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En-route Speed Reduction for the Mangement of ATFM Delays

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In this paper a new concept aimed at better dealing with delays caused by regulations is presented. Inspired in future 4D trajectories, where a time constraint can be applied at each way-point, it is proposed to spread the total delay imposed by a regulation over the trajectory that goes from the departing airport to the regulated airspace. Given a nominal cruise speed, there exist a set of possible lower speeds that allow a longer flight (and then, a cumulative flight delay) with the same or less fuel consumption if compared with the nominal situation. In this way, the aircraft that has been delayed can consider to take-off on time and loose this time by flying slower and requiring the same or less fuel than initially planed. Besides the positive environmental impact, the airliner can bet that finally the regulation at the congested airspace may be not applied and being the departure on time, the delay can be absorbed more easily in flight with a minimal or null fuel consumption increase. Finally, this concept is applied to some example flights.

I. Introduction

As it is well known, the number of flights is growing all around the world. The forecast of aircraft movements in the Eurocontrol Statistical Reference Area (ESRA) for 2030 is between 1.7 and 2.9 times the traffic of 2007. This leads to an amount of traffic between 16.5 and 22.1 million of Instrumental Flight Rules (IFR) movements. Therefore, an average growth of 2.3%-3.5% per year is expected.[1] In the most-likely growth scenario, by 2030 the 11% of actual demand will not be accommodated.[2] In addition, new challenges that go further than demand capacity management are also arising like, for example, fuel consumption or the environmental impact of aviation. During the year 2008 the price of oil reached prices over 100 USD per barrel. During this year most of the airlines reported that fuel costs where in between the 30%–40% of their total expenses. Therefore, some research effort has to be done in order to manage capacity-demand imbalance while taking into account other constraints like CO_2 emissions or fuel efficiency.

In the actual operational scenario, the airspace and airports are already suffering from congestion problems.[3] In order to deal with capacity and demand imbalance in Europe, the CFMU (Central Flow Management Unit) uses a ground based delay management criteria. By using a Computer Assisted Slot Allocation tool (CASA)[4] the take-off time is delayed to deal with en-route capacity constraints. According to ref. 5, in the ECAC area, only during December 2008, 2 470 traffic per day was regulated and 1 443 of these flights were delayed. A total of 28 690 minutes of delay per day were achieved. Therefore, the average delay per delayed flight was of 19.9 minutes, and all this delay was on-ground delay.

At research level, some work has been done in order to improve the behaviour of the CASA algorithm,[6] or to avoid conflict generation by the use of on-ground delay strategies.[7] In ref. 6 Barnier et al. presented a study of different models that, based on constraint programming techniques, solve the slot allocation problem. Moreover, in references 7 and 8 the models where extended to deal with conflict resolution and not only capacity imbalance. With these algorithms, and by using ground delays, not only the imbalance between capacity and demand is solved but flown trajectories are conflict free. However, these results have never been put into practise due to the computational time required to find a solution and, in the actual operational scenario only ground delay is used.

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Nowadays, three options are possible to deal with delay: on-ground delay, re-routing and holding. However, the use of 4D trajectories, that will be developed for SESAR and NextGen, makes possible the idea of delay management by aircraft speed control. In this paper this concept will be discussed.

In Section II the operational context is presented showing how aircraft operators deal with fuel and time management for their scheduled flights. In addition, the current and future (SESAR) strategies for balancing demand and capacity are also presented in this section. The concept of speed reduction for delay management and its potential in both scenarios is presented in Section III. On the other hand, in Section IV a feasibility study is presented, where the effects of this speed reduction strategy on fuel consumed are shown. At the end of this section, the advantages and drawbacks of the proposed idea are summarised. Finally, Section V contains the conclusions and proposed forthcoming work.

II. Operational context

In the majority of civil aviation flights, aircraft operators have to trade-off between the fuel consumed and time needed to fly a certain route. Aircraft equipped with Flight Management Systems (FMS) use a *Cost Index* (CI) parameter when optimising the flight profiles. The CI express the ratio between the cost of the fuel and the cost of the time.[9] Thus, a CI set to zero means that the cost of fuel is infinitely more important that the cost of the time and the aircraft will fly at the maximum range (MR) speed. On the other hand, the maximum value of the CI gives all the importance to the time, regardless of the needed fuel. In this case, the aircraft will fly at the maximum operating speed (VMO/MMO) with, in general, some safety margins. Airlines can reduce their operation cost by an efficient management of the CI settings among their scheduled flights. Actually, a CI value not only affects to the cruise airspeed but will determine the whole profile of the flight. This means that the optimal flight level may change and that the climb and descending gradients might be different for different CI values.

As the CI is the main parameter to manage airline operating costs, it is a subject of continuous research. For instance, Cook et al. propose in ref. 10, the concept of a Dynamic Cost Index. This strategy would allow airlines to continuously compute and change the cost index during the flight. Therefore, they will be able to optimise their cost to the uncertainties of a real flight in order to recover, for example, a certain delay.

A. Air Traffic Flow and Capacity Management (ATFCM)

The capacity of the controlled airspace or at the airports is not sufficient to accommodate all the traffic demand. Air Traffic Control (ATC) centres schedule define hourly capacities for each active control sector. Air Traffic Flow and Capacity Management (ATFCM) is a ground-based service that, in an pre-tactical phase, evaluates the traffic flows in order to balance capacity according to a demand baseline. The goal is to avoid the overload of the Air Traffic Control (ATC) services and minimise the penalty imposed to the aircraft operator due to the congestion.[3] Nowadays, to accommodate demand to capacity, the main ATFM measures are re-routing aircraft over non-congested areas or imposing on-ground delays.[5]

1. Ground delays

The solution that as been implemented in Europe is the use of the Computer Assisted Slot Allocation tool (CASA).[4] Using this tool, the allocation of a certain amount of *slots* is computed by using ground delays. The ATFM delay is defined as the duration between the last Take-Off time requested by the aircraft operator and the Take-Off slot given by the CFMU.[5]

One main advantage of CASA algorithm is that it is able to take into account operational constraints and updates. On the other hand, CASA use a greedy algorithm and, therefore, can not guarantee to find a correct solution or an optimal one.[7] In addition, ground delay regulations generate congestion at the departure airports.[11] Moreover, the actual implementation of the algorithm suffers from the discrepancies between planed and actual flights,[12] leading to a misuse and/or overuse of the airspace.

Research efforts have been done in order to optimise the allocation process using Constraint Programming[6] but they have the problem to deal with equity issues[13] and it is difficult for these algorithms to deal with real time challenges.

