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Estelle Malavolti, Marion Podesta

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Estelle Malavolti*
Marion Podesta †

Preliminary version

Abstract

The air transport sector is going to enter the European Trading Scheme in 2012. The regulation of CO2 emissions is costly for airlines and modifies the organization of their market. Our paper proposes an economic analysis in which the regulation but also CO2 emissions of airlines are modeled. We show that, in a perfect competition setting, the difference between passengers carried without regulation and when the regulation is considered is negative for the best-performing planes. However, for the less efficient aircraft, the implementation of the regulation entails a reduction of airlines activity, and therefore a low level of carbon emissions.

JEL classification: L51, L93, Q53

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*TSE-ENAC, estelle.malavolti@enac.fr
†TSE-ENAC, marion.podesta@enac.fr

1 Introduction

Since the Kyoto Protocol in 1997, several governments have made significant progress toward improving air quality. In this sense, the air transport sector in Europe will be fully included in the European Union Emissions Trading Scheme (EU-ETS), in 2012. Despite the relatively low level of greenhouse gas emissions (only 3% of the total European emissions), this sector has known a rapid growth until recently: from 1990 to 2005, the EU aviation emissions increased by 87% and it is expected to double from now to 2020 (See Commission Staff working document 2006 and EU directive 2003/87/EC). On top of this, the air transport sector is also responsible for other releases like nitrogen oxides, water vapor or noise, which effects are not easy to account. Nevertheless, a regulation of these external effects is to be expected. It is thus important to evaluate which impacts a regulation may have on the market and its organization.

The environmental literature defines pollution as an externality which is not taken into account by the market. Several instruments have been put forward (taxation, subsidies, norms or allowances trading) resulting in State intervention, and the literature deeply analyzes the efficiency of these different tools (see for instance Myles, 1995 or Salanié, 2003). Our work builds on this general literature focusing on the specificities of the air transport sector to model the impact of an environmental regulation. The environment problems have raised several questions. For instance, Portney (2005) makes a review of the existing regulations and tries to evaluate what will be the regulations of the future. Among the economic tools used to regulate, the taxation is the means which has the most received attention. Barthold (1994) presents the different taxes used for environmental regulation and their efficiency to regulate emissions.

The European Commission would include aviation sector in the EU-ETS from 2012 in relation to the airlines' carbon emissions. The aim of carbon markets is to provide incentives to reduce CO2 emissions. The environmental problems have raised several questions. Scheelhaase and Grimme (2007) focus on financial impacts to include aviation in the ETS on airlines. They show that the financial impact on airlines subject to the ETS is relatively moderate. Since the regulation concerns all flights departing from and arriving at EU airports, Scheelhaase and al. (2010), under a model-based empirical estimations, analyze how the EU directive affects competition between european and non-european airlines and if competition distortions are likely to appear. They compute fuel consumption, CO2 emissions and number of allowances to know the difference between allowances allocated free of charge and the total amount of them needed by the airlines (with a price assumed to €20 per ton of CO2 and two scenarios considered for emissions growth). Moreover, regarding consumers' surplus, they show that the impact on prices is relatively moderate.

On an macro-economic view, Anger (2010) shows that there is not expected to have a negative impact of the EU-ETS on economic growth in the UE or to reduce the UE's competitiveness relative to the rest of the world. However concerning the impact of EU-ETS on the carbon emissions, the results are ambiguous. Mayor and Tol (2007) find a negative impact on the carbon emissions whereas Anger (2010) concludes in a positive way. It seem difficult to have an economic model which combine the regulation of EU-ETS, the financial impact on airlines and the level of carbon emissions.

In this sense, we built an economic model which offers a precise framework of nonetheless the regulation but also of emissions of airlines. The regulation system includes two different elements: the first element concerns free allowances that will be given to airlines according to their current activity. The second element is the payment of rights to pollute on the CO2 market. There is a strategic stake in the setting of the "free of charge" quotas, since their number depends on the activity of the airlines: with this system, the airlines will receive a number of rights to pollute proportional to their activity. On the other hand, the rights to pollute, i.e. the internalization of the pollution, will represent an additional cost, which will be higher, the higher the activity. As a consequence we have paid very much attention to the modelization both of the regulation and of the production of emissions. We model the emissions as a joint product of the airlines activity that comes from the use of the fuel. Models of joint production are presented for instance by Baumgartner et al. (2000, 2003). Hence a particular attention is given to the estimation of the fuel cost function, which is calibrated using real data. We chose to model the EU-ETS as an increase of the variable cost, which means that it can be similar to a tax (or a subsidy) on the airline activity, because the regulation is designed as such. A particular attention is given to the study of the use of the fuel by airlines because of its direct relationship with CO2 emissions (See the IPCC report 1999 for an evaluation of the impact of aviation on global atmosphere and the EU Directive 2007/589/EC for the determination of a precise coefficient linking fuel consumption and CO2 emissions). Harris (2005) makes an exhaustive analysis of the US airlines operational costs. Miyoshi and Mason (2009) focus on the evaluation of the carbon emissions of airlines. They propose an original methodology to compute these emissions. They distinguish between short, medium and long hauls and they take into account the load factor, however in our paper we model it. Therefore, we use our method to evaluate the emission,[1] but the contribution of our paper is more on the economic modelling of the EU-ETS consequences on airlines and therefore on their strategies. Our paper is also directly related to papers such as Viera et al. (2007), in which the authors emphasized the importance of having several instruments to reach efficient result. By focusing on the current regulation and trying to describe it as close as possible from the reality, we propose a more positive view. Hofer et al. (2009) try to reach the same aim with the taxation in the US, however no economic model is presented in their paper. Finally, our model is the extension of the paper of Albers et al. (2009) and Anger

[1]See in appendix A.

and Kholer (2010) which try to evaluate the impact of the EU-ETS on airlines. Again, no economic model is presented in this literature.

We will focus on the regulation of CO2 in EU and try to model it as faithful to reality as possible, the following section presents the system of European Union Emissions Trading Scheme. In section 3, we introduce a modelisation of the EU-ETS system and we show stylised facts on some financial consequences for airlines. This section ends with the equilibrium of the economic model in which we derive the results and give interpretations. The final section presents some concluding remarks.

2 On CO2 emission trading scheme in EU

The European Union Emissions Trading Scheme (EU-ETS), created in 2003 (EC, 2003) and implemented in 2005, is the first international trading system for carbon dioxide (CO2) emissions in the world. The aim of carbon markets is to provide incentives to reduce CO2 emissions. This system was implementable between european countries under several measures. Allocation is a unique feature of cap-and-trade systems. Indeed, a critical issue in dealing with climate change is deciding who has a right to emit carbon dioxide (CO2), under what conditions, and to what extent those emissions are limited. The EU-ETS is the first instance of creating explicit rights to emit CO2 and distributing these rights among sub-national entities. One of the main measures in the EU-ETS is to provide free allowances. The cap for these free allowances in the aviation sector will be limited to 97% of an annual rate of reference from 2012 and this limit will be restricted to 95% from the period 2013 to 2020.

Moreover, the system was able to take advantage of the experience of the United States in the field of the acid rains. The US's success with sulphur dioxide emissions trading provides to European economists insights to apply to the European situation and provides to, in the Member States and the Commission, a body of literature and individual experiences to learn from. The EU-ETS program was divided into two phases, a pilot phase (2005-07) and a second or "Kyoto" phase (2008-12) to ensure a quality program.

The allocation methodologies applied by the 25/27 participating nations were remarkably similar. Four choices seem particularly interesting:

- Auctioning was only little used. One of the most striking features in the EU allocation process was that most Member States chose not to take advantage of the Directive's provision allowing states to auction up to 5% of allowances in Phase I and 10% in Phase II.

