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Split incentive problem in the uptake of new ATM technology

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Abstract—*We analyse the problem of split incentives between Air Navigation Service Providers (ANSP) and airlines in adopting disruptive technologies. We develop a simple theoretical model which allow us to analyse the uptake of technologies based on the potential efficiency gains of both the ANSP and the airlines. Next, we illustrate this model numerically. Our first, intuitive, result is that while regulation of navigation fees is necessary, it also hinders the investments in new technologies. Secondly, we see that the uptake of technologies would be faster in a one-to-one setting. Thirdly, it is not certain that increased competition between ANSPs will stimulate innovation. Finally, an overall technological mandate can be welfare improving as it reduces uncertainty.*

Keywords-air traffic control; technology uptake; innovation, split-incentives; network effect

I. INTRODUCTION

The air transport industry is facing a host of new challenges. Airlines are going through an era of strong competition, while at the same time facing new restrictions related to climate change and a dwindling capacity for slots in airports. The SESAR Joint Undertaking leverages the latest digital technologies to improve European’s aviation infrastructure, focusing on combining future growth with safety, efficiency and minimal environmental impact. This strongly centers on technologies that automate, virtualize and enhance digital connectivity in air traffic management (ATM). However, despite all the efforts undertaken, the results have not lived up to the expectations [1].

Researchers and stakeholders alike [2] point to the high level of protection that surround ATM management. The sector is still dominated by national monopolies and strong labor unions [3]. There is a general lack of customer awareness and competition. This is shown to affect the uptake of disruptive technologies [4], which has led some researchers [5] to propose regional forerunners to adopt new technologies and/or increase competition between providers [6]. Other reasons for the slow pace in technology adoption are the very demanding safety requirements and the host and variety of the stakeholders

Economic based research on the topic of Air management has mainly focused on the economic mechanism for handling the problems of the high delay costs in the European airspace. In [7] they focus on the optimal charging of the Air Navigation Service Provider (ANSP). In [8] they argue that a slot allocation system and a First Planned First Served allocation could reduce delay costs. [9] considers more general networks and allows for oligopolistic markets. The authors derive, under which conditions the uptake of the Master Plan could be encouraged. They found that tendering rights for air traffic control services can lead to a better uptake of the Master Plan.

This paper focusses on the specific characteristics of ATM technologies and how these characteristics could be an obstacle to their uptake. Indeed, many ATM technologies possess some specific characteristics, namely: (i) often both the ANSP and the airlines need to make an investment, (ii) there is an imbalance in the allocation of benefits and costs as most of the investment costs are often born by the ANSP, while it is the airline that will enjoy most of the benefits and (ii) ATM technologies often display network features, in which the full benefits of upgrading a system are only realised if the whole network is upgraded leading to externalities and hence non-optimal investments.

Within the economic modelling we use the CPDLP messaging system as an example, although the model is applicable to other technologies with similar features. CPDLP is a text message transmission between aircraft and ground control. It has the possibility to drastically increase efficiency of air traffic control, by standardizing operational control messages. CPDLP communication can offer a solution by increasing the effective capacity of the communication channel, the number of flights one controller can handle, and the cost efficiency of the ANSP. The main implications for the airlines are that they will suffer less delay costs and rerouting will be minimized. Airlines are then able to use their preferred route and will not incur extra fuel costs. The ultimate result being a reduction of the operational and delay costs for the airlines. Given the benefits of the technology for both ANSP and airlines, the uptake remains below expectations. Given the benefits of the technology, the uptake remains below expectations. We combine modelling with numerical analysis to get a better insight in this problem. We develop a simple model that uses elements of principal-agent modelling, game theory and transport economics to analyze the uptake of certain technologies based on the potential efficiency gains by both ANSP and airlines.

We start from a simple set-up with a single ANSP and airline. We then enrich the model by allowing multiple types of airlines. This adds realism to the model as it introduces competition between airlines and allows us to gain insight in the difference in reaction of low-cost carriers (LCC) or legacy carriers (LC). In our last step we generalize the model even further considering two ANSPs, either in serial or in parallel connections on the same origin and destination. This is inspired by how transport network capacity decisions are reached. As the ANSPs will need to recuperate at least a part of the cost of the investment in new technologies, both the structure of the market and the possibility of an airline to reroute are taken into account in this model variant.

II. Model

We consider four economic agents: the regulator, ANSPs, airlines and passengers. The regulator (e.g., EUROCONTROL) can impose policies and rules on the ANSPS and the airlines. These can be monetary incentives, such as subsidies, or certain mandates or price regulations such as caps on the navigational charges etc. The ANSPs provide ATM services to the airlines in return for navigational charges and finally, the airlines provide air kilometres to the passengers in return of ticket fares. (1)The model could be modified to include airports instead of airlines but to keep the analysis as simple as possible we focus on the interaction between airlines and ANSPs.

Our model is set up within a two-stage game (summarised in Figure 1). In a preliminary stage, the regulator sets the rules or policies. These are taken as exogenous to our model. In the first stage, the ANSPs set the navigational charges and will decide whether to adopt the new technology or not. We consider several ways in which the ANSP set its charges; one option is to assume the current situation where the ANSP is allowed to set its charges as to recover its costs, another option is to impose a cap and finally we also look at the possibility that there are no restrictions and the ANSP simply maximizes its profits. In the second stage, airlines chose the desired flow to maximize its profits and make investment decisions. In the version of the model where we consider a simple network, the airlines will also choose its route.

