Ninth USA/Europe Air Traffic Management Research and Development Seminar (ATM2011)

Green Delay Programs

Absorbing ATFM Delay by Flying at Minimum Fuel Speed

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Abstract— **Delaying aircraft on ground is one of the most used strategies when an imbalance between planned demand and actual capacity arises, either at an airport or in an airspace sector. This paper focuses on a new strategy consisting in delaying aircraft from their nominal cruise speed to the minimum fuel consumption speed. Therefore, trip times are increased and air traffic management delay can be partially performed in the air. For these flights, fuel consumption is reduced and consequently, their environmental impact. Based on data from ground delay programs at San Francisco International airport during 2006, this paper quantifies the impact that such a strategy would have had if applied to all delayed flights. Results show that for the majority of flights, the 5% to 15% of the initially assigned delay could have been absorbed in the air, leading to fuel savings in the order of 4% to 7% for each individual flight, if compared with the nominal situation.**

***Keywords-** airborne delay; delay management; fuel management; speed reduction; air traffic flow management (ATFM); ground delay program; environmental impact*

I. INTRODUCTION

A central tenet of traffic flow management, as practiced in the US, Europe, and elsewhere, is that ground delay is more benign than airborne delay. Traffic flow managers thus week to anticipate capacity shortfalls and impose traffic management initiatives that assign ground delays in such a manner that airborne traffic flows do not exceed what can be handled with available resources.

As high fuel costs and greater environmental concerns have increased the focus on reducing fuel burn in the aviation community, it has become apparent that the above logic is somewhat flawed. While a minute of *time* does indeed involve much more fuel burn in the air than on the ground, the same is not always the case for *delay*. This is because a certain quantity of airborne delay can be absorbed by slowing an aircraft from its normal cruise speed to a speed that minimizes fuel burn per unit distance.

In [1-2] this en-route speed reduction concept, aiming at absorbing air traffic flow management delays, was presented. The main idea of this strategy is that once a departure delay has been imposed to a certain aircraft, this delay can be absorbed partially, or even totally, in the air by flying slower than initially planned instead of on the ground. In particular, it is proposed to fly at the minimum fuel speed (more precisely, at the maximum range cruise speed), reducing in this way, the environmental impact of the affected flights. Nevertheless, large airborne delays are not expected since actual nominal cruise speeds are already very close to this minimum fuel speed. However, the aggregate results over a large period of time may be already appealing, not only for aircraft operators but also for the sake of the environment.

This paper extends this speed reduction concept to the entire flight and analyses a whole year of Ground Delay Programs (GDP) implemented at San Francisco International airport. The effect that this speed reduction strategy would have had is quantified in terms of the amount of delay that could have been absorbed airborne and consequently, in fuel savings if compared with nominal flights. Next section gives some background in GDP and aircraft operations. Then, Section III presents the speed reduction concept while Section IV explains the experimental setup for this analysis. Finally, Section V shows and discusses the results that were obtained and Section VI concludes this paper.

II. BACKGROUND

A. Ground Delay Programs

In the US, a ground delay program (GDP) is implemented when an airport is expected to have insufficient arrival capacity to accommodate forecast arrival demand. The FAA, acting in its role as traffic flow manager, first proposes a program in which flights are assigned slots in order of the original schedule. This is known as Ration by Schedule (RBS). Next, individual airlines are given an opportunity to reassign and cancel flights based updated flight status information and their internal business objectives. This is an intra-airline process—a carrier can only use slots that were originally assigned to its flights based on RBS. In some instances, inter-airline slot transfers are desirable. Mechanisms for such transfers include

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[◊] This work was carried out during a visiting period at the University of California, Berkeley sponsored by the Catalan government under the research mobility grant program: *Beques BE del departament d'Economia i Coneixement.de la Generalitat de Catalunya.*

compression, in which FAA assigns unused slots to other carriers, and slot credit substitution, in which airlines can request an inter-airline trade from FAA. The trade will be allowed when—as is often the case—it also benefits other carriers. This joint and iterative effort is known as collaborative decision making (CDM) and gives aircraft operators the opportunity to have greater control over the economic impacts of a GDP.