- Strong reliance on recent historical emissions. The disparity between advocacy and practice was in no aspect greater than for benchmarking. Benchmarking was strongly advocated however little used, which is a striking difference from US practice.

- Expected shortage was allocated to the power sector. Another distinctive feature in the EU allocation process was that the power sector was compelled to bear almost the entirety of the emissions reduction burden. When a Member state was short on allowances, this shortage was almost entirely allocated to the power sector.

- Highly novel new entrant/closure provisions. All Member States have set up reserves for new entrants, and most require closed facilities to forfeit post-closure allowances, even though there are significant differences between the specific Member State choices.

The first lessons of the pilot phase are that the European Commission has harmonized allocation rules across Member States and has tightened the carbon constraint in Phase II. Moreover, free allocation does not necessarily lead to "windfall profits" and first studies, as presented in the next section, show that the increase of costs due to CO2 regulation affect consumers' price but firms do not put the total cost on prices. Finally, new entrant/closure provisions provided perverse incentives. Indeed, the main effect of these provisions was to preserve pre-policy incentives to invest in polluting technology.

Concerning the quantity of allowances exchanged, these quantities in 2005 was relatively low at 262 Mt. Trades increased nearly fourfold by 2006, when 809 Mt were exchanged. The maturation of the market was confirmed in 2007, when almost 1 500 Mt were traded. These transactions are made with an average price of €22 per tonne in 2005, therefore the allowance transactions totaled €5.97 billion during the year. This total increased to €15.2 billion in 2006 before reaching €24.1 billion in 2007.

Once quantities exchanged are estimated, the EU allowance (EUA) price can be fixed. This price is determined by the equilibrium between supply and demand. Between the phase I and II, EUA price tends to decrease nearly to zero due to surplus saved on the period 2005-2007. Phase I allowance prices' fell under 1 €/tCO2 in February 2007 and ended 2007 at 0.02 €t/CO2. Finally, The EUA prices for 2008-2012 remain stable and reach a peak at €25.

Therefore, the collapse of the first period carbon price has not jeopardized the expansion of the trading scheme. This is probably one of the most impressive results of this first trial period: all the big industrial and financial partners now accept that carbon is no longer free in Europe and that the carbon emissions will continue to be costly in the future.

Finally, concerning the level of carbon emissions, we can conclude that a modest amount of abatement occurred in 2005-2006. In a preliminary but detailed analysis of this data, Ellerman and Buchner (2010) concluded that a reasonable estimate of the reduction in CO2 emissions attributable to the EU-ETS lies between 50 and 100 Mt for each year, or between 2.5% and 5% from what emissions would have been without the EU-ETS.

The EU-ETS system is the first carbon market and is now implementable in the aviation sector. To know how is the impact of this regulation on the airlines, consumers' surplus or CO2 emission, we present the economic model.

3 Model Settings

3.1 The Emission Trading Scheme regulation

Airlines are responsible for externalities such as pollution (NOx, CO2, noise...) congestion and accidents. These externalities have social costs which differ from individual costs. For instance, the air transport sector produces CO2 emissions while the Society would prefer a lower level of these emissions. The levels of production of CO2 differ because the air transport sector is producing CO2 at a zero cost while the Society values negatively the emissions of CO2. The Society would be willing to pay to reduce the level of CO2 emissions. The problem is that the market failed to take into account the social costs and finally, a public intervention is needed because the right level of production is not reached. The economic literature suggests different instruments like norms or emission quotas (regulation in quantity) or taxes or subsidies (regulation in prices) to consider social costs (as pollution). The European Commission has chosen to create a market for pollution in order to make firms buy the rights to pollute. This market for allowances is thus used to regulate the CO2 emissions. The principle is simple: The regulator sets a maximum quantity of CO2 emissions tolerated by the Society for a given period (generally a year) and firms exchange rights to pollute. On this market, there will be firms from different sectors, sectors which pollute and thus have to buy for their emissions and sectors which receive rights because they pollute less than what they are entitled to emit. Airlines will be included in the European cap-and-trade system starting 2012.[2] They thus will have to pay for their CO2 emissions and follow a certain path in terms of reduction of their CO2 emissions. The principle of the regulation is to give part of the total emissions of a given airline for free and to let it buy on a market the rights to pollute for the other part of its emissions. As it is costly, one expects airlines to take measures to reduce their emissions. 85% of the allowances will be given for free. The EU defined a benchmark of emissions which corresponds to the average of the emissions calculated for the period 2004 to 2006. The target of the regulation is then to reduce the emissions with respect to this average level by 3% for the year 2012 and by 5% beyond 2012. The CO2 emissions are depending directly on airlines activity: the more activity, the more they have to pay. It is thus important to define precisely a measure of the activity of the airlines. The indicator which we choose as relevant is a weight and distance indicator. Indeed the CO2 emissions depends proportionnaly on the quantity of fuel used. This quantity itself is sensitive to

[2] For a detailed description of the legislation, see http://www.euractiv.com/en/climate-change/aviation-emissions-trading/article-139728.

the distance covered together with the weight carried. Therefore the relevant measure is expressed in tons times kilometers. Let us define W_i as the activity of airline i expressed in tons.km (one passenger with his luggage stands for 100kg) during a given time period (typically one year). Airline i will thus receive a share of its yearly activity RW_i for free, where R is defined as follows:

$$R = r\lambda c_{ETS}$$

r is the target of reduction of the regulator. It equals $0.97 * 0.85$ for the year 2012 and $0.95 * 0.85$ beyond 2012.

λ is a constant which represents the tons of CO2 emitted by burning one liter of fuel. It equals $2.52 * 10^{-3}$tons of CO2/l.

We define c_{ETS} as the average consumption of fuel (expressed in liters of fuel per tons.km) for the benchmark period 2004-2006.

R is thus the benchmark used by the regulator to set up the emissions it authorizes for a given period. R is constant for all the airlines. Their emissions rights are adapted with respect to their activity (W_i).

As a consequence, each airline i has to buy exactly $\lambda W_i(c_i - rc_{ETS})$ allowances, where c_i corresponds to its average consumption of liters of fuel per tons kilometers over the given period.[3] The number of allowances asked to each airline relies on the efficiency of the airline. Indeed, it is not only relying on the activity of the airlines, which would have pushed airlines to increase their activity. The allocation also depends on the distance between the average fuel consumption of the airline and the benchmark chosen by the ETS, which is calculated over all the airlines for the period 2004-2006. If airline i is more efficient than the benchmark, which means that its fuel consumption is lower than the average consumption, airline i receives allowances which will be sold on the market. On the contrary, if the airline fuel consumption level is higher than the benchmark, airline i has to buy allowances. At this stage, the number of allowances depends also on the global activity of the airline, which creates a leverage effect. The cost of the emissions of an inefficient airline which operates a lot will be very high. These costs will result in adjustments for airlines in terms of technical progress or different strategies. Indeed, the renewal of the fleet, the modernization of the equipment, the optimization of the planes' trajectories, as well as the reorganization of the network, the reallocation of the planes are the different actions an airline can take.

[3]The average consumption of fuel is computed as follows, for airline i, which operates J routes $c_i = \frac{\text{conso of fuel for all } J \text{ routes}}{\sum_j W_{ij}}$, with $j = 1, ..., J$.

3.2 Stylised Facts

Once the system of regulation described, the first question which seems interesting is the evaluation of the cost of this regulation. Indeed, the airlines will go from a situation in which they were not paying for their pollution to a situation in which they will have to pay for their emissions if not sufficiently efficient. This will necessarily modify the market organization, adding costs that will be probably passed on to consumers. In this section, we aim at giving a first evaluation of the cost or benefit of the ETS regulation for some of the airlines for which we have the CO2 emissions for 2008 (source: carbon disclosure project).