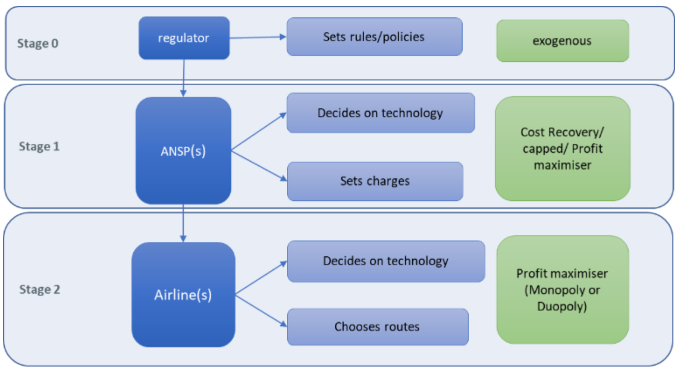

Figure 1: Two stage game and agent's decision tree

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III. Simplest set up: one airline and one ANSP

In this section we consider the situation where there is only one ANSP and a single airline using the airspace. Both the ANSP and the airline decide whether to invest in the new technology, but the technology only brings benefits when both agents adopt it. The technology is such that the ANSP faces a substantial upfront investment cost in terms of new equipment while the airline's investment costs are more moderate. Both parties benefit from the new technology through a reduction of operating costs such as labor costs and maintenance for the ANSP and fuel and delay costs for the airline.

To finance the large investment costs, the ANSP is allowed to recuperate their costs through higher en-route charges but are restricted by national price caps. We consider the case where the agents have perfect knowledge about the benefits and costs for the other agents and where the ANSP can be considered as a first mover.

A. The airline

We assume one airline (or multiple homogenous airlines) serving a single market, i.e. using the airspace of a single ANSP between a single origin-destination pair. For analytical purposes we assume linear demand and cost functions. The inverse demand for trips is given by

$$P = A - Bq, \tag{1}$$

where q is the number of trips served by the airline and both A and B are positive demand parameters. We assume a fixed load factor per flight and thus the number of flights will be proportional to the number of passengers, and we can express everything in terms of passenger km without loss of generality.

The airline total costs (TC_A) consist of three categories; a variable cost, a fixed cost and a cost associated with congestion. Variable costs are the sum of the direct operational costs (c_A) such as fuel, labor and maintenance and the navigational fee (τ) which the airline pays to the ANSP for the ATC services. Navigational fees accounts for up to 10% of the variable costs [9]. The fixed costs (FC_A) are the non-operating costs (also called overhead costs) such as acquisition of aircraft or investment in infrastructure or technology. Fixed costs are typically high in the airline industry and can make up more than 50% of the total costs [10]. Finally, the delay or congestion costs increase the costs per flight proportional to the number of flights (or passengers) and depends on the available capacity. We assume a linear marginal congestion cost, with congestion parameter ϕ, such that the total congestion costs are a quadratic function of the demand. This set-up was also used in [9].

The CPDLP technology reduces fuel and congestion costs for the airlines whilst requires investing in new equipment and retrofitting aircrafts. The technology will, however, only be beneficial if the ANSP has also invested in the technology. Denote k the decision variable for the airlines and K the decision variable of the ANSP so that $k = 0$ (or $K=0$) if the airline (or ANSP) chooses not to invest and $k = 1$, (or $K=1$), if the airline (or ANSP) do invest. The airlines revenues are determined by the demand times the average fare p per passenger kilometer and the profit function (Π_A) is then simply given by deducting the total costs from the revenues:

$$\Pi_A(K,k) = pq - [c_A(K,k) + \tau(K)]q - \frac{\phi(K,k)}{2}q^2 - FC_A. \quad (2)$$

Airlines are profit maximizers and will choose output (number of passenger kilometers) to maximize profits. When operational costs or the navigational charge decreases, prices decreases and output increases. In the presence of congestion costs ($\phi>0$), the price will be higher, as the monopolist airline absorbs the full congestion cost in the price. Hence there is no congestion externality in this case. If both the ANSP and the airline invest in the new technology, the operational costs decreases whereas the navigational charges increase. The relative importance of the two effects will determine whether output increases or decreases and the airlines need to weigh up both effects. Whether the airline has an incentive to switch to the new technology will depend on the overall benefits it can gain.

B. *The ANSP*

In this simple model we consider only one ANSP which acts as a private monopoly. Indeed, their fixed costs, the national sovereignty, and the fact that there can only be one ANSP controlling a flight corridor makes them natural monopolies. Like the airline we assume a linear cost function for the ANSP being the sum of variable costs (c_G) such as labor and maintenance and fixed costs (FC_G) which consist of the investment costs and other sunk costs. We assume here that the ANSP does not face costs of congestion on the airspace directly. However, indirectly it leads to lower provision of airflight kilometers. Hence, it is in the interest to reduce congestion for the ANSP. Besides congestion the ANSP also can have a direct benefit of investing; as was the case with the airlines, investing in new technology affects the costs of air traffic control. It will reduce the variable cost but increase the fixed costs. The ANSP collects revenue from navigational and can have a source of outside funding from a regulator (government). This can be fundamentally different in each country. In Europe, most ANSPs receive a navigational charge directly collected from the airlines. The navigational charge τ depends on the number of km flown and the weight of the aircraft [12] which is directly correlated with the size of the aircraft. Under the current European regulations, ANSPs can recuperate part of its investment costs through higher charges, and these will thus depend on the investment decision of the ANSP. The profit function of the ANSP is:

$$\Pi_G(K,k) = [\tau(K) - c_G(K,k))]q - FC_G. \quad (3)$$

We can make several assumptions about the ANSP. It could use cost recovery charging which would imply that the higher the demand or the lower the marginal cost, the lower the charge. We could, alternatively consider the case where the ANSP sets its charge as to maximize its profits. The optimal navigational charge in this setting will, however, drive profits for the airline to zero. To prevent this, the ANSP needs to be regulated and charges need to be capped. Other possibilities are to impose performance targets.