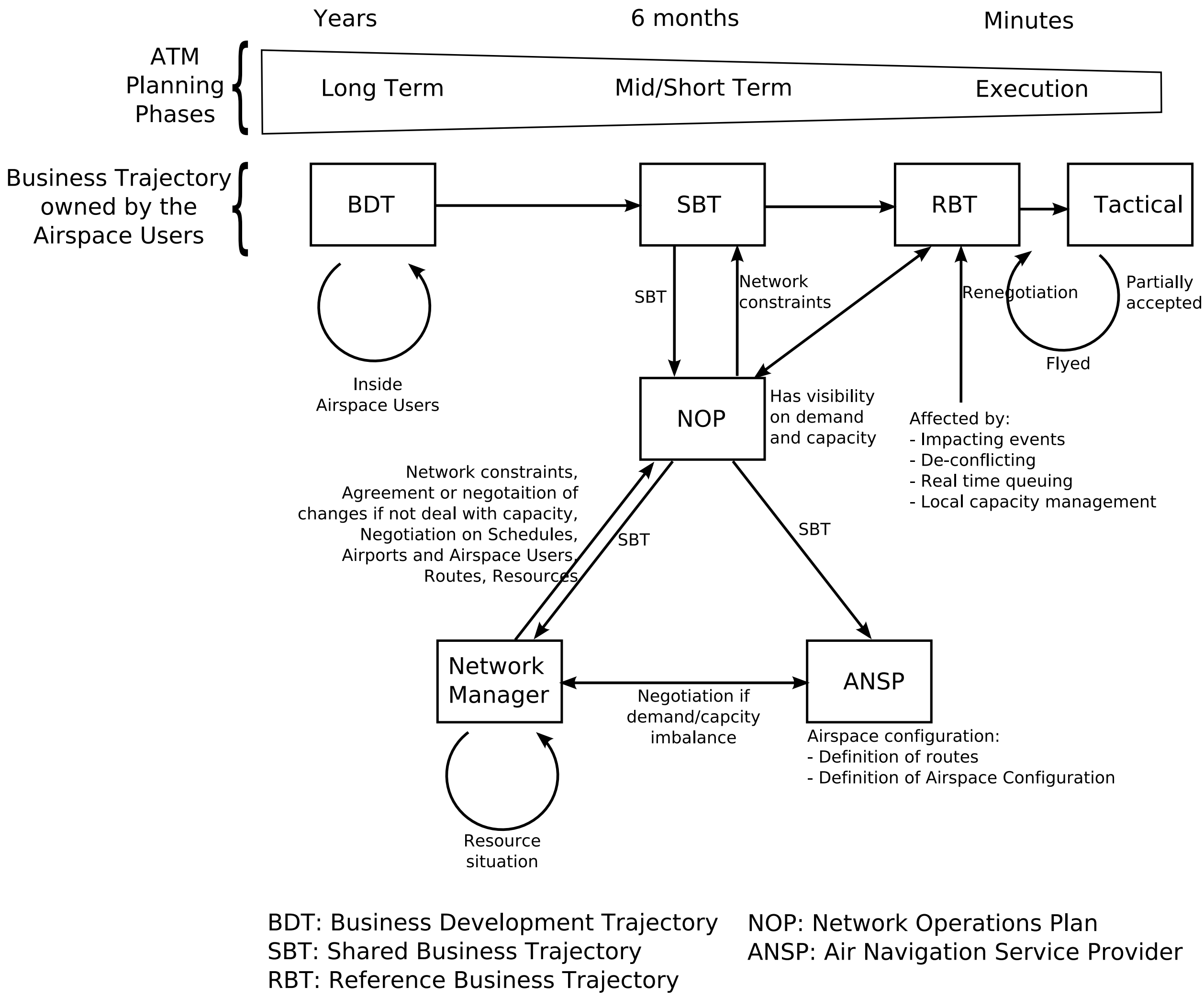


Figure 1. The concept of operations of SESAR

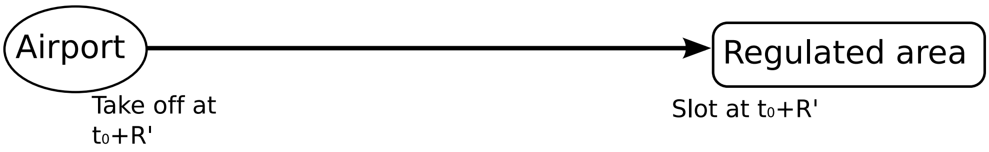
2. En-route delays

If it is not desired to deal with ground delays, in order to keep the demand below the maximum capacity, it will be necessary to apply en-route delays. In this case, three options are available: holding stacks, re-routing and speed control. Some previous studies suggest that ground delays are better than en-route ones from an environmental point of view. In ref. 11 the fuel burned due to ground delays and to en-route delays was computed and translated into CO_x, SO_x, NO_x, HO_2 and HC emissions. Then, the same computations were done for re-routing and holding solutions showing a minor environmental impact when using ground delays. However, the possibility of using en-route speed regulation techniques supported by forthcoming 4D trajectories was not explored.

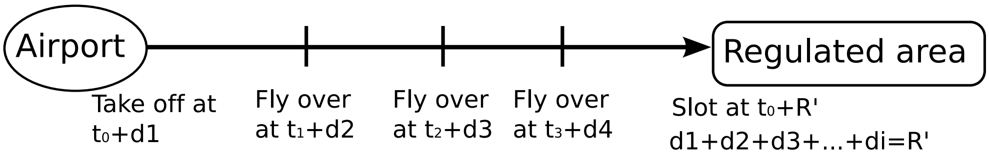
B. SESAR operational concept

In the new concept of operations that has been developed for SESAR, some changes have been done with respect to the actual operational scenario. Figure 1 shows the processes that will be used in the new operational concept.

According to SESAR, the Airspace User (i.e. the aircraft operator) is owner of the trajectories and a protocol has been established to develop and modify these trajectories. In the long term (years before the operation day), the Business Development Trajectories (BDT) are developed inside the user's organisation. This BDT evolves up to a moment when they become available to other users via the Network Operations



(a) Current situation: ground delay



(b) Proposed situation: delay (R) split along a 4D trajectory

Figure 2. Comparison between current and proposed delay management strategies

Plan (NOP) who distribute it to the Network Manager and the Air Navigation Service Provider (ANSP). At this moment, the BDT trajectory become the Shared Businesses Trajectory (SBT). This process is done in a mid/short term, from 6 month before the execution day up to hours before the execution. With this information, the ANSP is able to make the configuration of its airspace, routes, resource allocation, etc.

After a negotiation process between the Network Manager and the ANSP, in order to adapt as much as possible the capacity to the demand, the NOP will receive the network constraints and a negotiation will be hold with the Airspace Users. They will modify their SBT trajectory to try to fit the constraints, and a new iteration will be done. This iterative process ends when an optimum is obtained. At this point the SBT trajectory become the Reference Business Trajectory (RBT) that the Airspace Users agree to fly and the ANSP and Airports agree to facilitate.

However, the RBT is not a clearance. The trajectory will be cleared by steps and it will be affected by many events like de-conflicting, local capacity management, etc. Therefore, the RBT trajectories can be changed during the flight. The changes will come from the Airspace User or from the ANSP to deal with separation, queue management or changes in constraints or in resource availability. If it is the Airspace User who proposes a RBT amendment that meets the new constraints, the ANSP will have to accept the modification if no additional problems are created after the change.[14]

III. Delay management by en-route speed reduction

Many projects have been done with the objective of solve or minimise the conflicts that controllers have to deal with by the use of speed reduction. See, for instance, references 15 or 16. In ref. 15 is analysed how uncertainty in speed can produce a false detection of a conflict. Moreover, it is proposed the use of speed for the resolution of conflicts. On the other hand, in ref. 16 the ERASMUS project is presented, where changes in speed are proposed aiming at solving conflicts before the air traffic controller could realise. In this project a study is done to determine if controlers could detect or not some automatic speed reduction of the aircraft in their scope. In ref. 16 two scenarios are used: one with a changes of speed of $\pm 3\%$ and another with changes between -6% and 3%.