On the other hand, some flights are exempted from the FAA assigned delay. A first set of exempted flights are those being airborne at the time the GDP is implemented and international non-Canadian flights. The second set is GDP dependent and exempts flights originating outside a certain radius from the affected airport [3]. One of the main reasons for applying this policy is because of the uncertainty when estimating the arrival capacity of the airport. These predicted capacity reductions are often caused by adverse weather conditions which in turn, are sometimes forecasted several hours before. Thus, too pessimistic forecasts can lead to excessive ground delays. Since flight originating farther from the airport must execute their ground delay well in advance of their arrival, most of the delay is usually assigned to shorter-haul flights by exempting flights originating outside the abovementioned radius. The actual value of this radius is fixed at the GDP implementation and depends mainly on the severity of the capacity reduction. Then, for each non-exempt (or *controlled*) flight in a GDP, a controlled time of arrival (CTA) is assigned at the destination airport. Based on filed flight plans and weather forecasts, trip times can be estimated with a reasonable accuracy and consequently, the CTA is translated to a controlled time of departure (CTD) at the origin airport. Thus, the CTD is the CTA minus the trip time and the 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 [4].

B. *Aircraft operations and Cost Indexing*

Airlines are responsible to safely operate their aircraft, within the operational limits given by the manufacturer and according to a complex and detailed set of regulations. Part 121 of the Federal Aviation Regulations (FAR) [5] specifies how to compute the minimum amount of fuel before take-off, in the United States (US). In Europe, similar requirements are found in the EU-OPS regulations [6]. Essentially, the block fuel (the total amount of fuel before starting the engines at the origin airport) is decomposed by the required fuel for taxi; the nominal trip, with some route reserves; a trip to an alternate destination airport; and a hold for 30 minutes. Thus, in an ideal flight, with a perfect computation of fuel consumptions flight times and winds aloft; and no diversions, re-routes or holds; only taxi and trip fuel quantities would be burned.

Given an origin and destination airports, trip fuel can be minimized by computing appropriately the shortest route and optimizing the vertical flight profile (i.e. aircraft speeds and altitudes). Given an aircraft type, this optimal vertical flight profile depends on the actual weight of the aircraft. Thus, for the same route and aircraft type, optimal cruise flight levels and speeds, along with climb and descent profiles, will be different for different aircraft weights.

Besides fuel consumption, time-related costs are also important to consider in the majority of civil aviation flights. These costs include for instance, maintenance or flight crew related costs [7]. Moreover, as shown in Fig. 1, we have also a set of fixed costs that are constant for a given flight and do not depend on the aircraft cruise speed. Fuel and time-related costs, however, have a clear dependency on the chosen aircraft speed. As seen in this figure, 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 logically decrease as speed increases, since trip times become shorter. Therefore, a trade-off appears between the fuel consumed and the time needed to fly a certain route and it remains to the aircraft operator to assess this compromise, according to their operational policies. The optimal speed minimizing the total cost is often called the ECONnomic speed and is always greater than the MRC speed (see Fig.1).

Aircraft equipped with Flight Management Systems (FMS) use a Cost Index (CI) parameter when optimizing flight profiles. 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[1] of the CI gives all the importance to flight time, regardless of the needed fuel. In this case, the aircraft will fly at the maximum operating speed with, in general, some safety margins.

Airlines can reduce their operating costs by an efficient management of the CI settings on their scheduled flights [8]. In fact, the CI value not only affects the cruise airspeed but determines the whole flight trajectory. This means that the

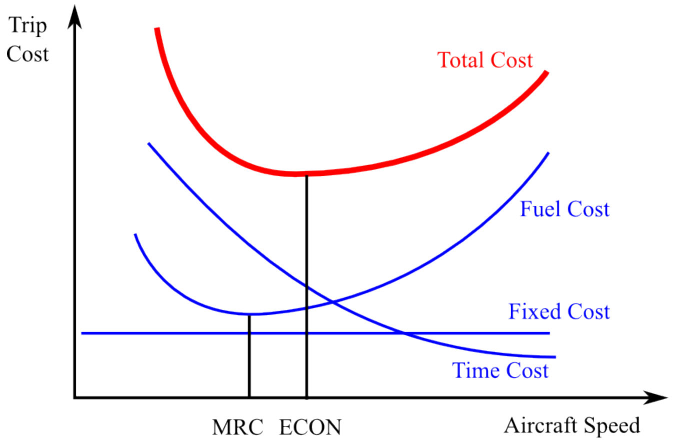

Figure 1: Aircraft operating costs in function of the cruise speed

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[1] Strictly speaking, CI is defined as the cost of time divided by the cost of fuel and multiplied by a scalar. Depending of the FMS vendor, this scalar might be different and therefore, the actual value of the maximum CI too. Typical CI maximum values are 99 or 999.

optimal flight level may change and that the climb and descending profiles might be also different for different CI values. For example, a high CI will lead to higher aircraft speeds and therefore shallower climb angles. In general, typical CI values being used nowadays by aircraft operators range between 30 to 70 kg/min [7].