The main driver of the ANSPs profit is the amount of traffic. The ANSP has therefore an incentive to maximize the traffic using its airspace and its capacity (or minimize the congestion). But the more inelastic the demand, the lower the potential benefits for the ANSP.

We first analyze what happens when no policies (other than a cap) are in place. In the next section we analyze the different scenarios of investments and use game theory to see whether either the airline or the ANSP have the right incentives to adopt the new technology.

C. *Investing with perfect information with ANSP as first mover*

In the case of perfect information, we can consider a two-stage game where the ANSP moves first and decides to adopt the technology or not. Given this decision the airline then makes its decision. Firstly, if the ANSP doesn't adopt the technology, there is no incentive for the airline to invest. The more interesting question is when will the airline be interested to make the investment too. There are four possible outcomes:

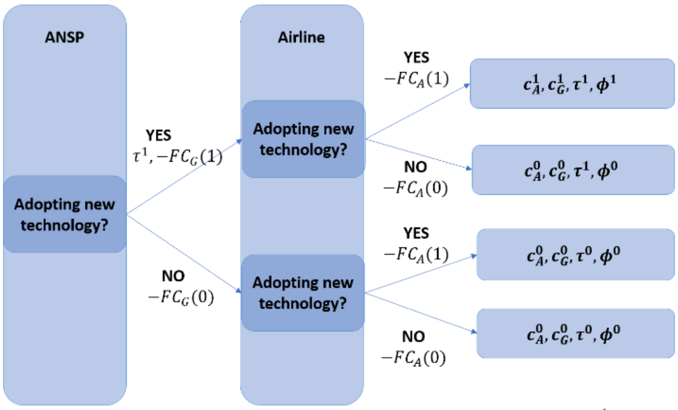

Figure 2: Two stage game with one ANSP and one Airline.[1]

Only in the case when both the airline and the ANSP invest the full benefits of the new technology (CPDLP) are realized. To solve this problem, we need to determine the specific outcome of each case.

Using the envelope theorem, in our setup, the impact of the technology on the profits of the airline is determined simply by the extra amount of traffic demand it generates. Indeed, for a small incrementation of the operational costs, charges or delay costs the following applies (we don't have to consider a change in the charge as we assume the ANSP has adopted the

[1] As notation becomes quickly cumbersome, we introduce the following notation: $c_A(1,1) = c_A^1$ while $c_A(0,k) = c_A^0$ (similarly for ϕ) and $\tau^K = \tau(K), with\ K = 0,1$.

technology and the charges will be the same regardless of whether the airline adopts the technology or not):

$$\frac{\delta \Pi_A}{\delta c_A} = -q^*, \frac{\delta \Pi_A}{\delta \tau} = -q^* \ and \ \frac{\delta \Pi_A}{\delta \phi} = -\frac{q^{*2}}{2} \qquad (4)$$

A necessary condition for the technology to be beneficial to the airline is that the benefits of the demand increase outweigh the investment costs.

$$\Delta \Pi_A = -\int_{c_A^0}^{c_A^1} q^* dc_A - \int_{\phi^0}^{\phi^1} \frac{q^{*2}(\phi)}{2} d\phi - \Delta FC_A > 0, \qquad (5)$$

where Δ denotes the difference between situation with and without the new technology and ΔFC_A is the investment cost. The impact on profits can be rewritten as:

$$\Delta \Pi_A = \frac{1}{2}\left(\frac{((A-(c_A^1+\tau^1))^2}{2B+\phi^1} - \frac{((A-(c_A^0+\tau^1))^2}{2B+\phi^0}\right) - \Delta FC_A > 0. \qquad (6)$$

If the technology reduces the operational costs and congestion cost substantially and the investment costs are not too high, the airline will be willing to make the switch provided the ANSP has switched.

We now turn to the ANSPs decision. The technology allows the ANSP to handle more traffic and reduce the operational costs. At the same time the ANSP must charge more to recover its costs which reduces demand. If the airline does not adopt the technology, only the latter remains and as the ANSP sees a drop in its profits. The ANSP will therefore only want to adopt the technology if the airlines follow. Even then the benefits need to outweigh the costs. The changes in profits for incremental changes are:

$$\frac{\delta \Pi_G}{\delta c_G} = -q^*, \frac{\delta \Pi_G}{\delta \tau} = \tau \frac{\delta q^*}{\delta \tau} + q^*, \frac{\delta \Pi_G}{\delta \phi} = (\tau - c_G)\frac{\delta q^*}{\delta \phi}. \qquad (7)$$

For discrete changes this becomes:

$$\Delta \Pi_G = q^1(\tau^1 - c_G^1) - q^0(\tau^0 - c_G^0) - \Delta FC_G > 0. \qquad (8)$$

The ANSP balances difference in income with and without investing against the costs of investments. If the ANSP is not able to increase it navigation fee, it has only limited benefits in terms of reduced operation costs and of the additional margin it has on the increased demand.

