their information about their actual noise disutility. Third, an auction could elicit information about airlines' flight profitability rather than about residents' disutility.

To make this idea clearer, let us suppose a unique route with two zones, each one holding a noise license. Then, a (combinatory) auction will give the two licenses to the airline company that bids the highest amount of money. The auction will thus have revealed the profit of airline companies and city-pair connections, but not the disutility levels over zones.

It is nevertheless interesting to pursue this strategy of a rent reduction by assuming the existence of an institution that is able to perfectly discriminate among residents. Therefore, airline companies are assumed to collude perfectly. We now want to stress that such an institution relaxes the residents' rents. Let us assume full information and full bargaining power to airline companies and let the zones' representatives be presented "take or leave it" offers that are tailored to the noise characteristics of their zone and that make them indifferent between aircraft noise and quietness. In our model, this implies that the zone z on route r has a utility equal to $U_{rz} = p_{rz}y_{rz} - \delta_{rz}y_{rz}^2/2 = 0$. The price of a noise license over the zone is given by $p_{rz} = \delta_{rz}y_{rz}/2$. Since the number of flights is the same for all zones z on route r ($y_{rz} \equiv y_r$), the price to fly over that route is equal to $P_r = \sum_z p_{rz} = (\sum_z \delta_{rz}) y_r/2 \equiv B_r y_r/2$. Because routes are substitutes, the price of any route should be equal so that $P \equiv P_r$. From this one can see that the flight spatial distribution over routes satisfies $B_r y_r = B_s y_s$, $s \neq r$, or equivalently, $y_r/y = B_r^{-1}/\sum_s B_s^{-1}$ where y is the total number of flights. It can be checked that the latter formula corresponds to the planner's optimal spatial distribution among routes (See equation (1) in Bréchet and Picard 2010). So, an institution that perfectly discriminates among residents does not alter the spatial distribution of aircraft activities. The total number of flights is given by the last city-pair connection that breaks even, $\pi(y) = \overline{\pi} - y - P = 0$, which is equivalent to

$$y = \frac{\overline{\pi}}{1 + (2\sum_s B_s^{-1})^{-1}}$$

This formula is identical to the socially optimal number of flights reported in equation (1) in Bréchet and Picard (2010), when the planner puts a weight on the airline activity that is the double of the one it puts on residents' disutility. In other words, in this simple quadratic model, an institution that would leave no rent to residents should be implemented by a social planner that values airline profits to the double of residents' disutility. If the planner values airline profits more than that, noise licenses are useless because the compensation required for residents' participation is too large.

5   Conclusion

Noise pollution is a hot and topical societal problem for all major airports. Whereas many airport authorities try to manage this problem using aircraft noise limitation, aircraft movement procedures and land planning, they do not use instruments that make airline activities internalize the noise disutility of the residents located below the takeoff and landing routes. By contrast, we propose to implement local markets for noise licenses as a way to allow airlines internalize their harm on residents. In those markets the supply of noise licenses is made by residents who are organized in geographical zones under the aircraft routes (e.g. municipalities, districts, communities, associations) and who are allowed to emit and sell noise licenses to airline companies. In the equilibrium, the prices of noise licenses reflect both the marginal noise disutility of residents in various zones and the smallest profit made by the aircrafts moving in and out airports. As the licenses for carbon or sulfur dioxide emission, noise licenses offer interesting efficiency properties.

In this paper we discuss various economic features of the management of noise license markets around airports. We argue that the implementation of such markets is robust to some important airport features. For example, aircraft heterogeneity can be dealt with by a system of noise quota counts and wind contingencies by the creation of formal or informal secondary markets for noise licenses. Noise licenses affect airport activity in the same way as an endogenous tax on aircraft movements. They therefore affect hub activities as a simple tax would do. When noise license markets are introduced after airport extensions, the rent to residents can be limited to the new aircraft activities. Nevertheless noise license markets raise some issues. Although noise license markets do not generate victim activity in the short run, they do so in the long run and necessitate specific urban planning restrictions around airports. Also, markets for noise licenses may conflict with airport managements as they reduce the latters' rents when their airports operate under capacity constraints.

At this stage of the discussion, we do not believe that the present economic theory of noise licenses can convince all the stakeholders involved in airport noise issues. We however advocate the economic instruments that allow polluting parties to internalize the harm on the victims have superior efficiency properties. Noise license markets are such instruments. They deserve a dedicated attention by policy makers and further research in the field of air transport management.

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