Airlines performance

Airlines	RTK000 (2008)	Emissions2008 (tons)	Fuel cons.(l)	c_{avg} (l/RTK)
Easyjet	4012513	4307000	1709126984	0.4259
Air France-KLM	29284393	27506144	10915136508	0.3727
British Airways	15228809	16840627	6682788492	0.4388
Iberia	5910594	5839469	2317249603	0.3920

The first column concerns the Revenue Ton Kilometers which stands for the total carried mass (passengers and luggage, cargo and freight) on the network of a given airline. This variable represents the activity of the airline since the fuel consumption which explains the CO2 emissions is highly related to the weight carried over the network. These figures come from the ENAC database. The RTK include the whole network for a given carrier. However some of the airlines have part of their network outside the perimeter of the regulation. This is for instance the case of BA or AF-KLM. The figures are probably too high (and thus the cost or benefit probably too optimistic), since the emissions are considered for Europe. We are nevertheless not able to obtain exactly the figures corresponding to the relevant area of the ETS. From the figures on the emissions, we can derive the fuel consumption for the current year (2008). The (technical) coefficient used is denoted λ which value is 2.52×10^{-3} tons of CO2/liter. The average consumption of fuel c_{avg} expressed in $l/tons \times km$ is then easy to compute. The average consumption is used to compare to the EU benchmark in order to determine whether the regulation is a cost or a benefit. If c_{avg} is lower than c_{ETS}, the airline will receive allowances to be sold on the market. Its profits will be higher due to its efficiency with respect to the other airlines.

Exogeneous data	
c_{ETS} (l/RTK)	0.4724
benchmark = 85% $\times$ 95%c_{ETS}	0.3814
λ (T_{C02}/L)	0.00252
CO2 price p_a	€13

The benchmark of the European Commission is not available yet. We decided to rely on Airbus analysis of the fuel consumption for the year 2007, i.e. $c_{ETS} = 0.4724l/RTK$. The price of the allowances chosen is the average one for 2009, i.e. 13€. This price is relatively low, due to the worldwide recession for 2008-2009 and a slowdown in the demand, which relax constraints in the energy market. The entry of the airlines on the market for allowances together with an expected economic upturn suggest to interpret our result as a lower bound for the costs/benefits for airlines.

Extra consumption for airlines

Airlines	Efficiency measure (%)	Cost per pass km	Total cost in €
Easyjet	0.0445 (+12%)	0.015	5850244
Air France-KLM	-0.0087 (-2.3%)	-0.00285	-8346052
British Airways	0.0574 (+15%)	0.0188	28630161
Iberia	0.0106 (+2.8%)	0.0035	2052489

In the first column, we define an efficiency measure based on the distance between the average fuel consumption and the benchmark. We then can estimate the total cost (or benefit) of the regulation by multiplying by the price of allowances. We add a column to measure the cost with respect to one passenger km carried, considering that the whole activity (RTK) are explained by passengers carriage.[4]

AF-KLM is the only airline to have an average consumption just below the benchmark. It will thus receive more free allowances than needed to cover its emissions and will be able to sell them on the market. With an allowance price of 13€, it will receive 8.3 Million euros from the sale. However, we have considered the whole activity of AF-KLM (world wide) which is higher than the one for the european market. For instance, if we make the assumption that the RTK for Europe represents 90% of the total RTK, the difference between the average consumption and the ETS benchmark would amount +0.033l/tkm, which means a cost instead of a benefit of 28,27 Million euros. This remark suggests the importance of the reliability and precision of the RTK figures together with the CO2 emissions. This suggests as well that an economic model focusing on the exact modelling of the ETS and activity of the airlines would help explaining the driving forces at play.

Easyjet and British Airways are poorly efficient and will have to pay for this lack of efficiency. The amount is very important for BA since its activity is very much higher with respect to Easyjet. It represents for instance 2.7% of the total revenue of BA.[5] Iberia is close to the ETS benchmark, even though a little above, which means that it will have to pay for allowances.

[4] One passenger amounts 100kg.

[5] We can not easily compare with operating results since they are negative in 2009.

If we make the assumption that the average length of a flight is 1000km for Easyjet, the additional cost for this trip is thus 15€, which is quite important. For BA, taking a 6000km trip would add 113€ to the operating costs, which is very important. For Iberia, taking the same distance would lead to an additional cost of 21€, which is far less. This discrepancy is problematic since it will create among the airlines very important competitiveness problems. For an economist point of view, it is very interesting to find the reasons of why there so many differences among the carriers. However, what remains is that the truthfulness of the figures has to be ensured because the impacts are very substantial.

In order to make further comparisons, we compute the same tables using the figures from RDC report[6] for the CO2 emissions of 2009 (exactly from march 2009 to march 2010). These figures are an approximation realized by RDC according to the network, the fleet, the number of flights... Our results are presented in the following table:

[6] European Emission Report. Quarter 1-2010 in RDC Aviation.

Airlines performance

Airlines	RTK000 (2009)	Emi.2008 (tons)	Emi. 2009, tons (ev.)	Fuel cons.(l)	c_{avg} (l/RTK)
Easyjet	3722220	4307000	7753817 (80%)	3076911508	0.8266
AF-KLM	28770277	27506144	26407231 (-4%)	10479059921	0.3642
BA	14520041	16840627	18645484 (11%)	7399001587	0.5096
Iberia	5481678	5839469	8768755 (48%)	3479664682	0.6348
Lufthansa	21313185	na	19093956	7576966667	0.3555

Before interpreting this table, two remarks have to be made: at first, the emissions of Easyjet are very different in 2009. The evolutions of carbon emissions between 2008 and 2009 are given in the third column with the variable ev. We observe an increase of 80%, which cannot be explained neither by technical reasons, nor economical reasons. This figure has thus to be taken into account with much caution, especially because it will translate into huge costs. The same remark can be made in a lower range however, to the figure concerning Iberia. There is a difference of 48% between the emissions of CO2 in 2008 and 2009, with no reason apparently. The data on the CO2 emissions are not easy to obtain and what airlines have declared does not seem to correspond to what RDC model has computed. For instance, Easyjet seems to be poorly efficient in 2009 with respect to 2008. Nothing can explain this change: its fleet is very young, its network has not changed and its load factor is high.

Extra consumption for airlines

Airlines	Efficiency measure (%)	Cost per ton km	Total cost in €
Easyjet	0.4452 (+117%)	0.01458	54269968
Air France-KLM	-0.0172 (-4.5%)	-0.000562	-16168896
British Airways	0.1282 (+34%)	0.0042	60984172
Iberia	0.2534 (+66%)	0.0083	45505514
Lufthansa	-0.0259 (-7%)	0.00085	-18116207

AF-KLM and Lufthansa are pretty efficient and receive allowances. However the area of the activity considered (RTK) are overestimated because it includes other traffic than simply european traffic. BA and Iberia are less efficient apparently, even though we are not able to explain why. The recent merger between the two carriers and the restructuration will probably help improving these figures.

The diversity of the figures according to the years considered so as the different sources suggest that a deeper analysis is needed. Building an economic model in which different levers are present will help to identify the problem and the solutions adopted by airlines.