IV. One ANSP and multiple airlines

In previous section we assumed there was only one airline who acted as a monopoly. Although useful to introduce the main ideas behind the model, it lacks realism as in most cases there are multiple airlines serving a same origin and destination. For this reason, we relax this assumption and assume *n* airlines. Only a fraction (κ) of these airlines decide to invest (airlines of type A), these airlines enjoy a reduction of their operational costs (assuming the ANSP has invested in the new technology). This reduction will depend on how many airlines have invested (network effect). The marginal operational costs are taken to be linear and decreasing in κ for airlines of type A. For the airlines that do not invest (type B), the marginal costs remain unchanged. All airlines face same navigational charge τ. Following [13] the inverse demand function is a linear function and is given by

$$P = A - \kappa B q_A - (n-\kappa) B q_B \qquad (9)$$

The marginal cost per passenger is constant plus a congestion cost (ϕ) which is proportional to the total demand. The new technology increases the capacity and therefor reduces the congestion cost. There is a network effect in the sense that the congestion cost depends on the number of airlines that have invested:

$$\phi = \phi(K,k) = \phi_0 - \frac{\alpha}{e^\beta} \kappa e^{\beta\kappa} \qquad (10)$$

The larger β the more convex and the more airlines need to have invested to realize a gain. If β is zero the impact is linear. The cost and profit function are defined in the same way as in the monopolistic set up. As is customary in the aviation literature, we assume that the airlines engage in Cournot competition. We limit our attention to the Nash equilibrium, where airline of type A takes the output of the other airlines q_B as given. Solving the first order condition for airline A and B yield the Nash volumes:

$$q_A^N = \frac{A - 2c_A + c_B - \tau}{3\kappa(2B+\phi)}, q_B^N = \frac{A - 2c_B + c_A - \tau}{3(n-\kappa)(2B+\phi)} \qquad (11)$$

We can easily see that if a technology reduces the operational costs this increases the demand for the investing airline, but it negatively affects the output of the competing airlines that have not invested. This implies that there will be more pressure for the other airlines to invest too in order to regain part of their market. On the other hand, reduced congestion leads to an increase in demand for both airlines and there could be some free riding on the part of the non-investing airlines.

The assumptions for the ANSP are the same as in previous section. As previously we assume a constant marginal cost per passenger, which decreases if both the ANSP and the airlines can use the new technology. We assume that congestion doesn't enter the cost or profit function of the ANSP directly, but it will enter the profit through the demand. The operational costs for the ANSP decreases, as the more airlines use the new technology, it is clear that the ANSP would like that as many airlines as possible would invest. Not only will its direct operational costs go down, but there will be an increase in demand which increases the profits of the ANSP.

A. Investment game with one ANSP and two airlines

Again, we can consider a multiple stage game, where the ANSP decides to adopt the technology first and the airlines decide whether to invest. In this set up we consider the case where there are two airlines or there are two types of airlines: type A and type B. We are thus in duopoly case for airlines and a controlled monopoly for the ANSP.

The full benefit of the investment (CPDLP) can only be attained if all players choose to invest. In principle there are 8 possible outcomes. However, four of these outcomes are essentially the same. If the ANSP chooses not to invest, the outcome is that the technology is not operational, even when airline A or B would have made an investment to use it. This fallback position is the same as the original baseline, since we can assume that even when the airlines would have invested, this would be treated as a sunk cost and have no influence on the price setting by the airline.

If the ANSP invests, but neither of the airlines chooses to invest, the outcome is that ANSP increases its fee to recover the investment. This case is a worst-case scenario but is relatively unrealistic. More realistic are the partial and full uptake scenarios with the airlines either investing or partially free riding on the investment of the other airline.

This is a complex game and hard to solve analytically. We can simplify however, by assuming that both airlines move simultaneously instead of sequentially. This fits the overall modelling exercise as we already assumed that both airlines are in a Cournot equilibrium, where they decide the supplied passenger kilometers simultaneously and independent from each other. If both airlines move simultaneously, they decide to invest only if they have sufficient merit from the investment based on the expected decision of the other airline.

1) Identical airlines

We first look to the simplified case where the airlines are identical. Assuming the ANSP has adopted the new technology, we compare the profits of airline A in the three different scenarios: (i) only airline A adopts the new technology, (ii) only airline B adopts the technology and (ii) both adopt the technology.

Comparing the situation where only one of the airlines invests, the benefits of the improvements in terms of delays are the same in our symmetric setting and it will be the operational costs that determine whether it is worthwhile. It can be shown that it is **always better to be the one that has invested as it will increase its competitive advantage**. A similar unambiguous result holds comparing the case where both use the new technology and the case where only the competitor has adopted the new technology: **if the competitor has adopted the technology, it will be beneficial to follow suit**.

Whether it is better to be the only airline that has invested will depend on the which effect is larger: the reduction in market share due to the competitive advantage the competitor now has, or the decrease in delay costs thanks to an increase of the capacity.

A lot of the results hinges on the relatively importance of the reduction of operational costs and the network effects due to an increase of capacity and thus the characteristics of the technology. Compared to the monopolistic setting, airlines do not consider the full impact of CPDLP on the network delay cost, only the impact on their share of the market. This **will limit the benefits of any technology whose benefits are mainly network based and have only limited benefits on the operational costs of the airlines**. If the operational benefit or competitive benefit of CPDLP (or any other technology) is large enough and outweighs possible network improvements, the uptake of the technology will be stimulated in a competitive environment compared to the monopolistic one. Vice versa: if the benefit of the technology is **strongly network based and only has a limited benefit on the operation cost of airlines, the uptake of the technology in a fractured and more competitive market may be hindered.**

One way to encourage the airlines to adopt the technology is to give them some compensation. This could be either a monetary compensation such as a reduction in the navigational charge, but it could also be in the form of a better service by given them priority over the airlines without the new technology.

