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Simulation of airborne ATFM delay and delay recovery by cruise speed reduction

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***Abstract*—Air Traffic Flow Management (ATFM) regulations, such as ground holdings, are often cancelled before their initially planned ending time. This early cancellation leads to an unnecessary ground delay and a misuse of airport or airspace resources. In previous publications, the authors have suggested a speed reduction strategy aiming at splitting the assigned ATFM delay between ground delay and airborne delay. If the aircraft flies at the minimum speed that gives the same fuel consumption as initially planned, the airline can maximise the airborne delay without any extra fuel consumption. If the regulation is cancelled before it was initially planned, the aircraft already airborne will be in a better position to recover part of the delay without incurring in additional fuel costs. In this paper, this speed reduction strategy has been simulated with the FACET tool for a whole day of flights inbound San Francisco airport (California). For each flight in the data set, it has been computed the maximum amount of airborne delay that can be performed. Moreover, the amount of delay that can be recovered has been also computed as a function of the time the regulation is cancelled. Preliminary results show, at first glance, a linear relationship between this cancellation time and the delay recovery which encourages as future work, to develop a parametric model of this delay recovery.**

I. Introduction

In Air Traffic Flow Management (ATFM), when a capacity demand imbalance is detected in an airport or airspace sector, a Ground Delay Program (GDP) is executed both in the United States and in Europe. Its goal is to adapt forecasted demand to published sector/airport capacities by assigning delays to aircraft at their origin airport. GDP initiatives can be a frequent issue in some airports where capacity can be highly reduced if weather degrades. For instance, in San Francisco International Airport (SFO), in California, when low ceiling clouds are present, capacity drops from sixty planes per hour to only thirty. The reason being that in Instrumental Meteorological Conditions (IMC), SFO parallel runways can not be longer be used independently. When a regulation is implemented, one of the problems that is faced is when estimating how long the reduction of capacity will last. For example, if the weather clears before forecasted, it will lead to a misuse of capacity at the airport and some delay will be unnecessarily performed. If, on the contrary, the IMC conditions last longer than expected, the GDP will be extended and/or inefficient air holdings will be necessary near the destination airport.

It is widely accepted that ground delay is preferable than airborne delay from a fuel burn and environmentally point of view [1]. However, the authors propose a new concept which consist on absorbing part of the assigned GDP delay on the air, by flying slower than initially planned [2], [3]. Specifically, it is proposed to fly at the lowest possible speed such that the specific range (distance per fuel burnt) is the same as initially planned. Thus, the aircraft will use more time to perform the flight but with the same fuel as initially planed. In general, only few minutes of delay can be performed in the air by using this strategy and therefore, this airborne delay is usually lower than the assigned ground delay. In this way, the assigned delay is typically divided between airborne and ground delays. Some benefits arise form the fact that part of the delay is performed airborne, and the possibility to recover part of the delay, without extra-fuel consumption, is perhaps the most significant.

If weather clears (and the regulation is cancelled), the aircraft that are already airborne, and flying slower, can change their speed to the initially planned one and recover part of the delay at no extra fuel consumption. Obviously, aircraft crew can increase the cruise speed above this nominal speed, recovering even more delay, but at the expense of more fuel consumption than initially planned [4]. This possibility is out of the scope of this paper, which focuses on the case that delay recovery is performed at no extra fuel consumption. For an example set of flights inbound SFO, this paper studies the maximum amount of airborne delay that can be performed for each flight, along with the amount of delay recovery as a function of the time when the aircraft speeds up. In Section II, some background information on GDPs and the speed reduction strategy is presented. The simulations performed in this study are explained in Section III, while the results are found in Section IV. Finally the paper is concluded in Section V.