Summing up, given a flight distance, a payload weight[2] and a Cost Index, the optimal Flight Level, the optimal cruise speed and consequently, the fuel needed for that particular flight (block fuel) are determined and can be computed by using an iterative optimization algorithm.

III. ENVIRONMENTALLY FRIENDLY DELAYS

As explained before, when a GDP is issued, delayed departures are assigned to a subset of (controlled) aircraft arriving at the regulated airport. In this way, these aircraft arrive at fixed time intervals (or *slots*) which prevent to exceed the airport arrival capacity. On the other hand, and as discussed in Section II.B, airlines generally use a Cost Index greater than zero when considering the cost related to flight time. Therefore, usual operating speeds are higher than the MRC speed. However, if a particular flight is affected by a GDP the arrival time is fixed and time-related costs cannot be further optimized. Then, “taking advantage” of the imposed delay, the aircraft could depart earlier from the origin airport, save fuel, and consequently reduce the environmental impact, by flying at the MRC speed so that it arrives at the destination airport at its assigned time. Nevertheless, the “cost of time” might be higher when the aircraft is airborne than when it is waiting on ground at the origin airport; since for example, in some companies crew salaries are in function of actual flight hours. Even if this fact could eclipse the fuel savings of the proposed speed reduction strategy, it is out of the scope of this paper; where a unit of time will be supposed to have the same cost for the operator regardless if the aircraft is flying or waiting on ground.

Fig. 2 compares this speed reduction concept with the current ground delay strategy. In both cases, the aircraft is asked to arrive at the regulated area at the CTA with a given time window or *slot*. With the current GDP implementation, this requires delaying the flight at the origin airport by D minutes. After this delay, the nominal flight plan is executed with a total flight time of T_o minutes. With the proposed strategy, the aircraft incur a ground delay of d minutes (with $d \leq D$) and will fly slower than initially planned. In this way, it will take T minutes to reach the destination airport, such that $d + T = D + T_o$. Consequently, the ground delay at the origin airport is reduced and, in some cases, can eventually be suppressed. It should be noted that the aircraft will still experience the imposed GDP delay at the *arrival* airport, since this delay has been distributed by waiting on ground at the origin airport and by flying slower during the route. Therefore, all fairness aspects, regarding different aircraft of different companies, have been already considered during the CDM slot allocation process that leads to these initial GDP delays for each particular flight.

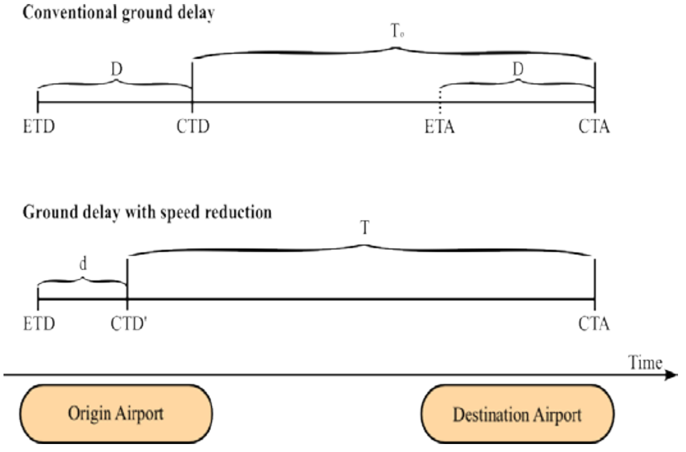

Figure 2: Schema of the conventional ground delay and the airborne speed reduction strategies

The feasibility of this strategy was shown in [1-2], where more details are given on the rationale for this speed reduction strategy for air traffic flow management purposes. In this reference, example results are presented for some European flights, showing that in general, the amount of total airborne delay remains below 15 minutes for a typical mid-haul flight. Obviously, the exact value of this delay highly depends on the aircraft type, trip distance, actual payload weight and nominal Cost Index. Therefore it is hard to extrapolate some general conclusions and a flight by flight analysis is indeed necessary.

IV. EXPERIMENTAL SETUP AND DATA AVAILABILITY

The case study presented in this paper focuses in San Francisco International Airport (SFO), which is the tenth busiest airport in the United States. Ground Delay Programs are frequently observed in this airport, especially in the spring and summer periods, due to the presence of low marine altitude stratus cloud layer, which reduces severely the airport capacity. In this example, all the GDPs that were implemented during 2006 are analyzed. For all delayed flights, the amount of airborne delay is computed and compared with the originally assigned ground delay. Then, the fuel benefits that this speed reduction strategy would have had are also shown.

A. Flights affected by Ground Delay Programs at SFO

Data from the Enhanced Traffic Management System [9] (ETMS) were used to filter all the flights with destination SFO, for the different GDPs thorough the year. For each flight, some essential information was extracted: the origin airport; the great circle distance between origin and destination airports; the aircraft type; the flight schedule and the firstly assigned ground delay.