2) What in the case of asymmetric airlines?

The model is essentially the same, but both operational and network level dynamics may be different for the two airlines. In the numerical analysis we distinguish a low-cost airline (LCC) and a legacy carrier (LC). In general, we expect relatively little difference between the symmetric case and the asymmetric case (legacy/low cost) except that **a legacy carrier will internalize more of the network delay cost** compared to a low-cost airline, as it behaves more monopolistically, has less flexibility to reroute and generally still has a large market share. This means that it responds more to technologies that have an impact on congestion. In addition, the legacy carrier will care more for service cost than navigation fees set by the ANSP. This means that it will be more responsive to 'best-equipped, best-served" policies by the ANSP. Since, the low-cost airlines generally don't own their fleet and invest less in staff training it could mean that retrofitting additional technology (in this case CPDLP) may be less obvious. On the other hand, **low-cost airlines will be more responsive if the technology leads to an obvious competitive advantage and reduced variable (also fuel) cost.**

V. MORE THAN ONE ANSP

A. Set-up of the model

Until now we considered a single origin destination pair linked by a single arc that is controlled by a single ANSP. The European airspace is, however, very fragmented and it is very likely that airlines need to cross several airspaces controlled by different ANSPs or that they can choose between different routes. To study the interactions between ANSPs we focus on two very simplified networks. The first case is a parallel network consisting of two parallel links between a departure and arrival airport. Each link is controlled by a different ANSP. The second case is a serial network consisting of one link where the first part of the link is controlled by another ANSP than the last part.

In the parallel case the ANSPs are in competition and the two routes are substitutes. This kind of network has been studied in [9]. It was shown that a price decrease on one route will lead to a price decrease on the other link. In terms of technology uptake, we analyse whether ANSPs are now more willing to invest in new technology to be able to offer better service and increase the traffic in their airspace. We would also expect that if one of the ANSPs invest, this will force the other to decrease its prices. The game is very similar to the one in the previous sections and follows closely the one used in [9].

The model formulation follows closely the one used in [14]. The difference is that here, the users are non-atomistic, implying that each account for a non-negligible proportion of the total demand and thus enjoys some market power.

B. Parallel case with one transit airline

We consider one single OD and two routes connecting the origin (O) and destination (D). The two routes crosses two different airspaces (M and N), controlled by two different ANSPs. Air traffic going from O to D can now choose between two routes. Air traffic in airspace $I=M,N$ for airline A is denoted by $q_{M,A}$ or $q_{N,A}$ and q_A the total volume. The two routes are perceived as perfect substitutes to the transit airline. We model the market for air transport in a similar way as previously with a linear demand and cost function. The total cost (TC_A) for any airline A using either route M and/or N is now the sum of the cost of using airspace M and N times the number of airkm flown in the airspace M or N respectively:

$$TC_A = (\tau_M + c_{M,A})q_{M,A} + \frac{\phi_M}{2}q_{M,A}^2 + (\tau_N + c_{N,A})q_{N,A} + \frac{\phi_N}{2}q_{N,A}^2 \tag{12}$$

When deciding on its route, the transit airline takes the volumes of competitors as given. We need to make some market assumptions about the transit airline. Suppose we have only one airline, which is in a monopoly position. Working this case out is relatively simple. Let α be the share of traffic that goes through airspace of ANSP N and (1-α) the share through the airspace of ANSP M. To simplify matters we assume that operational costs are the same in both airspaces. In this case the profit of the transit airline is

$$\Pi_A = \big(A - \alpha(c_M + \tau_M) - (1-\alpha)(c_N + \tau_N)\big)q_A - \frac{1}{2}(B + \alpha^2\phi_M + (1-\alpha^2)\phi_N)q_A^2 - FC_A \tag{13}$$

The optimal amount of flight passenger kilometres produced by A is:

$$q_A^* = \frac{A - \alpha(c_M + \tau_M) - (1-\alpha)(c_N + \tau_N)}{2B + \alpha\phi_M + (1-\alpha)\phi_N} \tag{14}$$

This means that if the airspace, navigation fees and cost structure of both airspaces are the same, this will lead to either route being equally used by the airline.

We can treat an investment game as an adaptation of the one we used in the previous section. As before we assume that the airline moves last. The ANSPs therefore base its investment on whether the airline will invest or no. At the side of the ANSPs, we assume they move simultaneously, so taking the behaviour of the other ANSP as given. This makes it easier to solve this relatively complex investment model.

The ANSP are assumed to control perfectly similar airspaces (equal in terms of complexity, size and length), a relaxation of this assumption is explored in the numerical exercise where one airspace is assumed to be more prone to congestion. The only element that can thus vary is whether the ANSP will invest or not.