II. Background

A. Ground delay programs

In the United States, a Ground Delay Program (GDP) is implemented when an airport is expected to have insufficient arrival capacity to accommodate forecast arrival demand. The Federal Aviation Administration (FAA), as traffic flow manager, activates a program where aircraft are assigned to available slots following a Ration by Schedule (RBS) principle. Once this process has been concluded, airlines might reassign and cancel flights if they consider that necessary or interesting for their business objectives. In this process, airlines can only use slots that were originally assigned to its flights

based on the RBS algorithm. Due to the uncertainty of the duration of the regulation, and the actual arrival time of long-haul flights, aircraft outside a certain radius from the affected airport are exempt from these delays [5]. The length of this radius is fixed at the GDP implementation and depends on the severity of the capacity reduction. For each non-exempt flight, a controlled time of arrival (CTA) or *slot* is assigned at the destination airport. With the information of the flight plans and weather forecasts, trip times can be estimated and the CTA is translated to a controlled time of departure (CTD) at the origin airport. Thus, the assigned ground delay is the CTD minus the estimated (scheduled) time of departure (ETD). Besides ground delay, other strategies can also be initiated in order to solve capacity-demand imbalance problems, such as rerouting or air holdings, being all of them less desired because of higher operating costs (mainly due to fuel consumption) if compared with ground delays [1].

In Europe a similar process is implemented being the main difference that all flights are affected regardless the distance of their original airport. Eurocontrol through the Central Flow Management Unit (CFMU) manages the slot allocation system based also on a RBS basis [6].

The predicted capacity at the airport is subject to uncertainties given the fact that most capacity reductions are often caused by adverse weather conditions. Thus, airspace managers are typically conservative with these scenarios. If the capacity of the airport is reduced due to bad weather conditions, the GDP is usually planned to last longer than actually needed. It is preferred to have planes on ground when not needed and cancel the GDP earlier than planned rather than having too many flights flying in the Terminal Manoeuvre Area (TMA) when the capacity is still reduced. As it can be seen in Table I, in average at SFO the GDPs are cancelled almost two hours before initially planned. This leads to a misuse of capacity at the airport and to unnecessary ground delays.

TABLE I
AVERAGE STATISTICS FOR SFO (2005-2007). [7]

Initial average affected flights	79
Initial average total delay (min)	3,642
Initial average maximum delay (min)	98
Initial average delay (min)	44
Planned average overall duration	4h51
Actual average duration (Cancel - Start time)	2h52
Early average cancellation time (Planned - Actual duration)	1h59

B. Aircraft operations

Fuel consumption is one of the major cost for airlines. However, time-related costs are also considered in the majority of civil aviation flights. These time-related costs include for instance, maintenance or flight crew related costs [8]. Therefore, for a given flight, three types of costs are present: fuel, time dependent and fixed costs which are independent of the time or fuel consumption, like landing fees. As it can be seen in Figure 1, fuel and time dependent costs vary with the flight speed.

There exists an optimal speed that gives the minimum fuel consumption for a given flight distance: the Maximum Range Cruise (MRC) speed. On the other hand, time-related costs decrease as speed increases, since trip times become shorter. Depending on the importance given by the operator to time related costs, the optimal speed for a given flight will change. To help the operator in assessing this trade-off, the Flight Management System (FMS) of the aircraft allows the pilot to enter a cost index (CI) parameter. The CI expresses the ratio between the cost of the flight time and the cost of fuel. 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 MRC speed. On the other hand, the maximum value of the CI gives all the importance to flight time. In this case, the aircraft will fly at the maximum operating speed with, in general, some safety margins.

By choosing the CI the pilot is changing the ratio of cost between fuel and time and therefore, is determining the speed which minimises the total cost (i.e the ECONomic speed), as seen in Figure 1. Airlines can reduce their operating costs by an efficient management of the CI settings on their scheduled flights [4]. The CI value not only affects the cruise airspeed but determines the whole flight trajectory. This means that the optimal flight level may change and that the climb and descending profiles might be also different for different CI [8].

Given a flight distance, a payload weight and a cost index, the optimal Flight Level, the optimal cruise speed (V_0) and consequently, the fuel needed for that particular flight (block fuel) are determined and can be computed by using an iterative optimisation algorithm.