3.3 The Cost Function

The regulation of the CO2 emissions means additional costs for airlines. These costs are related to their activity because of the regulation itself and because the regulation is associated to their fuel consumption. Hence, the relevant costs to be taken into account are the variable costs. There are several variable costs to be considered like labour costs, fuel costs, maintenance... depending on the time horizon considered (annual or infra-annual). One important element of these last years is the fuel consumption cost. Indeed, it has increased from 10% in 1994 of the total operating costs to 33% in 2008.[7] The air transport sector is also well known for the importance of its fixed costs, like the investment in planes, like administrative costs (to develop a network) or marketing costs. The fixed costs occur in the decision of launching an activity or entering a new market. Once engaged, what matters to determine firms strategies are the variable costs. In our economic model we will consider only variable costs and analyze the impact of the regulation on the determination of airlines activity: will they carry more or less passengers? according to which strategies? how will they modify their network?

The total costs function of the economic model is composed of three parts: the fixed costs, the variable costs concerning the fuel consumption and the variable costs due to the regulation. Let us define:

$$TC_i(q_i, d_i) = FC_i + C_{F,i}(q_i, d_i) + X_i(q_i, d_i),$$

where FC_i represents the fixed costs, $C_{F,i}(q_i, d_i)$ is the total fuel cost of airline i and $X_i(q_i, d_i)$ is the emissions cost of airline i. The activity of the airline is a combination of the tons carried, denoted q_i and the expanse of the network, denoted d_i for airline i.

At first, fixed costs are normalized to zero for each airline because we consider the situation of an airline which has its own network. Fixed costs will be reintroduced to consider the decision to extend a network or even maintain a given route afterwards. The economic model aims to show how the current activity of airlines is impacted by the new regulation.

As we focus on the regulation and its financial impact, we restrict our attention to the sole variable costs which are directly related to the regulation itself, i.e. the fuel costs. The fuel costs are depending on the price of the fuel denoted p_F which is given on the crude oil spot market. It increased continuously since 1994 to 2008 and now is more stable, due to the world recession. Nonetheless this price is structurally going to raise again because of non-renewable resources and increasing world demand, putting pressure on airlines for a better use of the kerozen. The other two parameters which determine the fuel costs, are the expanse of the network which expressed as a distance variable denoted d_i, and the

[7] Source: AEA and EIA forecasts.

activity on a network measured by the number of passengers carried expressed in tons, q_i.[8] Over a network, the fuel consumption is not homogeneous. Indeed, for a given route, the take-off is the phase of time which consumes more fuel. Differences also exist with respect to the distance of a given route: a long haul flight uses less fuel than a short haul flight per ton km. One reason is technical: as the take-off phase consumes more, it can be less amortized if the flight is short. Moreover, on a long haul flight, it is easier to optimize the fuel consumption as the cruise phase is longer. We have chosen to focus on the problem of capacity. Indeed, the airline supply on a given network is not fully adjustable because of the given capacity of aircraft. For instance if an airline owns 2 planes of equal capacity, let say 100 passengers for each, if the demand is 90 then only one plane is needed and the load factor is 90%. However if demand is 110, then the airline has to put one other plane and the load factor decreases drastically (110/200=55%). This has to be taken into account in the costs and especially in the fuel costs since there is a certain amount of fuel to be carried to fly with a zero mass (when the plane is empty) and the marginal cost of carrying one more passenger is also increasing since more power is needed to carry a higher mass. We thus choose the following fonctionnal form to represent the cost function:

$$C_{F,i}(q_i, d_i) = kC_{fuel,i}(\frac{q_i}{k}, d_i),$$

where q_i is the activity of airline i (in tons carried), and k is an integer, d_i is the scope of the network. This function is defined for all $(k-1)q_p < q \leq kq_p$, where q_p stands for the maximum seats offered for one plane (we assume that the fleet is composed of homogeneous planes of equal maximum capacity measured in tons). The total fuel cost is thus a piecewise function, increasing in q_i. The fuel cost function is also increasing with the km covered d_i. Besides we define:

$$C_{fuel,i}(q_i, d_i) = C_0(d_i)(1+a)^{q_i}$$

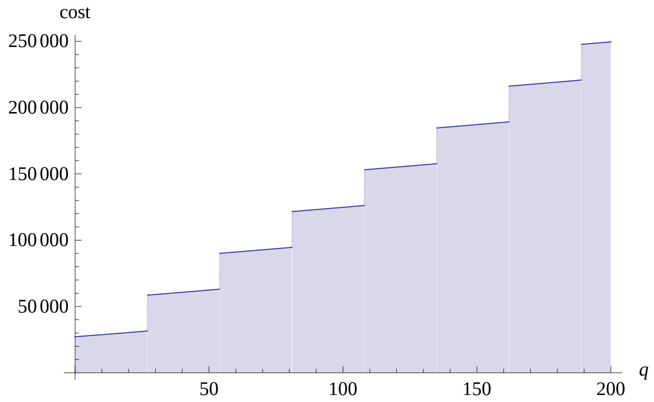
where $C_0(d_i)$ represents the minimum cost to be supported if one plane is used. It corresponds to the consumption cost for the route with all the carried staff and cargo but without passenger, on a given distance d_i. a is an efficiency measure of the aircraft fuel consumption. It corresponds to the fuel consumed for one passenger added in the plane. a is assumed to be small and can be checked empirically. We assume besides that the whole influence of parameter d_i is captured in C_0 and will use several values of this parameter to calibrate the model. For sake of simplicity, we use a Taylor series development and will use the following functionnal form[9]:

$$C_{fuel,i}(q_i, d_i) = p_F F_0(d_i)(1 + aq_i + \frac{a^2 q_i^2}{2}).$$

[8] A passenger with his luggage amounts 100kg.

[9] For a detailed analysis, see appendix 1.

For instance, if the plane (with a capacity of 270 seats) is such that the minimum quantity of fuel needed to travel is $F_0 = 68000$l, knowing that the average fuel price for 2009 is $p_F = 0.4$€/l, and taking the overconsumption due to one additional passenger to be equal to $a = 0.0055$.



$X(q_i, d_i)$ allows to take into account the cost due to the regulation of the ETS in aviation. This function is built in order to measure the additional cost incurred by the regulation. This cost depends on the activity and on the fuel consumption. It is in fact a measure of the distance between the emissions of the airline on the route expressed as a function of the fuel consumption and the emissions tolerated by the regulator, which we introduced in the previous section. The average fuel consumption of airline i, for a given network, is thus $c_i = \frac{C_F(q_i,d_i)}{d_i q_i p_F}$ and the regulation cost can thus be defined as follows:

$$X(q_i, d_i) = p_a(\frac{\lambda C_F(q_i, d_i)}{p_F} - Rq_i d_i),$$

where p_a is the price of an allowance in the market. Airlines are price taker, they do not have any influence on it. p_F is the price of the fuel, given on the market, R equals λrc_{ETS} as defined in the previous section. $X(.)$ can be positive or negative depending on whether the airline has a fuel consumption respectively above or below the benchmark. If the spot price of the emission rights p_a is higher, the costs of the regulation becomes more important if the airline has to buy rights. The airlines have thus an interest in forecasting properly the price of the allowances. The two instruments of the regulator to set a certain level of R are the target coefficient, r which is supposed to decrease over the years and the benchmark evaluation of the fuel consumption of airlines. If the price of the fuel p_F is higher, then the $X(.)$ function is less likely to be positive. Indeed, a low fuel price relaxes the constraint of being more efficient in using fuel. If the fuel costs are higher, then the costs of the regulation are also higher. It means that a less efficient firm will support higher costs for the regualtion of its emissions. Eventually, if the activity of the airline increases, then the fuel costs increase but the free allowances as well. There is a trade-off between increase of the fuel cost and free allowances, and the problem for the airlines is if the fuel costs increase at a higher rate than the activity.

