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Delgado, L. and Prats, X.

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Tenth USA/Europe Air Traffic Management Research and Development Seminar (ATM2013)

Effect of Radii of Exemption on Ground Delay Programs with Operating Cost Based Cruise Speed Reduction

Case study: Chicago O'Hare International Airport

Luis Delgado and Xavier Prats
Telecommunication and Aeronautical Engineering School of Castelldefels
Technical University of Catalonia – Barcelona Tech
Castelldefels (Barcelona), Spain
[luis.delgado,xavier.prats]@upc.edu

***Abstract*—When a ground delay program (GDP) is defined, a radius of exemption is typically set to exclude from having to realize ground delay aircraft departing from greater distances than the selected radius distance. A trade-off exists when defining this radius: big radii distribute the required delay among more aircraft and reduce the airborne holding delay close to the destination airport, while the probability to realize unnecessary delay increases if the program is canceled before planned. In order to overcome part of this drawback, a cost based cruise speed reduction strategy aiming at realizing airborne delay was suggested by the authors in previous publications. By flying slower, at a specific speed, aircraft that are airborne can recover part of their initially assigned delay without incurring extra cost if the GDP is canceled before planned. In this paper, the effect of the exemption radius is assessed when applying this strategy and a case study is presented by analyzing all the GDPs that took place at Chicago O'Hare International Airport during one year. Results show that by the introduction of this technique, more delay can be saved. Thus, it is possible to define larger radii of exemption, reducing partially the drawbacks associated with smaller radii.**

***Keywords*—Ground delay program; speed reduction; radius of exemption; delay savings**

I. Introduction

In the presence of capacity shortfalls and/or demand peaks, in North America, ground delay programs (GDP) are defined at airports. By realizing slot assignation at the congested arrival airport, the demand is not overpassed and costly airborne holding delays around the congested infrastructure are minimized. In order to meet their assigned controlled time of arrival (CTA), flights are requested to wait on ground prior to their departure. When a GDP is implemented, a radius of exemption is applied. This means that aircraft taking off outside that radius have a slot reserved for them but they are not required to realize the delay. The size of this radius has an impact on the amount of delay that is served on ground and on the airborne holding delay that will be needed close to the destination airport. Finally, it also affects to the amount of delay that is saved if the regulation is canceled beforehand [1].

On the other hand, speed control for air traffic management purposes has been the subject of several research studies and projects. Some works propose speed control as a mechanism to enable traffic synchronization strategies [2], [3]. In this context, [4] proposed en-route speed reductions to prevent aircraft from performing airborne holding patterns when arriving in the congested airspace. A similar rationale is behind the ATM long-range optimal flow tool developed by Airservices Australia [5], where aircraft within a 1,000 NM radius of Sydney Airport are proposed to reduce their flight speed in order to prevent them from arriving before the airport is open, and thereby reducing unnecessary holdings. More recently, a joint Federal Aviation Administration (FAA) and Eurocontrol study, estimated that half of the terminal area inefficiency in the system today could be recovered through speed control in the cruise phase of flight, without reducing throughput efficiency [6].

At a pre-tactical level, some research has also been conducted considering speed control as an additional decision variable to solve the Ground Holding Problem [7], [8]. However, the economic impact (or solely the impact on fuel consumption) caused by these speed variations is seldom investigated.

With the cruise speed reduction strategy presented by the authors in [9], it is possible to absorb part of the assigned delay while airborne maintaining the fuel consumption as initially planned. This strategy is interesting considering that air traffic flow management (ATFM) initiatives are usually canceled before initially planned [10], [11]. Thus, if a regulation is canceled, the aircraft that are already airborne can change their speed to the initially planned one and recover part of the delay at no extra fuel consumption. In [12] this strategy was applied to the arrival traffic to SFO. However, in that study the whole national airspace system (NAS) was considered and only international flights were exempt. In this paper, the effect

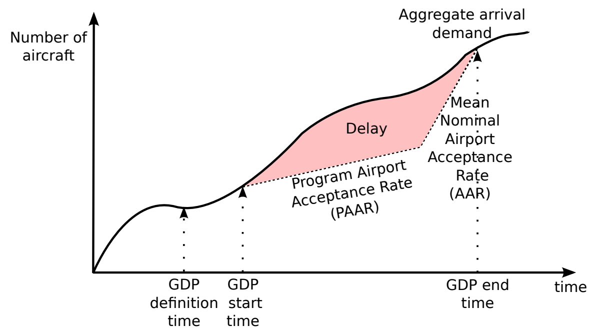


Fig. 1. Ground delay program scheme

of the radius of exemption on this strategy and the benefits that arise, in terms of delay recovered are studied.