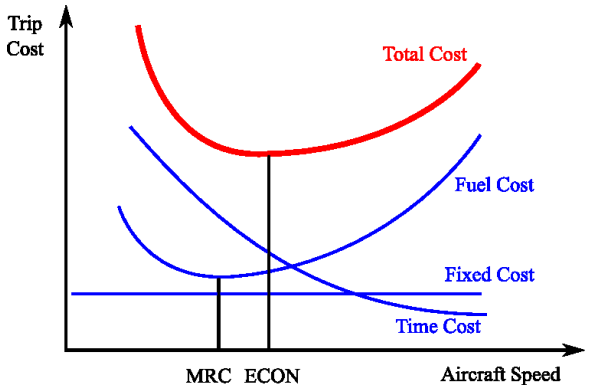
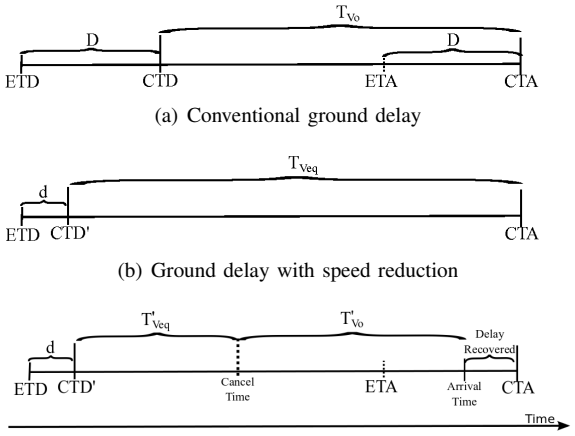


Fig. 1. Aircraft operating costs as a function of the cruise speed

C. Speed reduction strategies

Different ideas have been suggested to deal with the assigned ground delay and perform part of it as airborne delay. In [9], the *Green Delay Program* strategy is presented. Once the ground delay has been assigned, the aircraft instead of waiting on ground do part of the delay by flying at CI=0 (MRC speed). As it can be seen in Figure 2(a) and 2(b), by flying slower, the total flight time will be increased and therefore

a reduction of the ground delay will be done. By flying at MRC instead of a ECON speed (V_0), the operator will save fuel while performing the assigned delay and therefore the environmental impact is reduced.



(a) Conventional ground delay

(b) Ground delay with speed reduction

(c) Ground delay with speed reduction and regulation cancellation

Fig. 2. Ground delay with nominal and reduced speed concept

This Green Delay strategy emphasises the fuel savings at the expense of obtaining lower values of airborne delay. In [2] a different approach was suggested with the concept of the equivalent speed (V_{eq}). The goal of this strategy is to maximise the airborne delay but without incurring in extra fuel consumption. Therefore, the aircraft will fly during the cruise phase at the minimum speed which has the same fuel consumption as the initially intended cruise speed. This is achieved by flying at a speed which has the same specific range as the aircraft flying at V_0. The specific range is the distance that can be flown per unit of fuel and it is usually measured in NM/kg.

Figure 3 shows the usual relationship of the Specific Range (SR) with the cruise speed. The maximum SR is achieved when flying at the Maximum Range speed (V_{MRC}), which minimises fuel consumption. When choosing the Flight Level, the weight and the nominal cruise speed of the aircraft (V_0) (i.e. when determining the cost index), the operator is fixing the value of the specific range used for that flight (SR_0). Usual operating speeds are higher than the Maximum Range speed (V_{MRC}).

Let V_{eq} (equivalent speed), with $V_{eq} \leq V_0$, be the speed with the same SR as flying at V_0. The distance between V_0 and V_{eq} depends on the shape of the specific range function (Figure 3), which is aircraft, Flight Level and weight dependent. It is worth mentioning that V_{eq} might be limited by the minimum speed of the aircraft at that given Flight Level and weight with some safety margins. In this paper, a typical minimum margin against buffeting of 1.3g has been considered when computing the minimum operational (V_{min}) speed for a given weight and altitude[1]. As it was shown in [2], the value of V_{eq} also depends on the aircraft type, aircraft weight, flight level and V_0.