It should be noted that subsequent updates to ground delays, due to possible substitutions and cancellations arising from airline policies and the CDM process, were ignored and are out of the scope of this paper. Thus, we focus in the initial (and static) picture of the GDP: when an imbalance in demand and maximum capacity is detected at SFO and delays are assigned to a subset of (controlled) inbound flights.

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[2] Typically composed by passengers and luggage; freight; and mail.

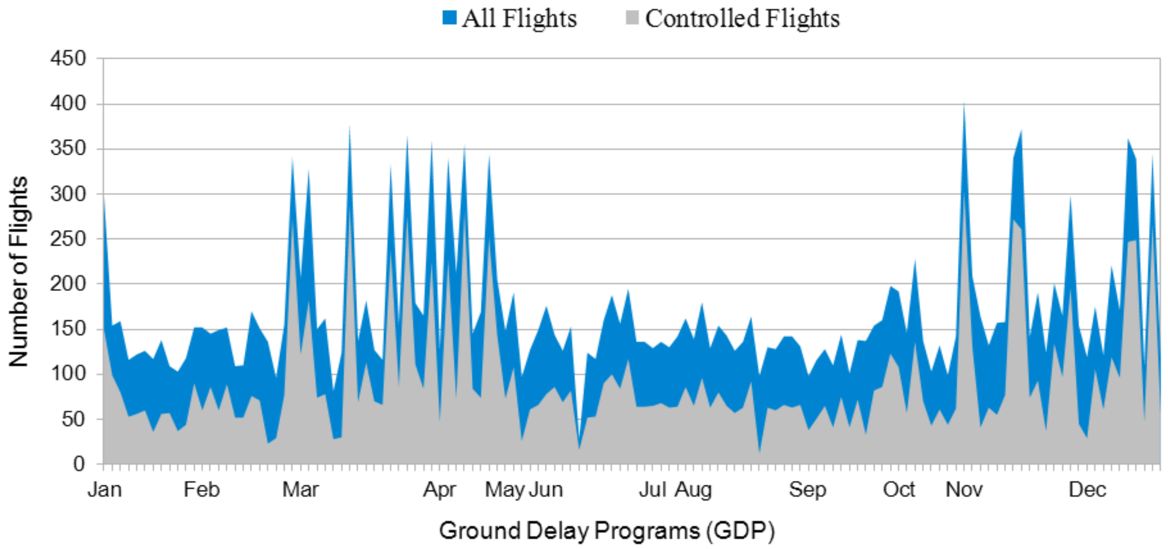

Figure 3: Number of flights affected by each considered GDP.

The goal of our study is to compare the differences in fuel consumption (and therefore, the impact of the environment) of this situation with respect to the same scenario but with the speed reduction strategy in place. Should this new strategy be executed in a real case, it will undoubtedly affect the subsequent decisions from the aircraft operators on substitution and cancellation, which might be different from what they had decided in the conventional GDP case.

According to the available data set, 130 GDPs were put in place in 2006 due to capacity constraints at SFO airport. During these GDPs, a total of 22,170 flights were scheduled to arrive at SFO. Among them, 15,917 had not departed from their origin airports at the time the GDP was filed, with the remaining 6,253 already flying to SFO. As explained in Section II.A, besides already flying aircraft, each particular GDP also exempts all flights departing from origins outside the GDP scope radius. The rest of the flights are not exempt, and a ground delay is assigned to them. For this data set, there were 12076 controlled flights. Fig, 3 shows the number of flights for each different GDP as they were distributed along the year. As seen in the figure, the majority of GDPs took place between the months of May and September. For each GDP, the typical number of affected flights (i.e. flights that were planned to arrive at SFO during the period the GDP was active) lies between 100 and 150, with few exceptions that included up to 400 affected flights. Aside from these unusual cases, we observe that roughly half of the affected flights were controlled while the rest were exempted, either because they were already flying or because their departure airport fell outside of the GDP scope radius.

On the other hand, Fig. 4 shows the histogram of the assigned delays to all controlled flights. We observe that around the 75% of all delayed flights experienced delays that were greater than 30 minutes. It is clear that with the speed reduction strategy presented here, it would not be possible to absorb in the air such large delays. However, even if a small part of them can be performed airborne, the impact in fuel consumption may be substantial, as we will show in Section V.