Next section discusses the required background for the paper with special focus given to the ground delay program initiatives. Section III is devoted to explaining the equivalent speed concept and its applicability to ATFM initiatives. In section IV the use of the speed reduction technique applied to Chicago O'Hare (ORD) traffic and the effect of the definition of radius of exemption are presented. The results are presented in section V and discussed in section VI. Finally the paper concludes with section VII, where the main findings are summarized and further research highlighted.

II. Ground Delay Programs

As stated in [1], when an imbalance between demand and capacity takes place, delay is generated. The total amount of delay required to balance this mismatch is approximately constant. For a reduced capacity at an arrival airport, this amount of delay depends only on the airport acceptance rates (AAR) and the flight demand at the airport, as shown in Fig. 1.

In the ATFM community, it is widely accepted that ground delay at origin airports is preferable than delay near the congested sector/airport, from a fuel consumption (and environmental) point of view [13]. In the United States of America, 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, acting in its role as traffic flow manager, activates a program where aircraft are assigned to available slots following a ration-by-schedule principle [14]. After this assignment, airlines are given an opportunity to reassign and cancel flights based on updated flight status information and their internal business objectives. This is achieved in a collaborative decision making (CDM) process motivated by a need to combine information sources [15], [16].

A. Exemption Radii

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 defined and international non-Canadian flights. The second set is GDP dependent and exempts flights originating outside a certain radius from the affected airport or outside a number of tier[1] from the center where the affected airport is located of the NAS [1].

One of the main reasons for applying this exemption policy is 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 forecast several hours ahead. Thus, too pessimistic forecasts can lead to excessive ground delays. Since flight originating further from the airport must execute their ground delay well in advance their arrival, if the ground delay is canceled, all that accrued delay would be unnecessary. For this reason, most of the delay is usually assigned to shorter-haul flights by exempting flights originating outside the above mentioned radius.

The actual value of this radius is fixed at the GDP implementation and depends mainly on the forecast severity of the capacity reduction. It is possible to define alternative programs by changing this radius. For the flights taking off outside that distance a slot is reserved for them at the arrival airport but no delay needs to be served. If the radius is small, then the majority of the aircraft are exempt of realizing ground delay. However, if the AAR does not increase, holding delay must be realized. As the radius of exemption increases, the pool of flights that receive ground delay increases and therefore, there is a decrease in the holding delay needed. Beyond a certain distance, the holding delay remains almost constant. A program distance shorter than the point where holding delay is minimized is not optimal since unnecessary and expensive holding delay could be transferred to safer and cheaper ground delay. As the radius of exemption is increased, the average and maximum delay are reduced, as the total amount of delay is divided between more participants, however, the unrecoverable and the unnecessary delay tends to increase.

B. Unnecessary delays

The unrecoverable delay is the part of the delay that will be incurred even if the program is canceled and the unnecessary delay is the delay that is realized when it was not needed because the regulation is canceled before planned [1]. If the delay is assigned to aircraft originating from far away airports, at a given time, more delay has already been accrued, as the delay needs to be realized long time before the arrival slot time. Therefore, in this case, less delay can be recovered if the ground delay is canceled. Thus, there is a trade-off between the holding delay needed (high costs), the maximum and average delay assigned (fairness of the GDP) and the potentially recovered delay if the GDP is canceled ahead planned (maximizing the benefit of uncertainty).

Finally, one of the problems faced when a GDP must be implemented is the estimation of the capacity shortfall and therefore, the duration of the GDP initiative. For example,

[1]At present, the NAS is divided into 20 centers, and for each center a first and a second tier are defined. The first tier is the set of all centers immediately adjacent to the center in consideration, and the second tier is the first tier with the centers immediately adjacent to the first tier centers, an so on.

for GDPs caused by degraded meteorological conditions, if weather clears before forecast it will lead to under use of capacity at the airport and result in unnecessary delays. Conversely, if reduced capacity conditions last longer than expected the GDP will have to be extended and/or inefficient air holdings will be necessary near the destination airport. Since the predicted capacity at the airport is often subject to uncertainties, airspace managers are typically conservative and the GDP is usually planned to last longer than actually needed. Essentially, it is preferred to have planes waiting on ground, even if not necessary, and cancel the GDP earlier rather than having too many flights arriving at the concerned terminal maneuvering area when the available capacity cannot yet accommodate all of them. Thus, it is common to cancel the restriction before initially planned. This leads to a under use of capacity at the airport and to unnecessary ground delays.