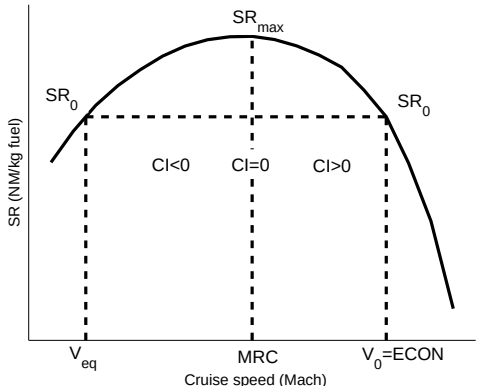


Fig. 3. Typical SR curve and equivalent speed (V_{eq}) definition

If part of the delay is absorbed with this strategy, no impact will be done on the fuel consumption nor on the delay, because the plane will fly with the same SR and will arrive to the airport at the designated arrival time (CTA). The benefit will arise in the case the regulation is cancelled while the aircraft is already on the air. With the current concept of operations, the aircraft would have performed the total delay on ground. Therefore, if the crew decide to arrive earlier (because the regulation is not longer in place), it will be necessary to speed up. Flying faster than V_0 will inevitably lead to use a lower specific range and therefore a higher fuel consumption for that trip. Yet, if the plane takes-off earlier and is flying at V_{eq} to absorb part of the delay in the air, it can recover part of the delay (once the regulation is cancelled) by increasing the speed to V_0. This will lead to a situation where part of the delay has been reduced but using the same fuel consumption as initially planned by the operator. This delay recovery strategy can be observed in Figure 2(c). When the regulation is cancelled, the plane is already airborne and therefore it can arrive to the airport earlier by flying at V_0. This strategy can be apply on any ATFM regulation which assign ground delay to a flight.

All these kind of delay management strategies will be easier implemented in the new framework of 4D trajectories envisaged in the SESAR[2] and NextGen[3] projects. These trajectories will allow to attach time windows constraints to waypoints and therefore will provide a more accurate control of the trajectory time management.

III. Simulations

In this paper the San Francisco International Airport (SFO) arrival traffic of August 24th 2005, has been used. Ground Delay Programs are frequently observed in this airport, due to the presence of low marine altitude stratus cloud layer, which reduces severely the airport capacity. The results presented in this paper are independent of the airport because the airborne delay and the time that can be recovered only depends on

[1] In order to ensure good aircraft manoeuvrability, while preventing the aircraft from stalling, the minimum operational speed is set to the stall speed at a given load factor. This load factor is typically chosen at 1.3g. [10]

[2] http://www.sesar.eu

[3] http://www.faa.gov/nextgen

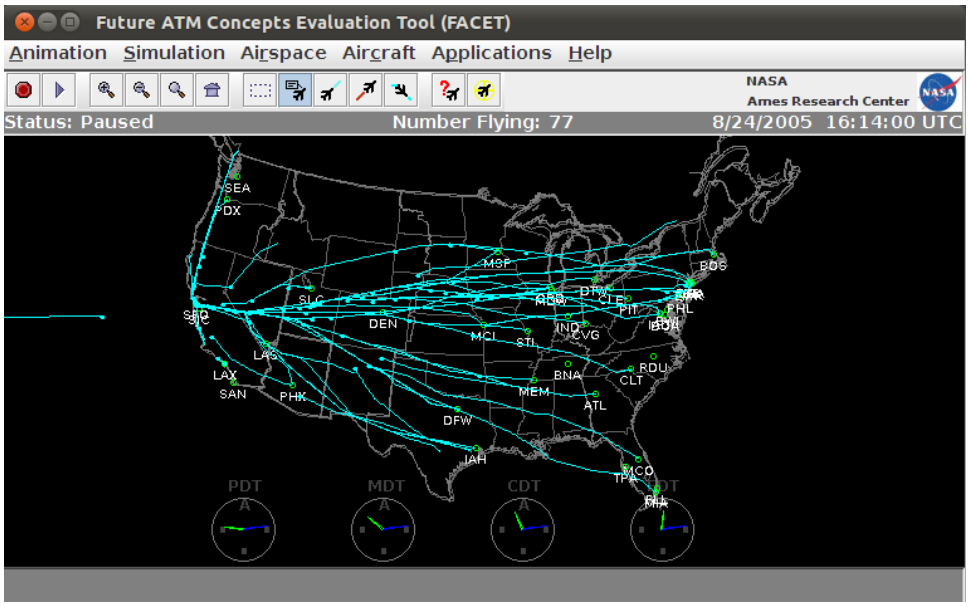


Fig. 4. FACET simulation

the flight characteristics. However, the use of real traffic data allows us to give an idea of the potential benefits of this strategy. The simulations of the strategy presented in Figure 2(c) without ground delay (d=0) has been performed using the Future ATM Concept Evaluation Tool (FACET) developed by NASA-Ames [11]. In Figure 4 it is possible to see the flow of aircraft flying to SFO during the simulation.