We first solve the decision of the airline in different cases. We adapt the expression from the section on a single ANSP and a monopoly airline and using superscript (k = 0,1) to indicate whether either ANSP M and/or N has invested in the technology. The share of traffic using corridor M will also be affected by the investment decision of the respective ANSPs. For this reason we introduce the superscripts M,N for α, where M (or N) is 1 or 0, depending on whether ANSP M (or N) uses the new technology.

$$\Delta\Pi_A = \frac{1}{2}\left(\frac{\big(A - \alpha^{MN}(c_M^k + \tau_M^k) - (1-\alpha^{MN})(c_N^k + \tau_N^k)\big)^2}{2B + \alpha^{MN}\phi_M^k + (1-\alpha^{MN})\phi_N^k} - \frac{\big(A - \alpha^{MN}(c_M^0 + \tau_M^k) - (1-\alpha^{MN})(c_N^0 + \tau_N^k)\big)^2}{2B + \alpha^{MN}\phi_M^0 + (1-\alpha^{MN})\phi_N^0}\right) - \Delta FC_A \tag{15}$$

As was previously the case, an ANSP will only want to adopt the technology if the airline will follow. Even then the benefits need to outweigh the costs. For the ANSP M we get (similar expression for N):

$$\Delta\Pi_M = \alpha^{1k}q_A^{1k}\big(\tau_M^1 - c_{G,M}^1\big) - \alpha^{0k}q_A^{0k}\big(\tau_M^0 - c_{G,M}^0\big) - \Delta FC_M \tag{16}$$

$$\Delta\Pi_N = (1-\alpha^{k1})q_A^{k1}\big(\tau_N^1 - c_{G,M}^1\big) - (1-\alpha^{k0})q_A^{k0}\big(\tau_N^0 - c_{G,M}^0\big) - \Delta FC_N \tag{17}$$

There are two critical differences between the model presented here and the previous one. The first is that the parallel routing could reduce the incentive for the airline to invest. In this version of the game there is a possibility that only one ANSP will invest. Suppose only ANSP M invests. When the airline uses the corridor of M, while investing in the new technology it will have a lower operational cost and delay cost. However, the benefits of the investment are not fully attributed to this corridor in this case. The airline uses the airspace of M (increasing α), but only until the benefit of using this corridor (lower operational cost, lower contestability) is compensated by the higher cost (increased navigation fee, increased congestion by increase in demand). There will, however also be another effect which is an increase in overall demand. Which effects dominates will depend on the parameters of the problem.

We can conclude that in a parallel network, the incentive for airlines to invest will be reduced, as they may only use the new technology on a part of their flying routes. Moreover, for the ANSP the decision to invest may be influenced by a possible competitive advantage. As such the ANSP's incentives may not be the dominant hindrance.

C. Serial case with one airline and two ANSPs

In the serial case the airline needs to use both airspaces to get from origin to destination. This is critical difference. Let us retake the expression on the total cost of the airline A and assume (like in the parallel case) that the airspace of each ANSP is equally large. We normalize the total distance travelled to 1, such that an airline travel half of the distance in each airspace. This gives:

$$TC_A = \frac{1}{2}\left[(\tau_M + c_M^A)q_A + \frac{\phi_M}{2}(q_A)^2\right] + \frac{1}{2}\left[(\tau_N + c_N^A)q_A + \frac{\phi_N}{2}(q_A)^2\right] \quad (18)$$

The optimal amount of flight passenger kilometres for airline *A* is:

$$q_A^* = \frac{\left(A - \frac{(\tau_M + c_M^A + \tau_N + c_N^A)}{2}\right)}{\left(2B + \frac{(\phi_M + \phi_N)}{2}\right)} \quad (19)$$

Using the same reasoning as in the previous sections we can now also solve the investment game. Just as before we solve for a situation where ANSP *M* makes the decision to invest, independently from *N*. This decision, as before is made based on the assumption that airline A will invest or not, given that *M* has invested.
The impact on profits of airline A is:

$$\Delta\Pi_A = \frac{\left(A - \frac{1}{2}(c_M^k + \tau_M^k) - \frac{1}{2}(c_N^k + \tau_N^k)\right)^2}{2B + \phi_M^k + \phi_N^k} - \frac{\left(A - \frac{1}{2}(c_M^0 + \tau_M^k) - \frac{1}{2}(c_N^0 + \tau_N^k)\right)^2}{2B + \phi_M^0 + \phi_N^0} - \Delta FC_A. \quad (20)$$

For the ANSPs we have that

$$\Delta\Pi_M = q_A^{1k}(\tau_M^1 - c_{G,M}^1) - q_A^{0k}(\tau_M^0 - c_{G,M}^0) - \Delta FC_M \quad (21)$$

As we can see this expression is very similar as the one of the parallel case but lacks a variable (α) as a means to divert traffic to another route.

Unlike in the parallel case, the decision of ANSP *M* to invest does not lead to a competitive advantage. On the contrary. In the serial case, ANSP *N* may profit from an increase in flight kilometres (reduced cost on airspace *M*). This means that the ANSP that keeps using the old technology may 'freeride' on the investment of its competitor.

For the airline, compared to a situation with a single ANSP the decision to invest or not, is still significantly reduced. The reason is that the potential reduction in cost may only be realized for half of the territory used by the airline. The main difference here is that there is no 'alternative route' available where the airline could avoid a possible increase in navigation fee after investment by ANSP *M*. So, all air traffic will still need to go through *M* and then *N* to arrive at a destination.

D. Cases with multiple ANSP and airlines

These cases are not worked out theoretically due to their complexity. We refer to the numerical analysis for final conclusions. We can however hint at a few possible conclusions based on the analysis above. If two ANSPs on parallel routes are combined with a duopoly (or oligopoly) the competitive advantage of an airline investing in new technology may be further diluted. The reason is that the non-investing airline may capitalize on a non-investing ANSP. This creates a situation potentially worse than the case we considered above with only airline operating on the airspace of two parallel ANSPs. Since gaining a competitive advantage (or avoiding one) is a serious element in the decision of the airline to invest or not, this may lead to a situation where no investments are made. So, a combined lack of interest by both airline and ANSP.