III. The Cruise Speed Reduction Strategy

In [17], it was proposed that ground delayed aircraft could fly at the minimum fuel speed (the maximum range cruise speed). In this way, the fuel consumption (and environmental impact) of these flights was reduced at the same time as some ATFM delay was absorbed in the air. The impact of this strategy was quantified by analyzing the historical data of all delayed flights to San Francisco International Airport over one year.

A different strategy was proposed in [9], where aircraft were allowed to fly at the lowest possible speed in such a way that the specific range (SR) remained the same as initially planed. In this case, the aircraft speed being slower than the maximum range cruise speed (MRC), higher values of delay absorbed in the air were obtained while exactly the same fuel as initially planed in the nominal situation was consumed. This strategy is useful if we consider the fact that air traffic management initiatives, such GDPs might be canceled before their planned ending time, as is often the case [10], [11].

A. The equivalent speed concept

The specific range is defined as the distance flown per unit of fuel burnt, and it is usually measured in NM/kg or NM/lb. The SR function typically presents a maximum that corresponds to the MRC speed. This maximum is present because at typical flight altitudes and aircraft weights, the function relating the fuel flow with the true airspeed is nonlinear and increases monotonically. The reason is that usually, the minimum operational speed is faster than the minimum drag speed. In this paper, a typical minimum margin against buffeting of 1.3g is considered when computing the minimum operational speed for a given weight and altitude[2].

Since typical operating speeds are higher than the MRC speed, as the aircraft operator considers also the cost of time[19], the actual specific range (SR_0) is lower than the

[2]In order to ensure good aircraft maneuverability, 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. [18]

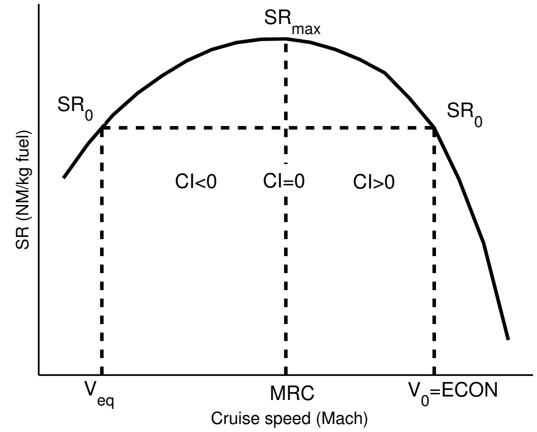


Fig. 2. Specific range as a function of cruise true air speed and V_{eq} definition

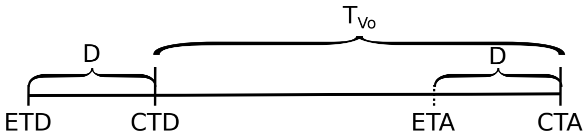
maximum one. The equivalent speed (V_{eq}) is defined as the minimum speed that produces the same specific range as flying at the nominal speed V_0, as shown in Fig. 2 The margin between V_0 and V_{eq} depends on the shape of the specific range curve which is aircraft, flight level and weight dependent. It is worth mentioning that V_{eq} might be limited by the minimum operating speed. In the presence of wind, the equivalent speed can be computed considering the specific range with respect the ground speed. However, the effect of wind is out of scope of this paper and its effects and results of the amount of airborne delay in the presence of wind environments are presented in [20].

B. Speed reduction applicability

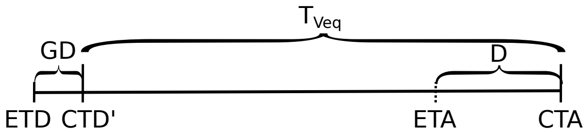
Flying at V_{eq}, the airborne delay realizable without incurring extra fuel consumption is maximized. Yet, only a few minutes of delay can be performed in the air by flying at this speed during the cruise. For example, in a typical Frankfurt International Airport to Madrid Barajas flight (769 NM), 7 minutes of airborne delay can be realized without using extra fuel consumption (see in [9] other example flights). Therefore, the airborne delay will be typically lower than the total assigned delay due to an ATFM regulation (such as GDP). Thus, the total assigned delay will be divided between some ground delay, at the origin airport, and airborne delay while flying slower, as depicted in Fig. 3.