B. *Aircraft Performance*

At the time this study was performed, only aircraft performance data from the Airbus commercial aircraft fleet were available. Furthermore, it would be computationally infeasible to simulate every single aircraft type in the data set. For these two reasons, aircraft were grouped into six different families, corresponding to six different Airbus aircraft models: A318, A319, A320, A321, A330 and A340. Then, each flight being analyzed was firstly assigned to one of these families in such a way that all aircraft in the same family had similar performances. Table I 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.

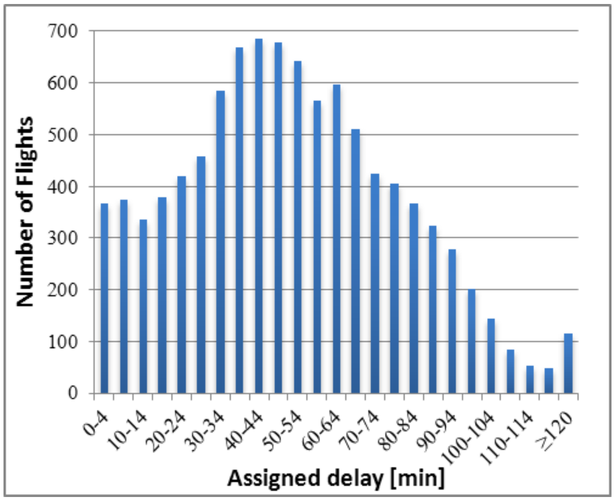

Figure 4: Distribution of the initially assigned delays

TABLE I. AIRCRAFT TYPES CONSIDERED AND THEIR ASSIGNMENT TO EQUIVALENT AIRBUS TYPES

Aircraft family	ETMS aircraft type
A318	A318, EMB-135, EMB-145, CRJ-200, CRJ-700, CRJ-900
A319	A319, B727-100, B737-200, B737-300, B737-500, B737-700, DC-9, MD-80, MD-90
A320	A320, B737-400, B737-800, B737-900
A321	A321, B757-200, B757-300, B757-700
A330	A330-200, A330-300, B767-200, B767-300, B767-400, B777-200, B777-300, DC-10
A340	A340-300, A340-600, B747-100, B747-200, B747-400
Aircraft type not considered	A300, A310, AS65, ASTR, BE40, CL60, CXX, DA90, F2TH, FAXX, GALX, GLF, H25X, HXX, LJXX, MU30, PRM1, R721, SBR1, WW24

TABLE II. COMPUTED PAYLOAD FACTORS

Aircraft family	Number of flights	Average Payload Factor
A318	20324	68.58
A319	25704	66.03
A320	27636	68.73
A321	24709	62.27
A330	10811	63.21
A340	218	58.31

C. *Payload mass*

As explained in Section II.B, the weight of the aircraft at take-off is one of the principal variables that affect the optimal flight profile and therefore, the actual fuel consumption. Given a Cost Index and a trip distance, the weight of the aircraft at take-off directly depends on the payload weight. For this example, data from the T100 database [10] were used to give an estimate for this payload weight for each of the analyzed flights. This database contains monthly traffic and operational information about every commercial flight segment that originates or terminates in the United States. However, for this study only domestic flights were available.

All 2006 passenger & cargo traffic with destination to SFO was filtered. For each aircraft type, origin airport and month, T100 data specifies the number of flights and the aggregated values of transported passengers, freight and mail weights. Thus, for each of the 29 aircraft types present in the data set, the average payload weight was computed[3]. Then, this value was normalized with respect to the maximum payload weight of each specific aircraft model, obtaining an average *payload factor*[4] for each aircraft type that flew to SFO in 2006.

As explained before, in this study performance data from only six different aircraft types were considered. Thus, payload factors were grouped according to the same aircraft family distribution depicted in Table I and proportionally averaged in function of the number of appearances that each particular aircraft type had. As a result, Table II shows these values for each aircraft family, along with the number of flights that were present at the T100 database that allowed this average computation.

D. *Operational and additional assumptions*

Some additional assumptions were considered in the flight optimization process that allowed computing trip fuel and times. They are summarized as follows:

- The Great Circle Distance (GCD) between each origin airport and SFO was considered instead of using the actual en-route structure and terminal area procedures. This assumption leads undoubtedly to shorter flight distances and therefore, to shorter trip times and airborne delays.
- Wind was not considered for any flight when computing flight times and fuel quantities. It is clear that wind conditions could notably affect the actual trip times and therefore, the amount of airborne delay. Yet, for this study it was out of the scope to consider the sensibility to different wind conditions.
- For all simulated flights, Sacramento International airport (SMF) was considered as alternate airport when computing the required block fuel according to FAA regulations [5].
- For all simulated flights, the flight optimization was performed considering one or two cruise altitudes[5], keeping the most optimal solution.
- Nominal flights were simulated at a Cost Index of 60 kg/min, which is a typical value chosen by aircraft operators.
- Flights with origins *too close*[6] to SFO were excluded from simulations because the benefits of the speed reduction strategy would be negligible. Moreover, the optimal flight profile for such a short flight does not correspond, in general, to the actual profile due to airspace structure, navigation procedures or ATC constraints. According to this consideration, Table III summarizes the number of flights involved in this study for each of the considered families.