4 Equilibrium

We first analyse a situation in which airlines are competing *à la Bertrand* on a given city pair. This means that parameter d is exogenously given. Firms are then price takers and their goods are perfect substitutes for consumers. The maximization program is thus

$$\begin{aligned} &\underset{\{q\}}{Max}\Pi(q) = pq - TC(q) \\ s.t. \quad &TC(q) = FC + C_F(q) + X(q) \end{aligned}$$

The first order conditions give

$$p = \frac{\delta C_F(q)}{\delta q} + \frac{\delta X(q)}{\delta q}$$

The airlines equalize what selling one ticket (or pricing one additional ton carried) yields to what it costs at the margin, i.e. the supplementary fuel consumption needed to carry this additional passenger (or ton) plus the additional regulation cost (if the carrier is less efficient than the average) or minus the benefit (if the carrier is more efficient than the average). Taking into account the definition of function $X(.)$, the expression writes:

$$p = (1 + \frac{p_a}{p_F}\lambda)\frac{\delta C_F(q)}{\delta q} - R$$

This equation corresponds to the supply of each (identical) airline. The demand is assumed to be linear[10]:

$$p = A - Bq,$$

where A and B are positive. A corresponds to the willingness to pay of consumers. Parameter $A(d)$ corresponds to the maximum price consumers want to pay for a given network (it can be not only an origin-destination but an aggregate network). It stands for their willingness to pay and is a representation of their preferences. This maximum price is increasing with the scope of the network. We do have typically very few information on the value of this parameter. Some airlines run surveys in order to learn about this value. However the information is quite difficult to estimate. B is a measure of the sensitivity of the variation of the price to a variation of the quantity. It is a very important parameter for the airline because while choosing a quantity to supply (or equally a price to fix), B is a measure of what reduction in the price is needed to attract one more passenger. We

[10] The demand is linear to make the model more tractable but results are robust to a log-linear shape of the demand.

make the assumption that demand is influenced by the distance parameter through A and consider that the consumer's reaction to a modification of the price is not infuenced directly by the destination chosen. More precisely, it means that the willingness to pay for a trip from Paris to San Francisco is assumed to be higher than the one for a Paris-Madrid. However, the sensitivity to the price is kept constant.

The equilibrium quantity is then[11]

$$q^{PC} = \frac{k(A - aF_0(p_F + p_A\lambda) + c_{ETS}dp_Ar\lambda))}{(Bk + a^2F_0p_F + a^2F_0p_A\lambda)}.$$

The quantity at the equilibrium depends on different sets of parameters. The first set of parameters includes technical variables, like k, F_0 and a. These parameters are linked to the technical efficiency in using fuel and capacity of the airline. Hence, they allow to take into account the technical progress that airlines may incorporate into their production process. For instance when an airline decides to renew a plane, both coefficient F_0 and a are modified to take into account a more efficient fuel consumption. Parameter k changes to take into account both the change in capacity and the induced modification of the load factor. The regulation levers are the price of an allowance p_a, the average consumption c_{ETS} used as benchmark and the target r. A strict regulation will be for instance a higher price of allowances, induced by a lower quantity of emissions rights decided by the European Commission. It also corresponds to a lower cap set r. Even though the regulator cannot play with all the instruments at the same horizon, it is still interesting to analyze the impact of a variation of the different parameters. Indeed, r is fixed till 2020 by the law and c_{ETS} is computed according to the past activity of airlines. However, the price of allowances p_a can be decided on a year basis. Finally, parameters A and B influence the demand and therefore the choice of equilibrium. For instance a positive demand shock would translate into a higher A (maximum of demand). Parameter B measures the sensitivity to a variation of the quantity of the variation of the price. The more sensitive the consumers' demand, the lower the ability of the airline to set a higher price at equilibrium.

If the airline chooses a more efficient plane with a lower F_0, the number of passengers carried at the equilibrium is higher. More activity is reached due to a better use of fuel. Coefficient a plays in the same direction as well: a lower a means a higher efficiency which enables the airline to carry more passengers. When the capacity of the plane k is increased, the quantity is increased at the equilibrium to take into account the cost of a having a "bad" load factor. A more stringent regulation resulting in an increase of the price of allowances p_a leads to a lower activity for the airline. If the average fuel consumption c_{ETS} decreases, the quantity decreases as well at the equilibrium. The effect of the target

[11] The second order condition is satisfied by the assumption made on the cost function: increasing at an increasing rate.

r plays in the same direction: if the regulator decides to strengthen the regulation (lower r), then the impact on the quantity is negative and less passengers are carried at the equilibrium. The price of the fuel has the same impact in our model than the price of an allowance: the higher the fuel price, the less the quantity. It is important to note that in our model, a partial taxation of the fuel price would have the same kind of effect than the ETS system. If demand increases, for example with a higher A, then the quantity at the equilibrium increases. If demand is less sensitive to the price, the airline is then able to set a higher price for the same quantity or to increase the quantity at the same price. Finally, d stands for the distance of the destination considered or more generally the scope of the network of a given airline. Parameter d has an influence on the choice of parameter F_0 because every type of plane will not be able to operate every destination. Without regulation, the airline programme is the following:

$$\begin{aligned} &\underset{\{q\}}{Max}\Pi(q) = pq - TC(q) \\ s.t. \quad &TC(q) = FC + C_F(q) \end{aligned}$$

The solution of this programme offers an interesting benchmark to evaluate formally the impact of the regulation on the activity. After computation, the solution is:

$$q^{PCN} = \frac{k(A - aF_0p_F)}{(Bk + a^2F_0p_F)}.$$

Proposition 1 *The regulation can have a positive impact on the activity of the airlines. The effect depends on the parameters.*

Proof. We compute the difference between the quantities with regulation and without regulation. This difference is

$$q^{PCN} - q^{PC} = \frac{kp_a\lambda(aBF_0k - Bc_{ETS}dkr + a^2F_0(A - c_{ETS}dp_Fr))}{(Bk + a^2F_0p_F)(Bk + a^2F_0(p_F + p_a\lambda))}$$

The denominator is always positive, for all acceptable values of the parameters, thus the sign depends only on

$$(aBF_0k - Bc_{ETS}dkr + a^2F_0(A - c_{ETS}dp_Fr)).$$

Note that this expression is not depending on the price of the allowances. On the contrary, it depends on the price of the fuel which has a negative impact on the difference. Indeed, an increase of the price of the fuel has more influence on the quantity without the regulation, it decreases faster. The technical parameters (a and F_0) are more likely to have a negative impact: if the plane chosen is less efficient (higher a and or F_0) then the difference is positive. Finally, if the regulation is less strict (higher benchmark c_{ETS} and or higher target r) the difference is more likely to be negative, since the quantity with regulation increases, while the other quantity is not impacted. We cannot say much more since there are too many parameters in the model. To go further we have to specify more and explore the relationship between these parameters. This is what we do in the following section. ■

Whether to know if the quantity of equilibrium is lower in case of regulation is not fully trivial. It is not clear whether this quantity is lower or higher to the quantity with regulation since the ETS can be either a cost or a benefit for the airlines. The regulation has been set in order to limit the CO2 emissions, which leads, if no technical progress is incorporated or simply available, to a direct decrease in the activity of the airlines. This result is thus all the more counterintuitive. However, it is due to the design of the regulation, which induces airlines to increase their activity in order to cover the cost of the regulation. Finally, results depend on the parameters values and we take several examples to illustrate the situation. They are presented in the following section.

5 Scenarii

The first parameters we set are the regulation, the price of the allowances and the price of the fuel.