Notice that in the ground holding problem literature, when the term airborne delay is used it is mainly referred to fuel consuming and undesired holdings and path stretching. However in this paper the term *airborne delay* is used to define the delay that can be realized during the cruise by flying at the equivalent speed without incurring extra fuel consumption and the term *holding delay* is used to define the delay realized at the arrival at the airport due to lack of capacity.

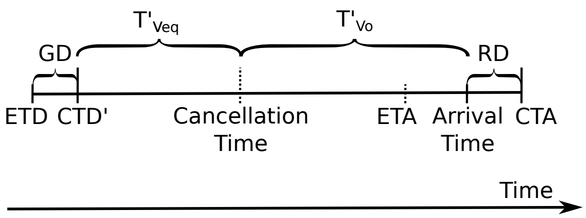
GDP controlled flights are expected to arrive at a given CTA at the destination airport, with a given time window or slot. With the current GDP implementation, this requires delaying the flight at the origin airport by D minutes. After this delay,



(a) Conventional ground delay (baseline scenario



(b) Ground delay with speed reduction



(c) Ground delay with speed reduction and GDP cancellation

Fig. 3. Application of speed reduction concept on ground delay programs

the nominal flight plan is executed with a total flight time of T_{V_0} minutes.

With the en-route speed reduction strategy, the aircraft incurs a ground delay of d minutes ($d \leq D$), takes off at a new departure time (CTD') and flies slower than initially planned. In this way, it will take $T_{V_{eq}}$ minutes to reach the destination airport, in such a way that $d+T_{V_{eq}} = D+T_{V_0}$ (i.e. the aircraft is arriving at the same CTA as in the baseline scenario).

For a particular flight, if the GDP is not canceled before the aircraft arrives at the destination airport the same amount of delay occurs in the baseline and in the speed reduction scenarios. Moreover, the same amount of fuel is burned in both cases (according to the V_{eq} definition). The benefits of this strategy occur when the assigned delay is reduced due to cancellation of the restriction: it is possible to recover part of the delay, by speeding up to V_0, without incurring extra fuel costs over the initially planned flight. With the current concept of operations, where and aircraft absorbs the total amount of assigned delay on ground, delay recovery can only be done by speeding up over V_0 leading to more fuel consumption for that trip than initially planned.

It is worth mentioning that aircraft crew could increase the cruise speed above this nominal speed, recovering even more delay, but at the expense of more fuel consumption than initially planned (as studied, for instance in [21]). However, this paper focuses on the case where delay recovery is performed at no extra fuel consumption. Finally, the suggested speed reduction strategy is difficult to implement if CTAs are not enforced as it is expected to be in the near future in the context of SESAR and NextGen.

The application of an exemption radius has two major impacts on the use of this speed reduction strategy. Firstly, the average assigned delay is increased, as fewer slots are available for the aircraft performing the delay, and secondly, the flying distances available to realize airborne delay are consequently reduced, among the reduction of the long haul flights.