In this paper we propose a similar speed reduction technique aimed at dealing with network constraints and the saturation of the airspace. Nowadays, if a regulation appears in a certain sector (i.e., the capacity for that sector has been limited) some aircraft that have planned to over-fly it will be delayed on ground. Then, they will arrive to the regulated sector at a fixed time in order to fulfil the capacity constraints for that sector.

The main idea of the speed reduction concept is that once a delay has been imposed to a certain aircraft, instead of waiting on-ground, this amount of time could be split over the different way-points of the intended flight plan before the regulated area is reached. This concept is valid if 4D trajectories are used, which means that fly-over time windows can be attached to navigation way-points.[17] As its presented in Figure 2, the total delay time when entering the regulated sector will be the same, but the on-ground delay can be reduced even to zero.

A. Use in current operational scenario

Two options seem to be possible if this speed reduction concept wants to be used in the current operational scenario: by using a centralised system or a distribute one.

1. Centralized use

Once the flight plans are send to the CFMU, instead of giving a ground delay the CFMU could compute the different time window constraints all along the intended 4D-route up to the regulated area. This approach has the advantage that the CFMU holds the information of all the flight plans and therefore, it is easier to handle with the possible network effects that can be derived from these computations. In other words, it would be simpler to find a global optimal solution for all the involved aircraft.

As we will see in next section, a major drawback for this solution is that the CFMU will need to know some sensitive data from the aircraft operators. Namely fuel consumption models and actual weights of the aircraft, which, in general, are jealously kept in confidentiality by the operators.

2. Distributed use

Another approach is to implement a distributed use of this concept. In this case, the CFMU first gives the ground delay that the aircraft should perform to the operator. Then, the operator (which has all the sensitive information related to weights and consumption data) can perform the calculations needed in order to know which is the best way to deal with the imposed delay. In this way, the operation will split the delay time optimally along the route and a new flight plan will be sent to the CFMU for validation. This flight plan will include the different times attached to the way-points and will fulfil the total delay requirement imposed by the CFMU.

B. Use in SESAR future operational scenario

As it has been previously shown, in the SESAR operational scenario ground delays will not be imposed. However, a negotiation will take place between the airspace users and the Air Navigation Service Providers (ANSP) in order to deal with network capacity constraints.

In this scenario, a centralised solution has less sense and a distributed solution seems perfectly to fit with the new paradigm. One can easily imagine that the ANSP proposes a SBT or an RBT that satisfy the required capacity constraints by using a speed reduction approach. However, the main idea of SESAR is to involve the actors into the decision process. Therefore, it is more reasonable that the airspace user would propose a new SBT (or RBT) to the ANSP.

The speed reduction for delay management, that is presented in this paper, will be useful during the negotiation phase. In addition it would be also possible to use this concept in a more real-time optimisation, during the flight phase, if the RBT trajectories need to be modified. In both cases, aircraft operators can use the speed reduction idea, in order to fit the network constraints, while minimising their fuel consumption.

IV. Feasibility study

Speed modifications have obviously a direct implication with fuel consumption.[18] In this section, the authors present how fuel is affected when an aircraft flies slower than initially planned. In order to have a more competitive solution than the ground delay option, from an environmental and economical point of view, it is expected that less fuel will be burned with the speed reduction management approach if compared with the ground delay solution.

To do this assessment, an analysis of the Specific Range (SR), the distance flown per kilogram of fuel, has been done. As an example, in Figure 3 the SR of an Airbus A320 is presented in function of the speed. As it can be seen in the figure, a distance of SR_{max} NM per kg of fuel can be covered when flying at the Maximum Range speed (V_{MR}). As a consequence, a minimisation of the fuel consumption is achieved when flying at this speed (i.e. with a Cost Index set to zero). However, airlines usually use a CI greater than zero to reduce the cost related to time. In this way, usual operating speeds are higher than V_{MR}. If the airline choose to fly at a speed of V_0, the distance covered per kilogram of fuel will be SR_0, being consequently lower than SR_{max}.

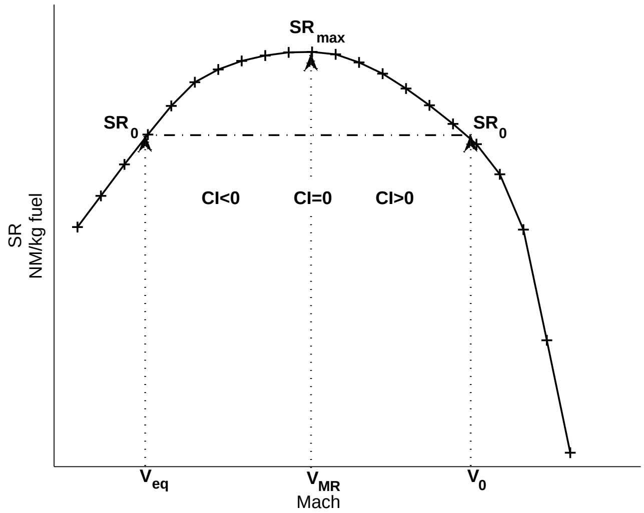


Figure 3. Specific Range in function of cruise speed.

Using ground delay management, if the flight has to be delayed for R minutes before take-off, almost no fuel will be burnt during the on-ground delay and, once in the air, the aircraft will fly at V_0 (see Figure 2). On the other hand, using the speed reduction concept the aircraft will fly slower than V_0 and therefore the distance that will be covered per kilogram of fuel will be bigger, leading to a smaller fuel consumption for a given distance (see Figure 3).

This reduction in consumption is valid if the new speed has at least the same SR that V_0. In the example shown in Figure 3, if the planned speed is V_0, the speed having the same SR is V_{eq}. Therefore, if the aircraft flies at a speed in between V_{eq} and V_0 the consumption will be the same or lower than initially planed and some time will be lost during the flight. However, if the speed needed to loose the R minutes in the distance available (D) is lower than V_{eq} the SR will be lower than SR_0 and thus, extra fuel will be lost.

A. Influence of the flight operational parameters

In this section we show how the variation of fuel consumption, with respect to the planned consumption, depend on many parameters like the aircraft type, the cruising flight level, the weight or the planned cruise speed (V_0). In addition, this consumption is clearly related with the speed that the aircraft will fly in order to loose a given time (R) in a given distance (D).