Exogeneous data	
c_{ETS} (l/RTK)	0.4724
$r = 85\% \times 95\%$	0.8075
λ (t_{C02}/L)	0.00252
CO2 price p_a	€13
Fuel price p_F	€0.4/l

The other parameters we have described (technical, demand) are not completely independent of the distance parameter which is considered as exogenous in this model. Indeed, on a long haul trip, the plane chosen will have different technical characteristics (F_0 and a) than on a short haul. The plane is typically larger when the distance is higher, which goes with a higher 'fixed' consumption of fuel i.e. with a zero load factor (higher F_0) and with a lower marginal consumption of fuel (lower a). For the moment, we cannot give a functionnal form to model the influence of the distance on the technical characteristics. We thus chose to distinguish two cases: a long haul trip, with a given distance and evaluate for what pair of technical parameters (a, F_0) the quantity with regulation is higher. Moreover, the demand is also influenced by the distance because the willingness to pay for a long trip will be higher than for a short trip. For this reason, we decide to examine two opposite cases: the first situation corresponds to a long haul flight, the second to a rather short haul flight.

5.1 Long haul scenario: Paris-San Francisco example

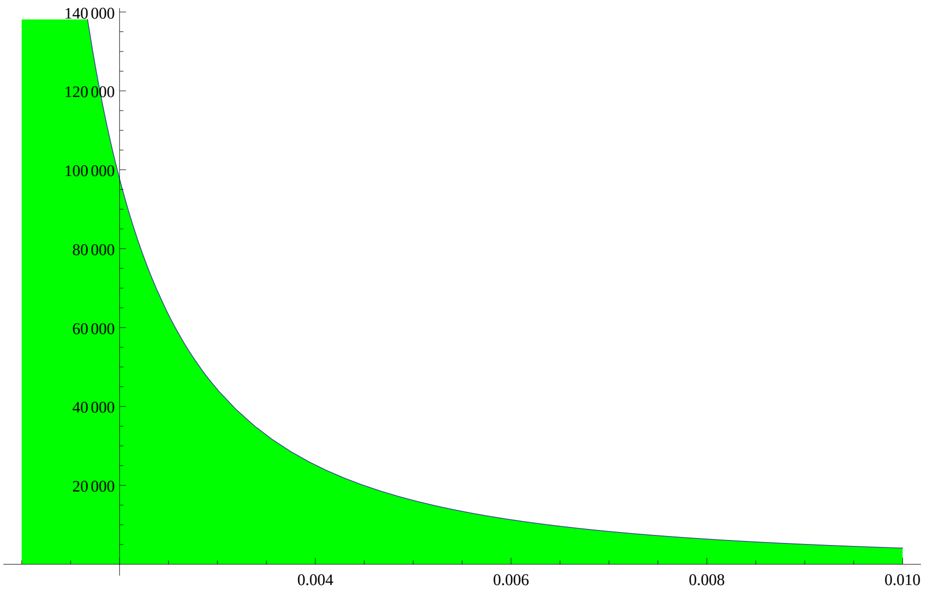
The distance between Paris and San Francisco is 9000km, thus we set $d = 9000$. The demand function is defined for a one way trip. It is the residual demand, given all the other costs especially variable costs (cabin crew, maintenance, catering...), thus the maximum demand is lower than the one addressed to the company[12]. We chose to set $A = 8000k$. Parameter k intervenes since the demand is defined by plane. k represents the number of planes used at the equilibrium to carry the optimal number of passengers and cargo, the maximum demand has thus to be multiplied by k to be homogenous. For simplicity, we set $k = 1$.

We chose to take two values for the sensitivity of the demand to the price. We consider first a demand which is rather inelastic, i.e. $B_1 = 0.8$. We then consider a rather elastic demand $B_2 = 1.2$.

Lemma 1 *The regulation leads to more activity when the airlines use efficient airplane. For instance, for an elastic demand, $B_2 = 1.2$, the equation gives*

$$q^{PCN} - q^{PC} \geq 0$$
$$\Leftrightarrow F_0 \geq \frac{2746.53}{0.8a + 6626.73a^2}$$

The following figure illustrates this situation. Results are robust to the assumption of inelastic demand.



For example, if the airlines use a A340 to operate the route Paris-San Francisco, the technical characteristics are: ($F_0 = 68000$, $a = 0.0055$). Then the difference is positive: the airlines reduce their activity due to the regulation.

[12] Our simulations are however robust to a large range of maximum demand and elasticity. We tried to make the examples as realistic as possible though. The simulations files are available upon request.

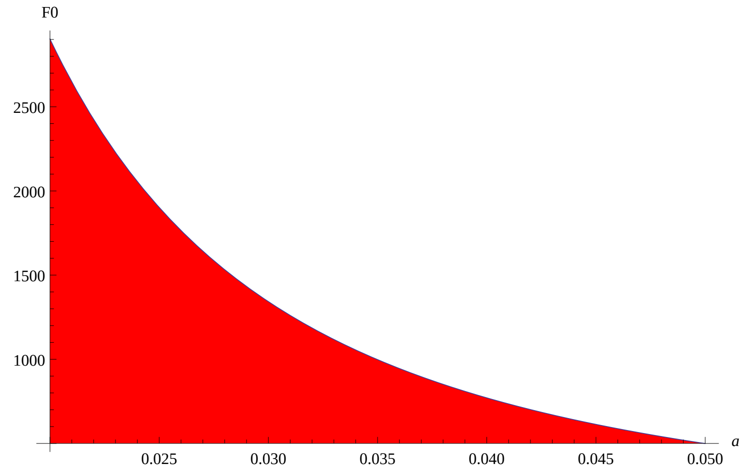
5.2 Short haul scenario: Paris-Madrid example

Let us now set $d = 1300$. The corresponding maximum demand is lower than for the long haul trip, around €500 per ton km, thus $A = 500k$. For simplicity, we present only the case for which $k = 1$. Both situations, elastic demand and inelastic demand are analyzed, but we present the results for an elastic demand, since results are consistent with an inelastic demand.

Lemma 2 *The regulation leads to more activity when the airlines use efficient airplane. For instance, for an elastic demand, $B_2 = 1.2$, the equation gives*

$$q^{PCN} - q^{PC} \geq 0$$
$$\Leftrightarrow F_0 \geq \frac{396.722}{0.8a + 301.639a^2}$$

The following figure illustrates this situation.



6 The duopoly situation

In this section, we study a duopoly situation where two airlines compete on a given network. We consider that distance is exogeneous, however in the sequel we will remove this assumption. Now consumers have the choice among different airlines. Each consumer can choose between two options of consumption according to their preferences. The preferences of consumers depend of intrinsic characteristics. Both airlines offer a journey, and consumers choose either one firm or another one depending of their preferences.

In the economic literature, there exist two types of differentiation.[13] The goods can be horizontally differentiated or vertically differentiated. The horizontal differentiation means that consumers have differences of opinion, even if prices are the same, some consumers

[13] This distinction is given by Lancaster (1966).

prefer buying from firm 1 and some from firm 2. Whereas, vertical differentiation expresses that goods have different quality, if prices are the same then every consumer prefers buying from the higher quality firm and latter holds onto some consumers even if its price is higher than its competitors. For instance, horizontal differentiation corresponds to the situation when an identical good is sold in different areas of a town (but at the same price), all consumers located in one area prefer to buy in their own area whereas to buy from other retailers. The horizontal differentiation is associated to spatial models introduced by Hotelling in 1929. The vertical differentiation corresponds to the case where there are some variants of a good, for instance high quality variants ("luxury") and standard quality. Sold at a same price, all consumers prefer to buy the luxury variant. The competition between firms when goods are horizontally or vertically differentiated is different and entails specific consequences in each case.[14]

In our model we consider that both airlines offer an horizontally differentiated good, and consumers purchase either from firm i or firm j, with $i, j = 1, 2$. Each consumer consumes one unit of one variant between the set of possible outcomes.

The introduction of competition allows us to better understand the reality of aviation sector.