A. Architecture

Figure 5 shows how the simulations of the flights are performed. The speed is only changed during the cruise phase leaving FACET to compute and simulate default climb and descent profiles for each flight using the BADA database [12]. Then, once the aircraft starts the cruise phase, its mass, nominal speed (V_0) and nominal flight level are initialised in the FACET simulation according to a nominal flight plan that has been computed using Airbus Performance Engineer's Program (PEP) suite. This ensures that the performances during the cruise phase are as close to reality as possible.

The same scenario has been simulated twice. In the first simulation, the weight, speed and flight levels are initialised at the beginning of the cruise and keep constant during the whole simulation or updated only when a change of cruise altitude is needed according to the nominal flight plan. This simulation is used to compute the parameters of the nominal flights. In the second simulation all the aircraft reduce their speed to V_{eq}. Since this equivalent airspeed depends on the aircraft mass, its value is re-computed at each time the mass of the aircraft is updated in the simulation. If a particular aircraft had a change in cruise altitude in the nominal flight, it will also be performed in this second simulation. The arrival time of the V_{eq} flight minus the arrival time of the nominal flight is the maximum airborne delay that can be performed.

The relationship between flight time and flown distance,

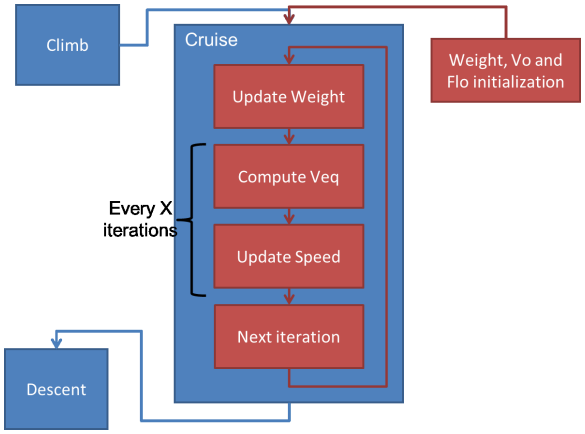


Fig. 5. Simulation diagram

at nominal conditions and at V_{eq}, has been computed in the simulations. Using this data, for each flight, it has been calculated, for each time step of the simulation at V_{eq}, the time needed to get to the destination airport if flying, from that moment, at V_0. By this computation, the aircraft is simulated at V_{eq} until that time step and at V_0 from the remaining of the flight, as presented in Figure 2(c) but with no ground delay (d=0). This will be equivalent to the simulation of a regulation which ends at that time step. The difference between the arrival time of the nominal flight and the computed arrival time, where the first part of the flight has been done flying at V_{eq} and the second part flying at V_0, is the airborne delay that has actually been done.

With the previously computed maximum airborne delay, for each flight, and knowing the amount of airborne delay that will be performed if the regulation is cancelled at each time step, it is possible to compute the delay that can be

potentially recovered. This potentially recovered delay will be the maximum airborne delay minus the actually performed airborne delay.

B. Simulation data

The Enhanced Traffic Management System (ETMS) data for August 24, 2005 was used to generate traffic information required to perform the simulations. A total of 437 planes were simulated departing from a total of 87 different origin airports. The 15 origin airports with more flights are presented in Table II, along with the average trip distances of the flights from those airports.