The situation described above will however only be true if there is little competitive advantage for the investing airline. If there are clear indications that an investing airline can reduce costs and hence increase revenues by taking away traffic from its competitors, this will be a powerful incentive to invest.

In the case of serially linked ANSP, this problem may not occur, as the airline may still gain a competitive advantage on a part of the airspace (which the competition cannot avoid).

VI. Numerical illustration

The aim of this section is to numerically illustrate the importance of the identified in the theoretical section. The numerical exercise performed here should not be viewed as a proper CBA of the technologies but as an illustration of the theory. The purpose is to gain insight into how the characteristics of ATM technologies might hinder the innovation in ATM provision. The focus lies in the comparison between the different set-ups rather than the absolute values of the obtained outputs.

A. Data

To concentrate on the relation between ANSPs and airlines we make some simplifying assumption about the European airspace. We first assume that all ANSPs are fully integrated in one ANSP that controls the whole airspace. The total amount of flights controlled by this fictious ANSP is then 10.8 M flights with a total distance of 12,288 M km. Using a (fixed) load factor of 150 passengers per aircraft [15] this amounts to a total demand of 1,833,840 M passkm. For the price elasticity for air travel, a range of estimates have been estimated in the literature ranging between -0.6 and -2.34 [18] to be consistent with our demand and cost data we use an elasticity of -2.

For the costs of the ANSP we use the Europe wide figures from [9]. We classified deprecation cost and cost of capital as fixed cost (1234 M euros). The variable costs consist of the staff and non-staff operating costs and the costs for exceptional items which amounts to 5360 M euros. The average navigational charge in Europe is equal to 0.64 euro/flightkm.

We use the figures used in [9] for the Cost per Available Seat Kilometer. In [9] they do not, however differentiate between variable and fixed costs which is needed in our setting. Based on the airline cost structure given in [16], we classify 60% of the total costs as variable. According to [15], the total delay minutes in 2018 was 24.81 M minutes, using a cost per minute of 83.64 (own computations) this amounts to a total delay cost of 2075 M euros.

In [19] estimate the cost to make an aircraft compatible with the new technology between 100.000 and 1 mio dollars. Taking an upgrade cycle of five years [19] and adjusting for inflation, this amounts to 2% of the annual fixed costs for the airlines. The investment on the ANSP side is much more important. . We use expert judgement and estimates found in [20] and results of the CAPAN model [21]. This leads us to assume a reduction of operational costs for the airlines of 20% (reduction in fuel costs and flight times) and for the ANSPs of 10% (mainly reduction in maintenance and staff costs) and an increase in capacity of 20%. with full deployment of the CPDLC equipage. This is also in line with estimations made by SITA [22] on CPDLC in Europe.

B. Main findings from the numerical excersice

The main results are summarized in Table 2 (for more detailed numerical results we refer to [17]) where the percentage change in the profits of the agents is given compared to the reference scenario where no one uses the new technology. For the charging regime of the ANSP, we assume they are allowed to charge 10% above the cost recovery charge. Without this assumption, either the ANSP profits remain zero (for pure cost recovery charges) or the airlines profits are reduced to zero (if charges are not capped). In the asymmetric duopoly setting we assumed that airline 1 has lower operation costs and fares are cheaper. In the case of the parallel network, we first consider identical ANSPs (symmetric case), then we assume that in the reference situation, ANSP 1 has a greater capacity. The blue cells correspond to the agents that uses the new technology.

Investment Scenario	Setting	Airline 1	Airline 2	ANSP 1	ANSP 2
One airline and one ANSP invest	Monopoly	+40%		+173%	
	Duopoly (sym)	+102%	-47%	+121%	
	LCC (invests) vs LC(no invest)	+87%	-14%	+118%	
	LCC (no invest) vs LC (invests)	-46%	+33%	+91%	
	Parallel (sym)	+96%	-40%	+180%	-51%
	Parallel asym	+99%	-44%	+102%	-93%
	Serial	+120%	-56%	+107%	+8%
All airlines but only ANSP 1 invests	Monopoly	*NA*	*NA*	*NA*	*NA*
	Duopoly	*NA*	*NA*	*NA*	*NA*
	Parallel (sym)	+42%	+42%	+437%	-201%
	Parallel (asym)	+45%	+45%	+224%	-396%
	Serial	+55%	+55%	+162%	+16%
Everyone invests	Monopoly	+40%		+173%	
	Duopoly (sym)	+48%	+48%	+187%	
	LCC vs LC	+40%	+16%	+161%	
	Parallel (sym)	+48%	+48%	+118%	+117%
	Parallel (asym)	+47%	+47%	+95%	+221%
	Serial	+120%	+120%	+191%	+191%

Table 1: main result of numerical exercise

The numerical illustration confirms the findings of the theoretical section. In the double monopolistic setting, with the values at hand, both agents could gain substantially from the investment; the increase in navigational charge is compensated by the reduction in delays and operational costs for the airline. So allowing the ANSP to charge above its pure cost recovery charge could be enough to encourage the uptake of the new technology. If this is not feasible or acceptable, **subsidies** given to the ANSP in the case it invests could give the right incentives for the ANSP to invest. As these are a one-shot lump sum transfer whilst the higher charges would give the ANSP a steady stream of income, they would be less effective. Another possibility is to impose a mandate on the ANSPs possibly together with some relaxation on the level of the navigational charges to increase the probability of compliance. In this setting with a monopolistic airline, there is no need for any policy for the airlines to increase the incentives to invest as they are willing to do so without.