- **Expliquer la demande: comment on modélise la concurrence**

We still consider that consumers' demand is linear and given by:

$$P_i(q_i, d) = A(d) - Bq_i + Eq_j$$

where $i, j = 1, 2$ with $i \neq j$. As in the previous section, $P_i(q_i, d)$ is the consumers' demand for firm i. The parameter $A(d)$ corresponds to the maximum consumers' willingness to pay for a given network. Quantities q^i and q^j are imperfectly substitutes for consumers and the relative degree of substitutability is given by B/E.

6.1 Duopoly with regulation

The airlines' costs are the same than previously and symmetric for each firm. The profit function is the same for both firms, therefore we can write the maximisation program of an airline i as:

$$\underset{\{q_i, q_j\}}{Max} \Pi_i(q_i, d) = P_i(q_i, d)q_i - TC_i(q_i, d)$$

$$s.t. \quad \begin{cases} P_i(q_i, d) & = & A(d) - Bq_i + Eq_j \\ TC_i(q_i, d) & = & FC_i + C_{F_i}(q_i, d) + X(q_i, d) \end{cases}$$

[14] For more details, see Gabszewicz and Thisse (1979, 1980) and Shaked and Sutton (1983).

with $i, j = 1, 2$. The first-order condition is the same than in monopoly context but now demand takes into account competition:

$$P_i^{'}(q_i, d) + P_i(q_i, d) = C_{F_i}^{'}(q_i, d) + X^{'}(q_i, d)$$

The maximization program gives us the quantity for airline i (and it is symmetric for airline j):

$$q_i^* = \frac{k\,(A + p_a r\lambda c_{ETS} d - F_0(d)a(p_F + p_a\lambda))}{k(2B - E) + F_0(d)a^2(p_F + p_a\lambda)}$$

As in the perfect competition situation, this quantity depends on the different sets of parameters. There are technical variables: k, $F_0(d)$ and a which refer directly to fuel consumption and capacity of the airline. For the regulation constraints, p_a is the price of allowances fixed by the market, c_{ETS} is the average consumption and r the target decided by european authorities. Finally, parameters $A(d)$, B and E influence the demand and the level of equilibrium. The equilibrium profit is given in the appendix.

We can compare the sum of quantities in duopoly with the monopolist quantity:

$$(\sum_{i=1}^{2} q_i^* - q^E) = \frac{k\,(A + p_a\, r\lambda c_{ETS} d - F_0(d)a(p_F + p_a\lambda))\left(k(2\,B + E) + F_0(d)a^2(p_F + p_a\,\lambda)\right)}{(k(2B - E) + F_0(d)a^2(p_F + p_a\,\lambda))\,(2\,Bk + F_0(d)a^2(p_F + p_a\,\lambda))}$$

The total quantity in duopoly is more important than the one in monopoly situation. As the monopoly is a price maker, it restricts its quantity to charge a higher price. The competition entails higher quantities and this quantity effect leads to decrease prices.

6.2 Duopoly without regulation

When we consider the case where European Comission do not regulate aviation sector, we can rewrite the maximization program without cost of regulation:

$$\underset{\{q_i, q_j\}}{Max} \Pi_i(q_i, d) = P_i(q_i, d)q_i - TC_i(q_i, d)$$

$$s.t. \quad \begin{cases} P_i(q_i, d) & = & A(d) - Bq_i + Eq_j \\ TC_i(q_i, d) & = & FC_i + C_{F_i}(q_i, d) \end{cases}$$

At the equilibrium, quantity is given by:

$$q_i^0 = \frac{k\,(A - p_F F_0(d)a)}{k(2B - E) + p_F\, F_0(d)a^2}$$

We can compare the situation with and without regulation to show its impact on quantities:

$$(q_i^* - q_i^0) = -\frac{kp_a\lambda\,\left[k(2B - E)(F_0(d)a - rc_{ETS}\,d) + F_0(d)a^2(A - rc_{ETS}\,dp_F)\right]}{(k(2B - E) + F_0\,a^2(p_F\, + p_a\,\lambda)\,(k(2B - E) + p_F\,F_0(d)a^2)}$$

This difference depends on the sets of parameters defined previously. To be continued...

7 Conclusion

At the beginning of the application, the EU will create an ex-ante benchmark *"so as to ensure that allocation takes place in a manner that provides incentives for reductions in greenhouse gas emissions and energy efficient techniques, by taking account of the most efficient techniques, substitutes, alternative production processes, efficient energy recovery of waste gases, use of biomass and capture and storage of CO2, where such facilities are available, and shall not provide incentives to increase emissions"* [source: European Directive]. Our economic analysis shows that the introduction of the ETS system tends to increase the airlines activity for the more efficient aircraft: more passengers are carried at the equilibrium. This result is due to the particular shape of the ETS cost function X, which we have modelled as closely as possible from the real system. Now, airlines cope with the necessity to improve their load factor and their consumption per tonne.kilometer. However, for all less efficient planes, the introduction of the regulation tends to decrease the airlines' activity and therefore to reduce the greenhouse gas emissions. For future research, we will endogenize the expanse of the network in a two-stage game since this variable is very important in the definition of the parameters, especially the technical ones.

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A Fuel cost function

We detail the fuel cost as a function of d, the distance of the route, q, the tons carried and p_F, the fuel price. The function $C_F(q, d, p_F)$ is defined as the fuel cost consumption for a given aircraft and a given route expressed in €. To design this function, we need to define variables and functions $C_0(d, p_F)$, a, q_p, which qualify an aircraft characteristics and performances.

- $C_0(d, p_F)$ is the consumption cost for the route with all the carried staff and stuff but without any passenger (with a load-factor equivalent to 0).

  $$C_0(d, p_F) = F_0(d) \times p_F,$$

  where $F_0(d)$ is the fuel consumption for the route with all the carried staff and stuff but without any passenger (with a load-factor equivalent to 0). This function is a non-linear function of variable d, the distance covered. $F_0(d)$ is expressed in liters so as $C_0(d)$.

- a is a parameter modeling the over-consumption due to an additional passenger (marginal cost). We assume that a is constant.

- q_p is a parameter modeling the aircraft capacity of passengers expressed in tons.

Besides, we introduce $C_{fuel}(q, d)$ which represents the fuel cost function of the aircraft carrying $q \in [0, q_p]$. We precise that we have $C_{fuel}(q, d) = F_{fuel}(q, d) \times p_F$ with $F_{fuel}(q, d)$ the total fuel consumption.

With a given aircraft, one cannot carry more passengers than the initial capacity. If $q > q_p$, the airline needs to use more than one aircraft or to use several times the same. If total demand is q and $q > q_p$, the airline must use at least $E[q/q_p] + 1$ aircraft to carry the passengers where $E[q/q_p]$ is the integer part of q/q_p. We will consider the airline uses exactly $E[q/q_p]+1$ aircraft, especially because of the fixed costs, with the same load-factor equivalent to $\frac{q}{(E[q/q_p]+1)qp}$. We define $C_{fuel}(q, d)$ as follows:

$$C_{fuel}(q, d) = C_0(d)(1 + a)^q,$$

with $a > 0$ and close to 0[15].