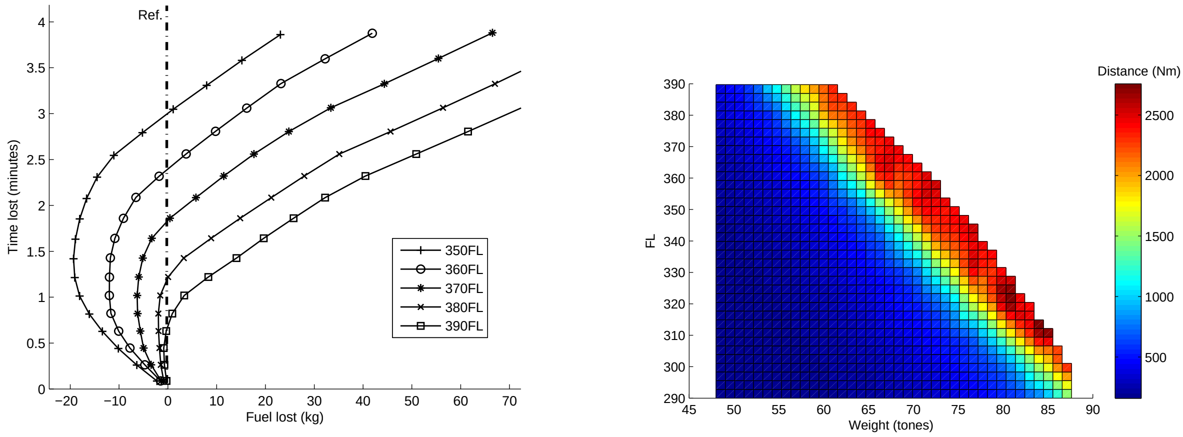
Table 1 presents the values chosen for this initial study. An Airbus A320 has been used because this represents a typical aircraft in mid-range flights in Europe. The distance to the regulation (D) is the distance between the top of climb and the regulated sector. R is the time that may be lost before entering the regulated sector (i.e. the imposed delay).

The Flight level (FL) is one of the main parameters that has an influence in the fuel consumption. In Figure 4(a), it is presented how much fuel is saved or spent with respect the intended flight at V_0. If the

Table 1. Case study parameters

Aircraft type	Airbus A320
Flight level	FL350
V_0	0.78
Weight	55 t
Distance to regulation (D)	100 NM
Regulation time (R)	10 minutes

speed is reduced, some time will be lost in the distance available before the regulation (D). As previously mentioned, the larger the time is needed to be lost (R) in the distance D, the lower the used speed will be. If the speed is between V_{eq} and V_0, some fuel will be saved, but if the plane flies lower than V_{eq} some extra fuel will be spent.



(a) Time lost

(b) Distance needed for loose 10 minutes

Figure 4. Influence of the Flight Level and the Weight of the aircraft

As can be seen in Figure 4(a), in function of the FL the margin between V_0 and V_{eq} will be different. It is possible to see how by flying at FL350, almost 3 minutes can be lost without spending more fuel than initially planed; if 1.5 minutes are lost the fuel burned will be almost 20 kg less than planed. However, if the intended FL was FL390 only less than 1 minute can be lost in D without spending extra fuel: the margin between V_0 and V_{eq} has been reduced considerably. Thus, as expected, intended flight level is one of the main parameters that affect to the available margin.

Another key parameter is aircraft weight. Figure 4(b) presents, for the flight of table 1, the distance needed to loose R=10 minutes in function of the weight and the intended flight level, without loosing extra fuel. It can be observed that the distance needed vary from less than 500 NM to more than 2500 NM. So, flight level and weight are critical values.

The flight level and weight values change the values of the specific range (SR) in function of speed. Therefore, they change the distance between V_0 and V_{eq}. In Figure 5 is presented how the specific range varies in function of flight level, speed and weight. As the weight increases, the SR is lower and the margin between V_0 and V_{eq} narrows.

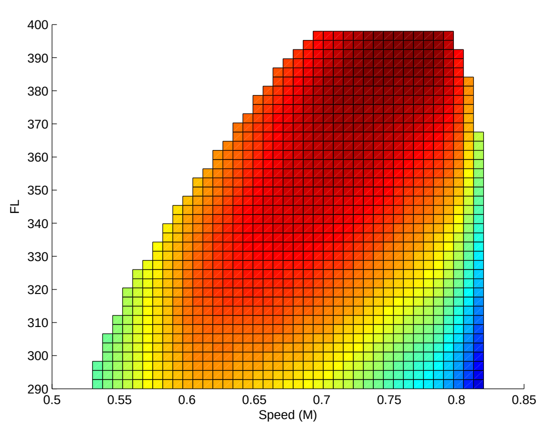
It is clear that the planed speed V_0 is a very important value, the faster V_0 the bigger distance with respect to V_{eq} will be (see Figure 3). When fixing the flight level, the weight and the cruise speed V_0, the operator is choosing a value of SR_0 and therefore is fixing the value of V_{eq} and, in this way, the range of possible speeds where the speed reduction technique could be applied without loosing extra fuel.

It is important to note that cruise speed and flight levels are not arbitrary chosen. In function of the desired CI, the weight of the aircraft and the length of the flight, the cruise speeds and altitude profiles will be optimally determined by the operator. Therefore, it is not possible to further assess the fuel impact of speed reduction strategies without analysing specific flights.

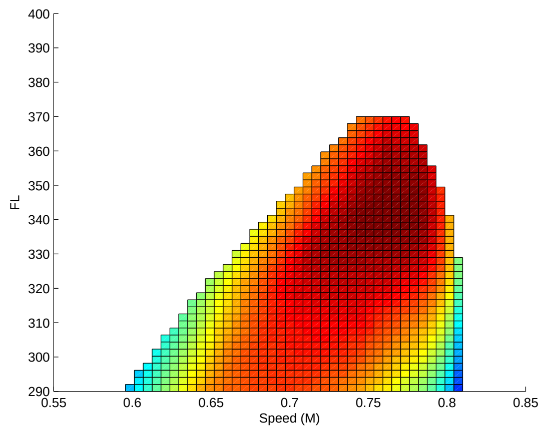
B. Example applications

Obviously, a specific route fixes the distance between the origin and the destination airports. Then, the aircraft operator will choose a CI value according to their operational polices. Once the payload weight is known, an iterative optimisation process determines the best cruise speed (V_0) and the cruise Flight Level(s) as well as the total amount of fuel required. In this way, the final weight of the aircraft is fixed.

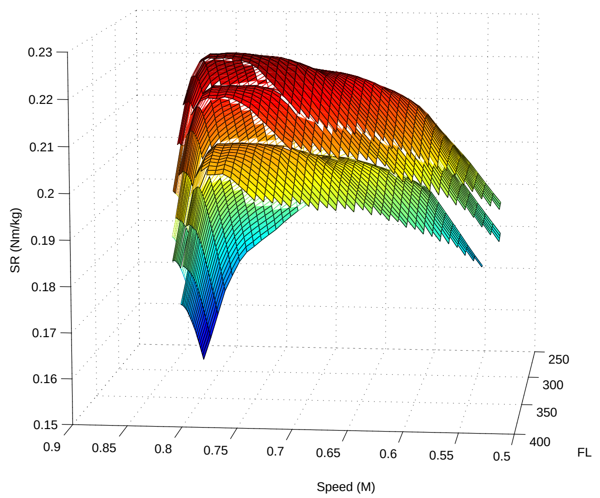
Table 2 shows a list of different flights performed by different aircraft types. These flights are representative for short, mid and long range cruise phases. In addition, different values of CI are proposed for some flights. For weight computations, a load factor of 81% has been considered when computing the payload weight for short and mid-range flights.[19] On the other hand, for long-range flights we have considered a 81%



(a) Weight = 54t



(b) Weight = 70t



(c) From low to big weights

Figure 5. Specific Range (SR) in function of speed, Flight Level and Weight

of the whole maximum payload, including passengers but also freight. Thus, for each flight, the optimal values of the cruise speed and Flight Level(s), the cruise time and distance values are computed and shown in the table.