Wrapping up, the experimental setup for this study consisted on assigning an Airbus equivalent aircraft (Table I) and an estimated payload factor (Table II) at each flight affected by a GDP at SFO during 2006. Then, for each single flight, two independent flight optimizations were performed at Cost Indexes of 60 kg/min (the nominal flight) and 0 (maximum range flight); and according to all previous assumptions. After these two computations, the optimal flight profiles for each simulated Cost Index were obtained and in particular, the required trip fuel and times.

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[3] In order to compute the weight of the passengers and their luggage, the standard value of 250 lb (113.4 kg) per passenger was used.

[4] Making an analogy with the *load factor* term, which denotes the ratio between the transported passengers and the total number of seats available in a given flight.

[5] As long as the aircraft burns fuel and loses weight, the optimal flight altitude increases. Therefore, in function of the aircraft type and payload, there exist a certain distance where it becomes optimal to perform a step climb and change the cruise altitude rather than keeping the original altitude.

[6] For this study we discarded flights originating at less than 75NM from SFO.

Figure 5: Schema of the flight optimizations performed for each flight in the data set

Fig. 5 shows a schema of this flight optimization process. The maximum airborne delay (*AD*) is simply the difference between these two trip times ($AD = T_o - T$), and the associated fuel savings correspond to $\Delta F = F - F_o$.

TABLE III. NUMBER OF FLIGHTS IN THE ETMS DATA SET

Aircraft family	**All flights**	**GCD from origin airport > 75 NM**		
		Exempted		***Controlled***
		Flying	***Not Departed***	
A318	2902	162	187	2407
A319	4587	1007	677	2884
A320	4486	883	983	2618
A321	3814	1359	906	1533
A330	2253	1207	591	450
A340	1588	1353	174	60
Aircraft type not considered	2540	1956	309	1647
TOTAL	22170	7927	3827	11599

V. RESULTS

For the majority of the analyzed flights, the maximum amount of airborne delay was between 5 to 9 minutes. Figure 6 shows the distribution of these delays. As mentioned before, these apparently low values are in line with the expected results, since the actual range of cruise operational speeds are relatively limited [1]. On the other hand, Figure 7 shows the distribution of the optimal cruise Flight Levels, either for the nominal flights (CI=60 kg/min) and for the flights at MRC speed.