TABLE II
ORIGIN AIRPORTS WITH MORE FLIGHTS IN THE SIMULATION

Airport	Number of flights	Distance (NM)
LAX	31	288
JFK	21	2,347
ORD	18	1,614
DEN	16	839
IAD	16	2,128
LAS	16	382
SEA	16	621
ATL	15	1,864
DFW	14	1,322
PHNL	13	2,108
SLC	13	556
PDX	12	489
PHX	12	587
BOS	10	2,276
EWR	10	2,245

C. Assumptions for the simulations

The aircraft cruise performances for these simulations have been extracted from the Airbus aircraft databases from the PEP suite. Thus, only the Airbus family performances where available and therefore, aircraft were grouped into six different families, corresponding to six different Airbus aircraft models: A300, A320, A321, A330 and A340. This allows us to have accurate cruise performances. Then, each flight being analysed was firstly assigned to one of these families in such a way that all aircraft in the same family had similar performances. Table III shows this grouping. Nevertheless, some aircraft types were not considered for this study because they were notably different from any of the Airbus models available. In general, these excluded types corresponded to turboprops, propeller driven aircraft and small business jets.

TABLE III
AIRCRAFT TYPE ASSIGNMENT TO EQUIVALENT AIRBUS TYPES

Aircraft Family	Aircraft Types
A300	A300, A310
A319	A319, B727, B737-200, DC-9, MD-90, E-145, CRJ-200, CRJ-700
A320	A320, B737-400, B737-500, B737-800, B737-900, MD-80
A321	A321, B757
A330	A330, B767, B777, DC-10
A340	A340, B747

As stated in section II, the equivalent speed depends on the chosen Cost Index and the payload mass of the aircraft. A Cost Index of 60 kg/min has been used for all the flights considering this value as a representative value for normal operations nowadays. Finally, to estimate the payload, an 80% of passenger load factor has been supposed for short and mid-haul flights. For long haul flights a 80% of the total payload has been supposed (including also freight) [13].

IV. RESULTS

Figure 6 and Figure 7 show the delay that will be actually performed on the air for each flight if it starts flying at the equivalent speed V_{eq} and a given moment changes the speed to V_0. It can be seen how the latest the plane changes to V_0, the bigger is the airborne delay. As it has been stated before, the climb and descending phases are simulated without reducing the speed. Therefore, if the regulation is cancelled while the plane is climbing no airborne delay is done (seen as flat curve at the beginning of the flights). Similarly, if the regulation is cancelled when the aircraft is already in its descending phase, all the possible airborne delay has already been performed (flat curve at the end of each flight). This corresponds to the maximum airborne delay that each particular flight can perform. For instance, an A319 with a 830 NM flight will perform 3 minutes of airborne delay if the regulation is cancelled one hour after its take-off, while a maximum of 8 minutes can be performed if the regulation is not cancelled while flying.

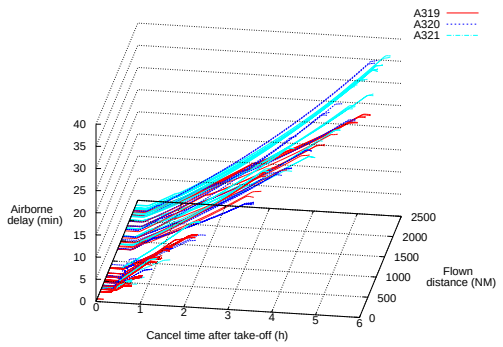


Fig. 6. Airborne delay that is performed if aircraft speeds to V_0 for A319, A320 and A321

As expected, the longest the flight, the higher is the airborne delay. The plane has a longer distance from the origin to the destination airport and therefore more airborne delay can be done without extra-fuel consumption. It is interesting to notice that there is not a big difference as a function of the aircraft type. Moreover, some flights present a sudden slope change in their graphs, specially for long-haul flights. The reason of this behaviour is due to the fact that the aircraft change their cruise altitude at that moment.