With a duopoly, total demand will be higher, and the profit margins of the airlines will be inferior to that of a monopolist. As for the incentives for the airlines to adopt the technology, the situation remains largely unchanged. According to our parameter values, they would both gain by using the new technology provided that the ANSP has done the necessary investments (in this symmetric setting, the benefits are shared equally among the two airlines if both invest). When one airline adopts the new technology, it will gain market share and the combination of an increase of revenues and a decrease of operational costs, means it sees its profits increase. Due to the increase in traffic, its delay costs will, however, remain similar. The competitor is heavily penalized for keeping the old technology and will have a big incentive to make the switch himself.

In a parallel network, it turns out that the ANSP can increase its profits substantially by adopting the technology and risks to lose considerably if it doesn't, but its competitor does. In the symmetric case, not much changes for the airlines in the case only one airline invests compared to the case with one ANSP. From the theory we could expect a reduction of the benefits from investment as the increased use of the corridor where the new technology can be used would temper the benefits. With this example, however, the increase of market share and the associated increase in revenues for the airline that has made the investment compensates for this reduction. If only one ANSP has invested, the airline with the new technology will shift its entire traffic to this corridor, the airline which has not invested will still use both but traffic in the airspace in the ANSP that uses the old technology will be reduced, leading to losses to this ANSP. The competition between the ANSPs will induce ANSP to follow the example of the ANSPs that uses the technology.

In a parallel network it would thus make sense to give extra incentives to the airline carriers in the form of subsidies or mandates to perform the switch to the new technology as the little profit changes might not suffice on itself. If the ANSPs do not belief that the airlines will carry out the investments needed they will play safe and prefer the status quo. This will be even more the case if there is a reluctance to change. We saw that the best-equipped-best-served charging regime could help to increase the airlines incentives although it is not clear whether this will always be enough.

In the serial network we see that the airlines have again a greater incentive to adopt the technology as they cannot divert their traffic to counterbalance an increase in congestion in one of the airspaces. The main lesson here is that a free riding problem may occur in such a setting; the ANSP that doesn't adopt the technology, will still profit from the investment of the other ANSP. Although it can increase its profits by investing, it might choose not to and settle with a less pronounced increase of the profits. This could be the case if other factors come to play that are not modelled here, such as company culture or a reluctance to change. A serial network setting makes investments less easy to implement although the welfare gains are more important and regulatory intervention will likely be necessary. The added difficulty with a serial network is that **all** ANSPs need to be given the right incentives.

VII. Conclusion

Using a simple theoretical model with elements from game theory, industrial economics, and transport economics we analyze the investment game between ANSPs and airlines for the uptake of new technologies. As an example, we take the CPDLP technology, but the model is applicable to any technology that reduces operational costs and increases capacity of the airspace.

The first insight from our analysis is that regulation of navigation fees is necessary, as without regulation the natural monopoly of ATM management would allow prohibitively large charges on airlines. On the other hand, too tight an enforcement of the fee may stimy any real investment in technology as the ANSP may not recover its investment cost. Regulation should therefore be tight, but not too tight to allow the ANSP to recover costs and make a small profit to allow for investment.

The second insight is that the market uptake of innovative technologies that are strong network based and have a significant impact on congestion or delay costs will be more probable in a one-to-one setting. A (close-to) monopolistic airline internalises the benefits of lower delay costs in the airspace and will reap more the potential benefits of a reduction of the latter. The ANSP is, therefore more certain about the uptake of the airline in this setting and that it can enjoy the benefits of its investment

The third and connected insight, is that it is not clear if increased competition between ANSPs stimulates the uptake of new technologies. Using a simple network analysis, we find that when airlines can choose multiple parallel routes managed by different ANSPs, the incentive of investing in CPDLP or similar technologies on the side of the airlines might be reduced. The reason is that airlines lacking the necessary equipment will find alternative routes by ANSP that do not make the necessary investments. The numerical illustration however, shows that this effect can be annihilated be the increase in market share thanks to the overall cost reduction and the associated revenue increase. Which effect dominates will highly depend on the case at hand. In a serial network one ANSP may free ride on the investment of another ANSP, while the overall benefit for airlines is reduced. This does not mean that pro-competitive policies on the side of ATM and airlines do not have other welfare benefits, but we find that in a more fractured market the investment incentives are reduced.

The fourth insight- which is also supported by numerical analysis - is that an overall technological mandate for a 'proven' technology such as CPDLP can be a welfare improving solution. This reduces the uncertainty that would be caused by a market-led uptake of the technology in a fractured and competitive market. One possible extension of the model would be to introduce uncertainty and drop the assumption of perfect information. Improving communication and signalling investment intentions between ASNPs and airlines could reduce uncertainty and accelerate the uptake of technologies, especially of the benefits of the technology are contingent on the investment decision of the other parties.

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Saskia van der Loo obtained her PhD in Economics at the KU Leuven and subsequently worked there as a post-doctoral researcher. She has been involved in various projects on the national and EU level, analyzing pricing and investment policies in the transport sector, developing a tool to perform CBA, and assessing sustainable policies in cities. In 2020 she joined TML.

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Eef Delhaye is a senior researcher at TML, specialized in transport economics. She can build on 20 years of experience as a project coordinator, project leader, and project assistant, and has a PhD in economics (KU Leuven). Her expertise mainly lies in cost-benefit analyses of (infrastructural) projects, impact analyses of (transport) policies, external costs, road safety, and the preparation of indicators and standards. In recent years she has focused more, but not exclusively, on regulated transport by carrying out projects related to rail and air traffic control. She was coordinator of the ACCHANGE and COMPAIR project and currently working on the ITACA project.