1. Case1: No extra fuel is burned

In this study it has been determined how much time can be lost without loosing more fuel than initially planned. It has been supposed that time can be lost during the cruise phase. The maximum time that can be lost has been computed supposing that the regulation is located at the end of the cruise. Thus, D is the whole cruise and it has been computed how much time can be lost in D without loosing fuel (see Table 3).

In a first approximation the weight of the aircraft has been supposed constant during all the cruise phase in order to ease the time and fuel consumption computations. Two different weights have been considered: the initial weight at the beginning of the cruise phase (W_0) and the final weight at the end of this phase (W_f). Then, two different results for time lost are given for each computation: T_0 and T_f. As the weight of the aircraft will change progressively from W_0 to W_f during the cruise phase, the real value of time that can be lost in the distance D will be a value in between T_0 and T_f. Therefore, the results reported for these two weights are, in fact, a bound of the actual values but they are significant enough to see the feasibility of

Table 2. Analysed flights.

Flight	A/C	Distance	CI	V_0	FL	Flight Time	Cruise Time	Cruise Distance (D)
DUB – LHR	A321	243 NM	25	0.76	310	0h43	0h06	46 NM
			60	0.78	320	0h40	0h05	39 NM
			999	0.80	300	0h40	0h06	44 NM
FRA – MAD	A321	769 NM	60	0.79	370	1h51	1h06	496 NM
	A320	769 NM	25	0.78	380	1h55	1h08	507 NM
			60	0.79	390	1h52	1h06	497 NM
LIS – HEL	A320	1 819 NM	25	0.78	380	4h14	3h23	1518 NM
			100	0.80	370	4h10	3h21	1526 NM
LHR - DXB	A340	2 972 NM	200	0.83	360†	6h25	2h16	1084 NM
					380*		3h18	1582 NM
			500	0.85	350†	6h19	2h41	1305 NM
					370*		2h49	1369 NM

† First step of the cruise.
* Second step of the cruise.

the speed reduction technique.

In the table 3 the results are presented. It can be observed how in long range flight the time that can be lost without loosing any fuel is bigger than for short or mid-range flights. This is a direct implication due to the fact that in long range the plane have a longer distance to loose the required time. This is the reason why in table 3 the percentage with respect the cruise time is also presented. It is possible to see how in very short flights the percentage of time that can be lost with respect the cruise is quite significative. This is due to the fact that for that flights, the plane does not have enough time to reach an optimum flight level and thus, the distance between V_0 and V_{eq} is wider.

It is possible to see how, as expected, if CI increases, the time that can be lost also increases. In Figure 6 is presented the time that can be lost in function of CI for a flight from Frankfurt to Madrid and from Lisbon to Helsinki with an Airbus A320. For the FRA–MAD flight, during the cruise the fuel that can be lost ranges from zero if CI is null and the plane flies at $V_0 = V_{MR}$, up to more than 10 minutes if the CI is greater than 130. These 10 minutes represent more than 18% of the cruise time.

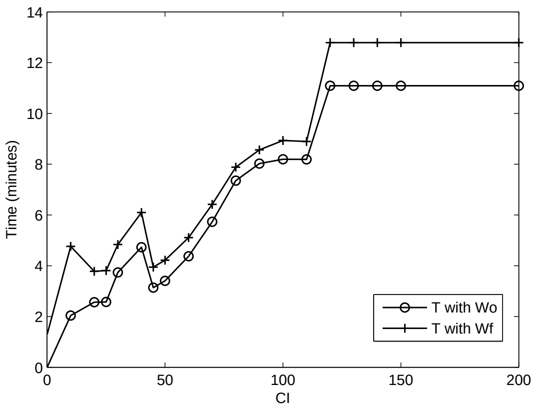
On the other hand, for the Lisbon to Helsinki flight more time can be lost. This is due to the fact that the distance is greater. If the time is translated to percentage with respect the cruise time, the values are quite similar for the two flights. In both cases they vary between 0% and 20%. Also the distance between the time that can be lost with W_0 and with W_f is larger in the Lisbon to Helsinki case, as the flight is longer, the difference between W_0 and W_f is also larger. In both figures some changes in the tendency of time in function of the CI are observed. For instance, in the Frankfurt to Madrid case, it can be observed that when the CI increase more than 40, instead of having more time lost, the time is reduced. And when increasing the CI from 110 to 120 a sudden increase in the time is produced. This is due to the fact, that when the CI is increased, the V_0 is also increased, and therefore the distance between V_{eq} and V_0 becomes larger. However, at some point the flight level is also changed and thus the SR curve is changed producing a different distance between the two speeds.

In the Frankfut to Madrid flight, from CI=0 to CI=10 the flight level used is 370, from CI=50 the flight level used is 390 and at CI=120 the flight level is 370 again. These changes in flight level produce the abovementioned changes in the tendency. Finally, for the Lisbon to Helsinki flight, the change in flight level is produced between CI=60 and CI=70.

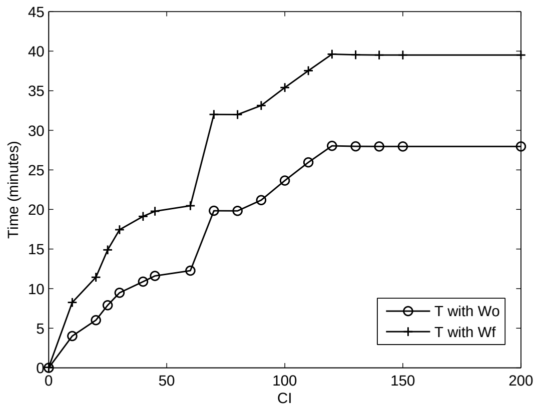
Table 3. Result of the flights.

Flight	A/C	CI	V_0	Cruise Time	Time lost W_0 (T_0)	Time lost W_f (T_f)	% lost W_0	% lost W_f
DUB – LHR	A321	25	0.76	0h06	1.0	1.0	16.7 %	16.7 %
		60	0.78	0h05	1.2	1.2	24.0 %	24.0 %
		999	0.80	0h06	2.2	2.2	36.7 %	36.7 %
FRA – MAD	A321	60	0.79	1h06	4.4	5.5	6.7 %	8.3 %
	A320	25	0.78	1h08	2.6	3.8	3.8 %	5.6 %
		60	0.79	1h06	4.4	5.1	6.7 %	7.7 %
LIS – HEL	A320	25	0.78	3h23	7.9	14.9	3.9 %	7.3 %
		100	0.80	3h21	23.7	35.4	11.8 %	17.6 %
LHR - DXB	A340	200	0.83	2h16†	10.0	13.1	7.3 %	9.6 %
				3h18*	15.1	21.4	7.6 %	10.8 %
		500	0.85	2h41†	25.3	31.0	15.7 %	19.3 %
				2h49*	26.9	33.1	15.9 %	19.6 %

† First step of the cruise.
* Second step of the cruise.



(a) Flight FRA-MAD



(b) Flight LIS-HEL

Figure 6. Time that can be lost without loosing time during the cruise.

Table 4. Delay distribution for the month of May 2009 in Eurocontrol area.