When a passenger is added to the flight, the airline needs more fuel because of two physical reasons. Firstly, more passengers means more on-board mass (100kg per passenger), so that the aircraft mass increases and it needs more power to fly. The airline has to take more fuel on board. Secondly, in aviation, we need to board fuel to the propulsion needs. Indeed, because of the fuel mass increases, the aircraft consumes fuel to transport

[15] See ENAC study for the fuel consumption in the air transport sector.

fuel. These two physical reasons illustrate the shape of $C_{fuel}(q,d)$. Moreover, parameter a is positive but close to 0. Indeed, the experience shows that additional passenger makes the necessary mass-fuel to increase however not tremendously because of the significant aircraft mass alone.[16]

The parameters which differentiate two aircraft with the same capacity are $C_0(d)$ and a. $C_0(d)$ and a are given by the aircraft manufacturers and the fuel market. Hence, an airline's fuel cost results of two factors : the price of fuel and the fuel efficiency. For sake of simplicity, the shape of $C_{fuel}(q,d)$ is approximated using the Taylor series, as $a > 0$ and close to 0, and with $0 < q \leq q_p$:

$$(1+a)^q = 1 + \sum_{i=1}^{n} \frac{1}{i!}(\prod_{j=0}^{i-1}((q-j))a^i) + o(a^i)$$

up to the second order, it is equivalent to:

$$(1+a)^q = 1 + aq + \frac{a^2 q(q-1)}{2!} + o(a^2).$$

Thereby, the cost function writes for $q \leq q_p$:

$$C_{fuel}(q,d) = C_0(d)(1 + a(1-\frac{a}{2})q + \frac{a2}{2}q2)$$

which we can simplify the expression (since a small and $a \simeq a(1-\frac{a}{2})$). Therefore we obtain:

$$C_{fuel}(q,d) = C_0(d)(1 + aq + \frac{a^2 q2}{2}).$$

Let us define function $C_F(q,d)$ which is the total fuel consumption over a network. $C_F(q,d)$ is actually a piecewise function since there exists a discontinuity in the capacity of aircraft. When the airline needs to use an additional plane, it might not be full and thus the cost is more than the double of the cost of one full plane. The total fuel cost, $\forall k > 0$ and k integer number $\forall q \in [(k-1)q_p, kq_p]$, can be rewritten as:

$$C_F(q,d) = k \times C_{fuel}(\frac{q}{k}, d).$$

For example in the model, if $q \in [q_p, 2q_p]$ thus $C_F(q,d) = 2 \times C_{fuel}(q/2, d)$. Total costs of engaging an additional plane (if not full) are increasing with the activity and distance.

B Equilibrium quantity

B.1 Linear function

We compute the first and second-order conditions to find the optimum of the profit function:

[16] Notice that in the model we consider a flight without wind and in the standard flight conditions.

$$\max_{\{q\}} \Pi(q) = \max_{\{q\}} P(q,d)q - TC(q,d) = \max_{\{q\}} P(q,d)q - FC - C_F(q,d) - X(q,d).$$

As $C_F(q)$ is a piecewise function equivalent to $kC_{fuel}(\frac{q}{k},d)$ on the interval $[(k-1)q_p, kq_p]$ with k integer, we consider:

$$\exists k \geq 0 \quad q^E \in [(k-1)q_p, kq_p].$$

The first order condition gives:

$$\frac{\partial \Pi(q)}{\partial q} = A(d) - 2Bq - C_0(d)k(\frac{a}{k} + \frac{a^2 q}{k^2})(1 + \frac{p_a}{p_F}) + Rd = 0.$$

The second order condition is such that:

$$\frac{\partial^2 \Pi(q)}{\partial q^2} = -2B - \frac{a^2 C_0(d)}{k}(1 + \frac{p_a}{p_F}) \leq 0.$$

As $\frac{p_a}{p_F} \geq 0$, $a^2 \geq 0$, $C_0(d) \geq 0$, $k > 0$, $B > 0$ then $\frac{\partial^2 \prod(q)}{\partial q^2} < 0$, which means that the program is concave.

At the optimum, marginal revenue equals marginal cost, i.e. $P(q,d) + qP'(q,d) = C_F(q,d)$ with

$$A(d) - 2Bq = C_0(d)k(\frac{a}{k} + \frac{a^2 q}{2k})(1 + \frac{p_a}{p_F}\lambda) - Rd.$$

At the optimum, when $q^E \in [(k-1)q_p, kq_p]$ we have:

$$q^E = \frac{k(A(d) + Rd - aC_0(d)(1 + \frac{p_a}{p_F}\lambda))}{2Bk + a^2 C_0(d)(1 + \frac{p_a}{p_F}\lambda)}$$

When we introduce $R = \lambda c_{ETS} r$, we have

$$q^E = \frac{k(A(d) + \lambda c_{ETS} r d - aF_0(d)(p_F + p_a\lambda)}{2Bk + a^2 F_0(d)(p_F + p_a\lambda)}$$

The equilibrium quantity is thus q_E when it is positive, which introduces a constraint

$$q_E \geq 0$$

$$\Rightarrow A(d) + r\lambda c_{ETS} d \geq aF_0(d)(p_F + p_a\lambda)$$

This condition is fulfilled if the market is sufficiently wide (high $A(d)$) so that the airline can have space to launch the activity. It corresponds for example to a sufficiently large network (high d). If the condition is not satisfied, then the equilibrium quantity is 0. The benchmark situation corresponds to the non regulation case in which the airline maximizes its profit:

$$\underset{\{q\}}{Max}\Pi(q) = P(q,d)q - TC(q,d)$$

$$s.t. \quad \begin{cases} P(q,d) &= A(d) - Bq \\ TC(q,d) &= FC + C_F(q,d) \end{cases}$$

The first order condition gives:

$$P'(q,d)q + P(q,d) = C'_F(q,d)$$

which leads after simplifications to:

$$q^0 = \frac{k(A(d) - aF_0(d)p_F)}{2Bk + a^2F_0(d)p_F},$$

where d is given.

B.2 Duopoly

Equilibrium profit with regulation is given by:

$$\begin{aligned}
\Pi_i(q_i,d) \quad = \quad & \frac{1}{2}\frac{1}{(k(2B-E) + F_0(d)a^2(p_F + p_a\,\lambda))^2} \\
& + kF_0(d)a^2((p_F + p_a\,\lambda)(A^2 + 2Ap_a r\lambda c_{ETS}d) + p_F p_a^2 r^2\lambda^2 c_{ETS}^2 d^2 + p_a^3 r^2\lambda^3 c_{ETS}^2 d^2) \\
& - kF_0(d)a^3(2Ap_a^2\lambda^2) \\
& + kF_0^2(d)a^3((p_F + 2p_a\,\lambda)(-2\lambda p_a r c_{ETS} d p_F - 2Ap_F) - 2p_a^3 r\lambda^3 c_{ETS}d) \\
& - kF_0^3(d)a^4((p_F + p_a\,\lambda)3p_F p_a\lambda + p_F^3 + p_a^3\lambda^3) \\
& + k^2F_0(d)a((p_F + p_a\,\lambda)(-4B(A + \lambda p_a r c_{ETS}d))) \\
& - k^2F_0^2(d)a^2((p_F + p_a\,\lambda)^2(6B - 4E)) \\
& + 2k^2B(\lambda p_a r c_{ETS}d\;(2A + \lambda p_a r c_{ETS}d) + A^2) \\
& - k^3F_0(d)((p_F + p_a\,\lambda)(8B^2 + 2E^2 - 8BE))
\end{aligned}$$

- **Parametre important (2B-C) qui doit être positif: qu'est ce que ça veut dire?**

Equilibrium profit without regulation is the following:

$$\begin{aligned}
\Pi_i^N(q_i,d) \quad = \quad & \frac{1}{2}\frac{1}{(k(2B-E) + p_F F_0(d)a^2)} \\
& - 2k^3 p_F F_0(d)(E(4B+E)) + 2k^2 p_F^2 F_0^2(d)a^2(-3B + 2E) \\
& - k(p_F F_0(d)a^2(p_F^2 F_0^2(d)a^2 + A^2 - 2Ap_F F_0(d)a)) \\
& + 2k^2AB(A - 2ap_F F_0(d))
\end{aligned}$$