Knowing the maximum delay that can be absorbed in the air, it is possible to compute the delay time that can be

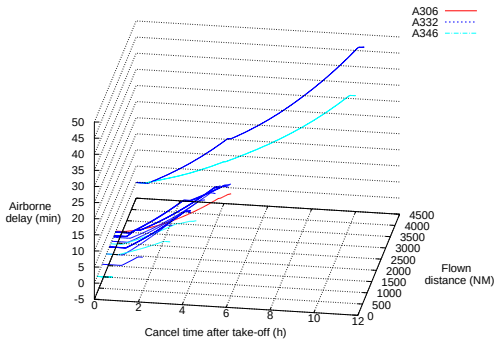


Fig. 7. Airborne delay that is performed if aircraft speeds to V_0 for A300-600, A330-200 and A340-600

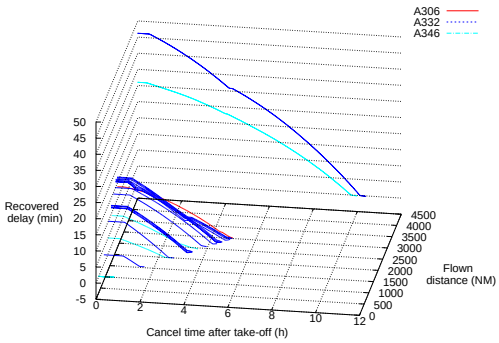


Fig. 9. Delay can be recovered if aircraft speeds to V_0 for A300-600, A330-200 and A340-600

potentially recovered for each flight (without using extra fuel) if the regulation is cancelled some time after its take-off. These results are presented in Figure 8 and Figure 9. The latest the regulation cancels, the latest the change to V_0 is done and therefore, the lowest is the time that can be recovered. For instance, in Figure 9 it is possible to see how an A330-200 with a 1800 NM flight can recover up to 10 minutes if the regulation is cancelled 2 hours after its take-off.

As it can be seen from the figures, the distances have not been analysed regularly. This is due to the fact that the analysed flights come from a specific origin airports as found in the used ETMS data set. This distribution is useful to show which aircraft are used in which routes, however it might difficult a thorough analysis of flights.

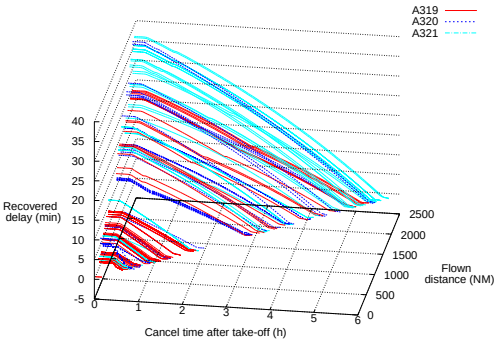


Fig. 8. Delay can be recovered if aircraft speeds to V_0 for A319, A320 and A321

V. Conclusion and Further Work

A cruise speed reduction technique, with aircraft flying at the equivalent airspeed, has been simulated with an air traffic tool (FACET). With these simulations, the amount of ground delay that can be absorbed in the air, as well as the potential delay that can be recovered without extra-fuel consumption, have been computed for each flight. This work does not focused on any particular GDP, nor tries to reproduce a GDP scenario where delay is split in ground and airborne delay. The aim of this paper is to show the airborne delay and the recovery time that can be achieved for each flight if a ATFM initiative which requires ground delay is cancelled after the aircraft has taken off. These results might be useful to airlines which would consider the potential benefit of the speed reduction technique in case of being affected by a ground delay. They will be able to predict the reduction of delay that can be achieved in function of the take-off time and the time when the regulation is cancelled.

It is worth mentioning that these results are independent of the airport of destination. In this case, the flights arrive to SFO, but the airborne delay and the potential time recovery only depend on the distance and on the flight characteristics (aircraft performances, payload and cost index). Therefore, general conclusions can be stated independently on the airport.

With the results obtained so far, it seems that the relationship between all the analysed parameters is quite linear and therefore, it would be interesting to create a fitting equation. This equation will depend on the trip distance and the time after take-off when the regulation is cancelled. Since the value of V_{eq} is cost index and payload dependent, the fitting equation will be also affected by these parameters. After performing a sensitivity study, it will be possible to use all the data to obtain an fitting equation which will allow to compute the maximum airborne delay, and the delay time that can be recovered, with the payload, cost index, trip distance and time after take-off when the regulation is cancelled as significant parameters. In this way, a rather simple equation could relate the the flight characteristics with the time that can be absorbed on the air and the delay time that can be potentially recovered if the regulation is cancelled before initially planed.

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