Delay duration [minutes]	% Total traffic	% Delayed traffic
no delay	93.29%	-
]0,15]	3.42%	50.97%
]15,30]	2.4%	35.77%
]30,60]	0.74%	11.02%
>60	0.15%	2.24%

2. Case2: Extra fuel is burned

In the previous section it as been shown how if not extra fuel is burned the time that can be lost depend of many parameters. However, in the whole cruise for a mid-range flight the time that can be lost during this phase is quite reduced (between 2 to 15 minutes). From ref. 20 we have obtained the delay distribution for the month of May 2009 in the Eurocontrol area. These values are shown in table 4.

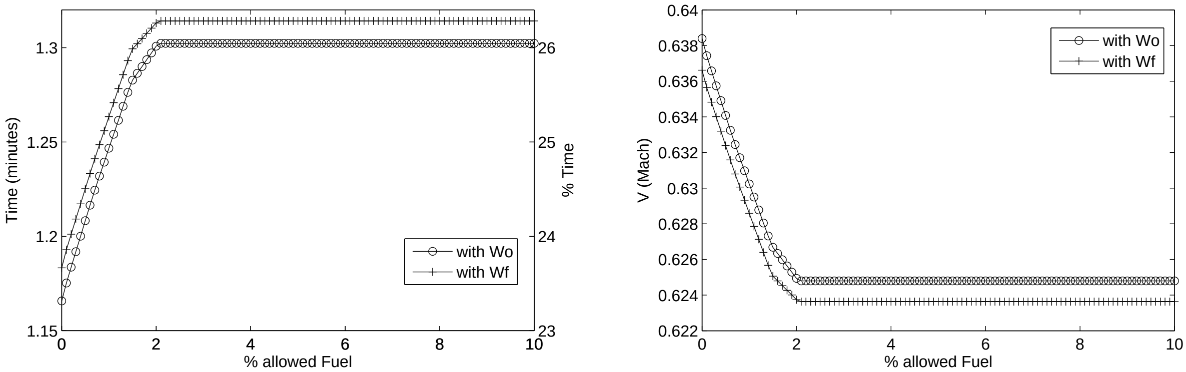
With this data it seems clear that delay times are, in general, larger that the times we have found in previous analysis, where we did not allow to burn more fuel. In additon, the regulation would be possibly located closer than the start of descent and, therefore, the distance available to loose time will be lower and the lost time will be even smaller. In this section it is presented how much time can be lost if an additional percentage of fuel with respect the initially planed is allowed to be burned. In this way, the aircraft will be permitted to fly at a speed lower than V_{eq} and the time lost would be increased.

In Figure 7, Figure 8 and Figure 9 there are presented the results for the Dublin London, the Frankfurt Madrid and the Lisbon Helsinki flights. As it can be observed, if the percentage allowed is increased, the time lost will increase up to reach a maximum value. This is due to the fact, that the plane is flying at the minimum speed for that flight level. For the Dublin London flight, it can be seen that with an extra fuel allowance of 2% the aircraft will be flying at the minimal speed. This 2% will represent around 4 kilograms of extra fuel burned. In the Frankfurt Madrid, the margin is bigger and it is at 4% that the minimum speed is reached. In this case about 80 kilograms will be extra burned. Finally in the Lisbon Helsinki flights depending on the weight the saturation point will be between 3% and 6% which means between 300 and 500 kilograms of extra fuel. If, for instance, the goal is to obtain 15 minutes of time lost, it can be seen that even allowing this extra fuel consumption this amount of time is only reached in the Lisbon Helsinki case. The reason is that in this flight the cruise is longer. If the focus is given to the percentage of time with respect the cruise time, it can be observed that the values are closer in all the cases.

If this concept of speed reduction is used during the negotiation phase before the flight to accommodate demand and capacity, it would possible to change the whole 4D trajectory and not only the speed during the cruise phase. The flight level that was used initially was the optimal one to flight at the given CI, for the given distance and with the given payload. However, if the aircraft has to fly at a lower speed this flight level will not longer be optimum. Therefore, as the speed is reduced, the optimal flight level is also reduced.

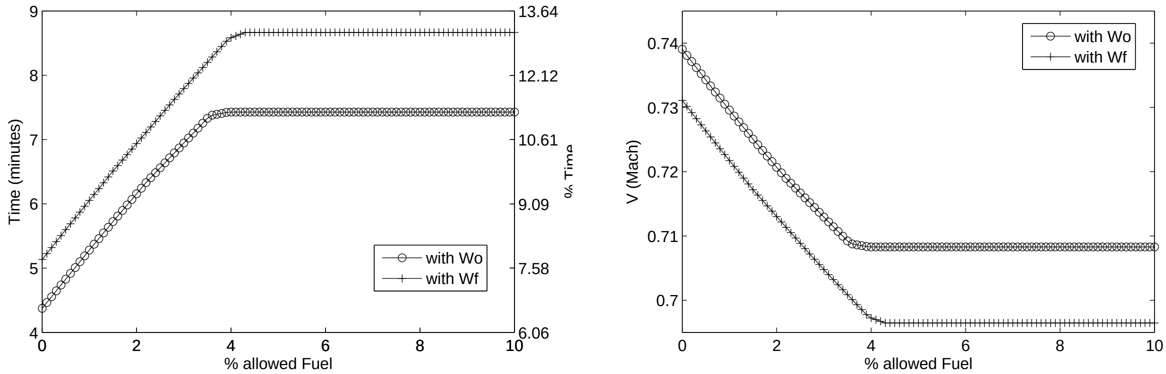
In Figure 10 and in Figure 11 are presented the time that can be lost, the percentage of time with respect the cruise time, the speed used during the cruise, the fuel lost and the flight level used for the flights from Dublin to London and from Frankfurt to Madrid respectively. As can be seen in Figure 10 and in Figure 11 even without loosing extra fuel the time that can be lost is significantly bigger if the flight level is changed. For instance, in the Frankfurt Madrid flight that was initially planed with a CI=60, the time that could be lost without loosing fuel was a value in between 4.4 and 5.5 (see table 3). However, if the flight level is changed, without loosing more fuel that initially planed, the aircraft will fly at flight level 350 instead of flight level 370 and around 8.5 minutes can be lost without loosing fuel.

Moreover, as can be seen in Figure 11(e) and in Figure 11(f), the maximum time lost will be reached with a higher loose of percentage of fuel than if flight level is not changed. This is due to the fact that if the flight level is keep constant the minimum speed is higher than if the flight level can change.