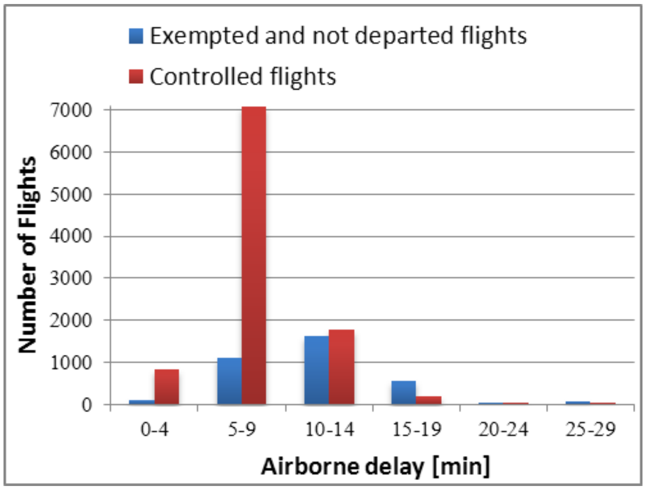

Figure 6: Distribution of the maximum amount of airborne delay

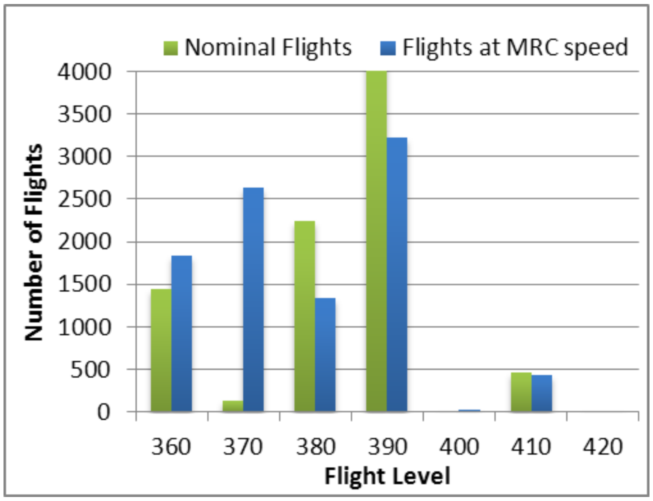

Figure 7: Distribution of the optimal flight levels

For each flight in the data set, the actual assigned delay was directly compared with the maximum amount of airborne delay that could have been performed for that flight. Figure 8 shows the histogram of this comparison, showing the percentage of assigned delay (originally expected to be executed on ground at the origin airport) that could have been performed in the air. As seen in the figure, the majority of the flights could absorb between the 5% and 15% of the original ground delay. It should be noted that for some 600 flights (around the 6% of the controlled flights during the whole year) the airborne delay was equal or greater than the assigned delay, meaning that these flights could have departed “on time” and absorb the assigned delay entirely in the air.

On the other hand, Fig. 9 shows the impact in fuel consumption that this speed reduction strategy would have had if applied to all controlled flights. We observe savings between 4% and 7% in the majority of the flights. These are very significant values economically and environmentally speaking. From the simulated flights, we computed a total figure of 42,759 metric tons of fuel when considered all controlled flights in nominal conditions (i.e. with CI=60 kg/min) and 40,837 tons for the case of all flights flying at the MRC speed and therefore, executing part of the assigned GDP delay in the air. This represents a total saving of 1,922 tons of fuel thorough the year (approximately a 4.5% of the total burned fuel). It is interesting to compare this global figure of 4.5% with the individual fuel savings for each flight as shown in Fig. 9. In general, individual flights show fuel savings greater than 4.5%, meaning that larger fuel savings (as percentage of the total trip fuel) are observed in flights with lower trip fuel quantities (i.e. short hauls).

Fig. 6 also shows the distribution of airborne delay minutes for those flights that were originally exempted from the GDP, but still not departed from their origin airport at the time the GDP was put in place. Therefore, these aircraft were exempted because their origin airports fell outside the GDP scope. As expected, having these flights, in general, longer hauls than controlled ones; the amount of airborne delay is consequently higher. This fact suggests the possibility to consider these

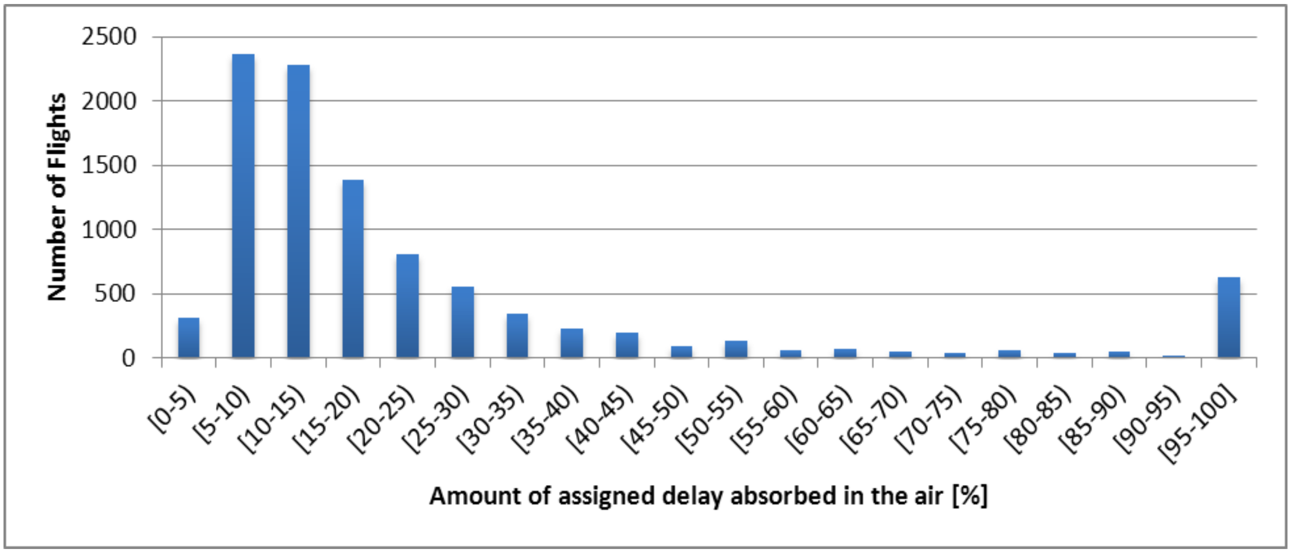

Figure 8: Histogram of the percentage of assigned delay that can be performed in the air by slowing the aircraft.

flights in all the GDPs (i.e. to increase the scopes of all GDPs to all US airports) and consequently reduce even more the fuel consumption by allowing them to fly at the MRC speed while absorbing part of the assigned delay.