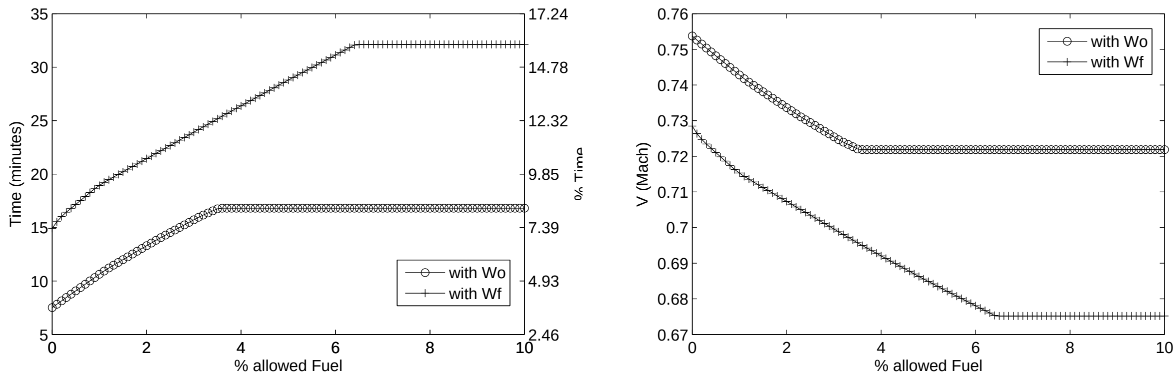
(a) Time lost (b) Mach used

Figure 7. DUB-LHR CI60 A321.



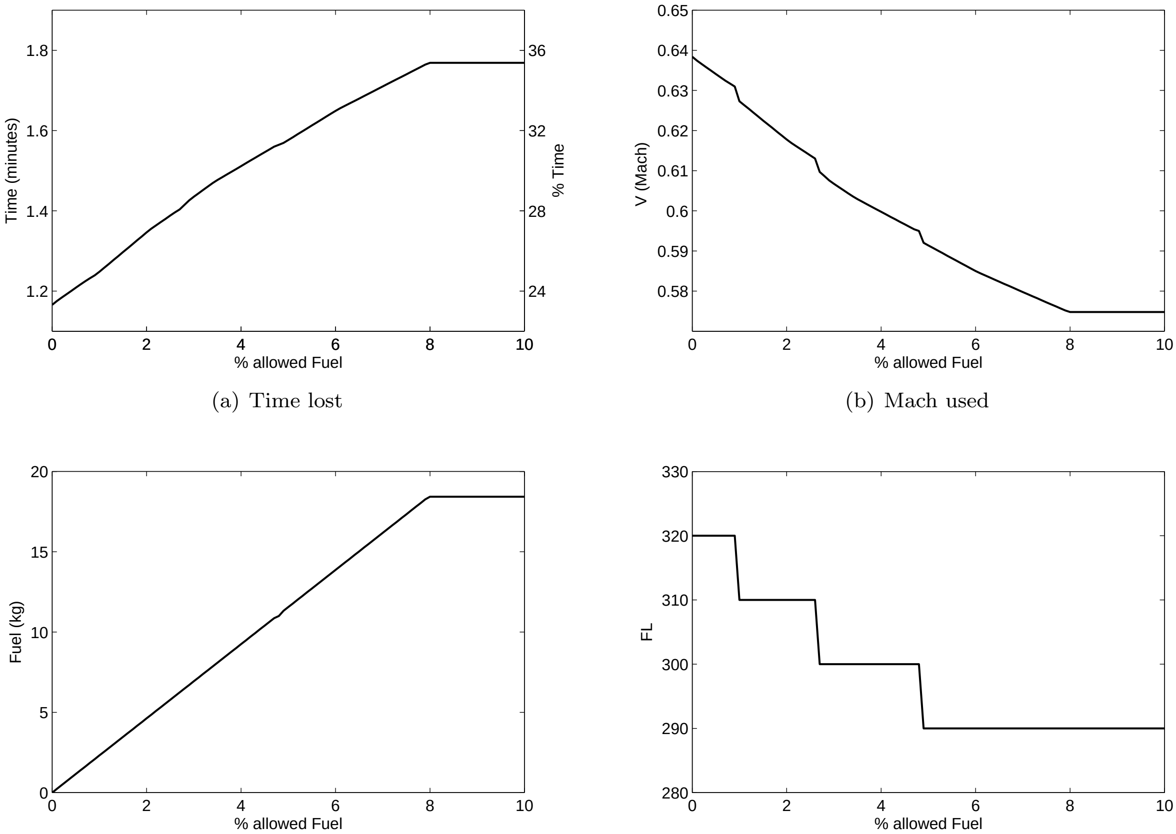
(a) Time lost (b) Mach used

Figure 8. FRA-MAD CI60 A320.



(a) Time lost (b) Mach used

Figure 9. LIS-HEL CI25 A320.



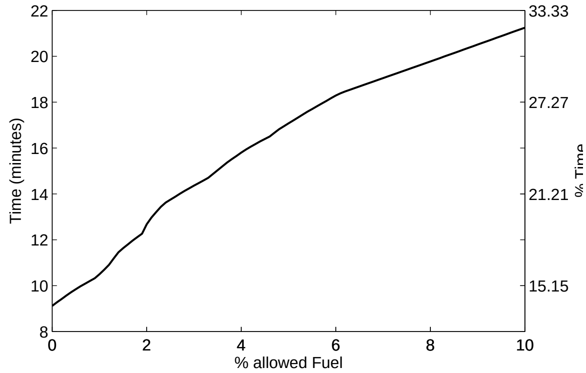
(a) Time lost

(b) Mach used

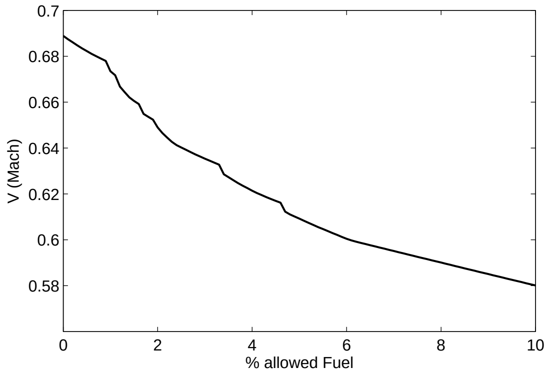
(c) Fuel lost

(d) Best FL

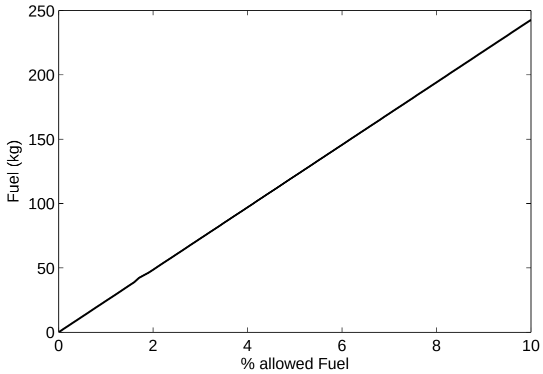
Figure 10. DUB-LHR CI25 A320. Optimal values in function of allowed % fuel lost