In fact, the main reason for these limited GDP scopes is the presence of several uncertainties when estimating the maximum capacity at the regulated airport (especially when the GDP was motivated for bad weather conditions [11-12]). Moreover, in some cases it may also exists a mismatch between planned and actual demand [13] and therefore, some GDPs are cancelled well before the planned end time. That is why longer haul flights are often exempted from delay assignment, since some chances exist that the GDP will cancel before their arrival. However, with the speed reduction strategy presented in this paper, long haul flights could actually perform an important part of the assigned delay airborne. Then, in the case the GDP is cancelled, since the flight is already in the air, it would be in a better situation to recover the performed delay. These probabilistic situations are subject of on-going research by the authors.

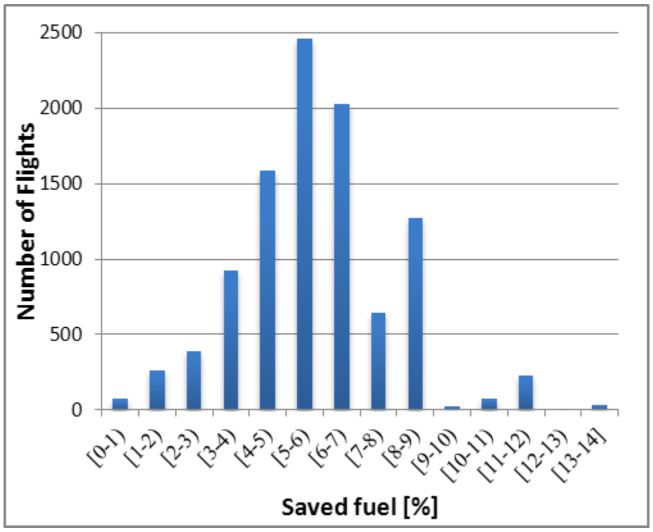

Figure 9: Histogram of the saved fuel per considered flight

VI. CONCLUSION

In this paper we introduce a special case of airborne delays: those originated by reducing aircraft speed along their routes. This concept offers twofold benefits: from the airlines point of view, it reduces the overall costs associated to GDP by reducing the fuel consumption of all affected flights. On the other hand, reductions in fuel consumption lead to lower gaseous emissions and therefore, contribute to lower the environmental impact of aviation.

The proposed strategy could be added to current flight planning decision-making tools used by aircraft operators in such a way that, once a GDP has been issued, the operator can decide on the best strategy to face the delays assigned to their fleet (and consider substitutions, cancelations, re-routings, ground holdings, flying slower, etc.). In the framework of future SESAR/NextGen improved operations, it is expected that airlines will negotiate and share information with the network planner and other companies in order to converge to a feasible solution when a capacity-demand imbalance appears. Therefore, if airlines are able to accurately compute the costs associated to all the possible actions they can take when facing these imbalances, they would be in a better position to minimize the impact that ATFM delays may cause to their operation [14].

It is clear that these airborne delays cannot substitute the current ground delay strategy, since the amount of time that an aircraft can be delayed in the air by flying slower is very limited. Yet, both strategies are indeed complementary and all the delay that cannot be absorbed in the air can be executed on-ground, as done with the current GDP implementation. The quantitative analysis performed shows very promising results, especially if considering the aggregate effects of the observed fuel savings, and not only for reducing costs at airline level but also for the consequences in the reduction of the environmental impact. Obviously, derived results from this study may not be reflective of what can be expected on a regional/national basis; since airborne delay and consequent fuel savings highly depend on parameters such as aircraft weight, optimal cruise altitudes or wind conditions aloft. However, flying at the minimum fuel speed leads always to some benefits, even if small; and the sum of these individual contributions can be significant at national/regional level.

It should be noted that aircraft speed can be even lower than the minimum fuel speed. Yet, fuel consumption increases again for speeds below the MRC speed (see Fig. 1). For example, one could reach the speed (below the MRC) that leads to same fuel consumption than the nominal flight. This case would lead to even higher airborne delays, but with no fuel (and environmental) savings. This situation was explored with some preliminary results in [1] and work is underway to extend this idea to the same data set used for this paper.

Future work will also deal with a new delay assignment algorithm that takes into account the possibility to slow down the aircraft in the decision variables. In fact, a potential asset of this strategy is when uncertainty is incorporated to the delay assignment algorithms by considering, for instance, probabilistic capacity scenarios at the destination airport.

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