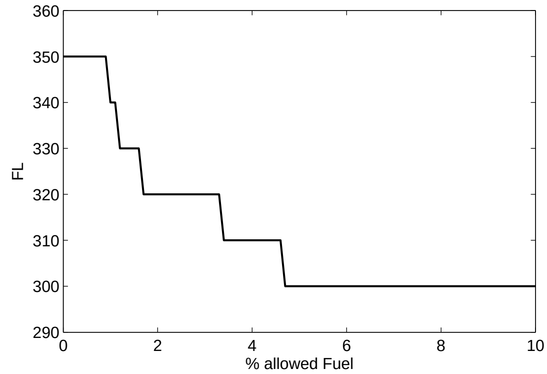
(a) Time lost



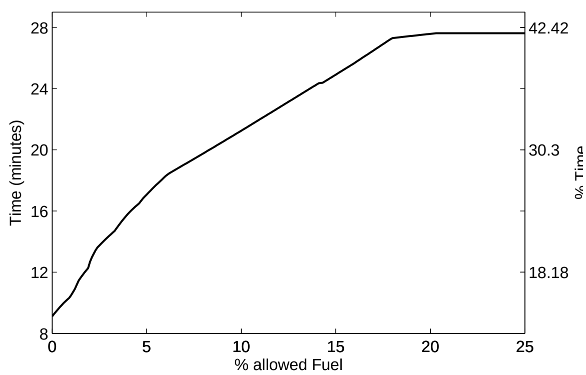
(b) Mach used



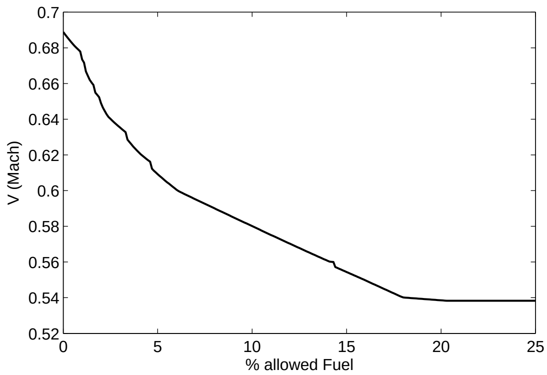
(c) Fuel lost



(d) Best FL



(e) Time lost



(f) Mach used

Figure 11. FRA-MAD CI60 A320. Optimal values in function of allowed % fuel lost

C. Advantages and drawbacks

Many advantages can be highlighted if using this speed reduction concept. The first one is that with the use of 4D trajectories it becomes possible to stablish regulations to already flying aircraft. The Air Navigation Services Provider (ANSP) can impose to an aircraft that are already flying to arrive to a restricted area at a given time. As it is know from previous studies,[12] it is common that there exists an imbalance between planned and realized flights. Moreover, it is common to have capacity restrictions due to weather conditions that might improve during the flight. This can lead to have a restriction that desapears in some point of the cruise. At this moment, if the aircraft is already on the air, it can speed up in order to recover time. If the delay has been done completely on the ground, this is not longer possible, unless the aircraft flies at a speed higher than V_0, burning in this case much more fuel than initially planned.

In previous section, it has been shown that an economy on fuel consumption with respect to the nominal situation can be achieved if the delays are well distributed along the trajectory. Thus, it is possible to minimize the environmental impact flying at a speed lower than the maximum range Mach.

If the aircraft takes-off as soon as possible, the origin airport will have to deal with less aircraft on ground. And therefore, the airport will be less congested on ground. Furthermore, with this concept, it is not necessary to modify the algorithm used by the CFMU to assign slots. Finally, there is a psychological aspect related to passengers, which will wait less at the airport or inside the aircraft.

On the other hand, the main drawback that can be highlighted is that the margins that have been found between V_0 and V_{eq} are quite reduced if the Cost Index is small. Therefore, if the regulation imposes a lost on time bigger than few minutes, some fuel needs to be burned during the flight. Even loosing fuel, if the flight level is not changed, the time that can be lost remains relatively small. Finally if this solution is implemented, more aircraft will be on the air. If aircraft are allowed to fly slower than initially planed, this can lead to a saturation of airspaces that initially were not affected. Then, a network effect analysis shall be done to assess the impact of the application of this speed reduction concept

V. Conclusion and Futher work

From this work, the main conclusion that can be highlighted is that the time that can be lost without loosing more fuel than initially planed is strongly related with the intended Cost Index (see Figure 6). However, the time that can be lost is generally relativelly small (see (table 3)). Moreover, in this study it has been supposed that the regulation is at the end of the cruise, and thus, the whole cruise distance has been used to loose the time. It should be expected to have a regulated area before the end of the cruise, and therefore, the distance available to loose time will be lower.

If some extra fuel is allowed to be burned, but the same flight level as initially planed is used, there is not a high gain (see Figure 7, Figure 8 and Figure 9). On the other hand, if the whole trajectory is changed, and therefore, the flight level is also changed, the results that have been shown are better. Even without loosing extra fuel, the time that is lost could be interesting for an operational scenario. If more fuel is burned than initially planed, with a low percentage of extra fuel burned a high amount of extra time lost can be obtained.

It could be interesting to burn more fuel than initially planed to loose more time during the flight because, as previously said, an imbalance may exist between planed and realized flights or an improvement in the weather conditions might occur. Therefore, it could be possible to recover time if the regulation is not longer needed. This concept will not be valid for SESAR because in SESAR the aircraft will follow their 4D trajectory and this imbalance between planed and realized flight should be reduced. In SESAR the trajectory will be changed before the flight take place, during the negotiation phase, to accommodate demand and capacity. It has been shown that if speed is changed, more consumption will arise, thus, it should be studied if in the new concept of operation, all the aircraft will prefer to do on ground delay instead of changes on speed or on their trajectories, to do not waist more fuel than initially planed. This will lead to a solution in SESAR, similar to the solution is nowadays implemented. The main difference will be that in SESAR it will be a distributed solution.

We would like to point out that many applications have been developed on the suppose that it is possible to change the time of arrival of the aircraft to already fixed waypoints. However, this change in their trajectory is impacting the consumption the aircraft is experiencing. And, therefore, it should be take into account on those projects. Many research work arise from this idea of delay management by speed reduction. A more deep analysis has to be done on the performances of different aircraft to see if the distance between V_0 and V_{eq} is high enough to loose the required time before the regulated area.

If for the flight that is been analized there is enough margin and the time can be lost during the flight, different optimization algorithms can be use in order to find the best distribution of the delay along the trajectories. A first approach could be keep the speed constant before the regulated area, but it is not guaranty that a minimum consumption will be achieved. It is known that weight is a key variable to determine how much time can be lost in a given distance. So, a consumption model has to be make in order to take into account the reduction of weight. With this model we can try to solve the problem of delay distribution regardless of the network effects. Once we know how much fuel can be earned, an environmental study can be done. And compare the results gets with the actual operational scenario.

Up to now, speed has been changed only during the cruise phase, it should be study how the change of speed during climb influence the time that can be lost. If speed is reduced, it is similar to choose a lower Cost Index, and if the Cost Index is changed, then the whole trajectory may change. Therefore, the whole trajectory should be optimized, changing the flight profile. A new study should be done based on the premises that the aircraft want to arrive to a point at a given moment spending an amount of fuel, and optimize the whole trajectory to arrive there burning less fuel than initially planed.

Simulations with changes in the regulation time can be done and using the idea of recovering time, see if the total delay the aircraft will get is better that with the actual configuration with ground delays. If this is true, this can allow Airspace Users to distribute the delay along the trajectory, even if this means spending more fuel, having in mind that maybe they will be able to recover time. This is useful in the concept of operations that nowadays is used, where imbalance between planed and realized flight can occur. It is clear that network effects will need to be also analysed and an optimization should be done when an airspace that initially was not saturated gets over used. On the other hand, this concept allows to apply regulations to already flying aircraft and this could be a good measure to deal with capacity. This has to be explored, and a real-time optimization will need to be performed.

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