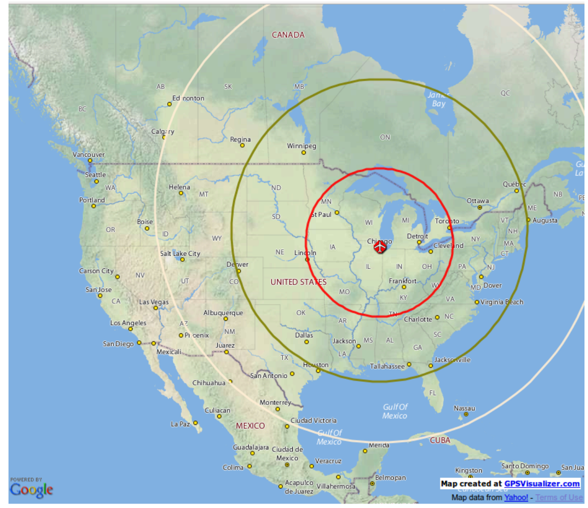


Fig. 4. Chicago O'Hare airport with 400 NM, 800 NM and 1,200 NM radii

IV. Case of Study: Simulation

In the United States, according to the CDM archival database, a total of 1,052 GDPs were defined in 2006 by a total of 49 airports. Chicago O'Hare International Airport was the third airport by number of GDPs with 120 (11.4% of the total). Since this airport is a hub for United Airlines, when a GDP is issued a high number of aircraft are affected leading to high quantities of assigned delay. For this reason, ORD is the airport with more minutes of GDP served during that year, with a total of 4,533,341 minutes (25.14% of all the delay generated in 2006 due to GDPs) and had a total of 92,816 aircraft affected. Moreover, by its location, a GDP defined in ORD includes origin airport gradually as the radius of exemption is progressively increased, as it can be seen in Fig. 4. For all these reasons, ORD is selected to be studied in this paper and the inbound flights to the airport are simulated subject to different GDP scenarios. The simulations are conducted using the Future ATM Concept Evaluation Tool (FACET) developed by NASA-Ames [22] and the Airbus Performance Engineer's Program (PEP) suite to obtain accurate cruise performance date to model the specific range functions of the aircraft and derive their equivalent speed.

A. *Traffic and ground delay program analysis*

For this paper, the August 24th and 25th, 2005 Enhanced Traffic Management System (ETMS) data is used to generate the traffic information required to perform the simulations. Moreover, all GDPs defined in 2006 in ORD are analysed and clustered according to their main characteristics.

1) Traffic analysis: A total of 2,846 flights are simulated to generate the demand. As only the Airbus families performances are available, aircraft are grouped into six different types, corresponding to six different Airbus aircraft models:

TABLE I. CLUSTERS CENTROIDS FOR 2006 GDPS AT ORD (HOURS IN LOCAL TIME)

GDP group	GDPs	Filed time	Start time	Planned end time	Cancel time
All–day GDPs	65	8h28	9h52	22h19	20h13
Afternoon GDPs	43	14h58	15h26	22h15	19h58
Early cancel GDPs	12	7h49	9h02	18h33	9h53

A300, A320, A321, A330 and A340. The families of aircraft types are created based on the characteristics of the aircraft, in such a way that all aircraft in the same category have similar performances, as done in [9].

After this grouping, 2,370 flights are simulated with Airbus performance, representing 83.3% of the total traffic. The 16.7% remaining traffic is not considered for the speed reduction strategy, either because the aircraft are already flying when the simulation started, or because they are notably different from any of the Airbus models available (i.e. small business jets, turboprops and propeller driven aircraft). All these flights, however, are simulated to correctly represent the demand at the airport. If any of those flights has assigned GDP delay, it will be done completely on the ground, as in the current concept of operations.

2) Ground delay programs analysis: In 2006, approximately the 75% of all the GDPs were defined due to weather related issues. Different scenarios in airport arrival acceptance rate reflect in most cases well-identified weather patterns in the regions where the airports are located [23]. As most probably a set of GDPs are defined at an airport for common reasons, it is expected that they have similar characteristics and therefore it is possible to determine representative GDPs for a given airport. The *K–means* clustering algorithm [24] is used in this paper to group all GDPs defined in ORD in 2006 in different categories. The GDPs are characterized by their filed time, starting time, planned ending time and actual cancellation time; and the Euclidean distance between these times is considered. It should be noted, that in this clustering the AARs are not used.

As a result from this analysis three representative clusters are obtained and their centroids are shown in table I. This clustering has a silhouette coefficient of 0.46[3]. Thus, according to this clustering in Chicago O'Hare there are three types of characteristic GDPs: the first category by number of regulations (65 GDPs) includes the ground delay programs that are declared in the morning and extended during the entire day (*All–day* GDPs). In general, these GDPs are canceled around 2 hours before initially planned. The second group (43 GDPs) is formed by the GDPs that are implemented during the afternoon (*Afternoon* GDPs). These programs are planned to be extended, in average, until 22h15, however they are canceled with 2h15 of anticipation. Finally, some days in 2006 (12 GDPs) regulations where declared early in the morning but they were probably not needed. In some cases they are canceled even before their start time (*Early cancel* GDPs). For this cluster, their average cancellation time is 7h40 minutes before planned, only 3h15 minutes after being filled and less than 2 hours before their start time.

[3]The silhouette coefficient is a parameter which ranges from -1 to 1, being 1 a perfect clustering [25].

B. Assumptions for the simulation

1) On the traffic: A cost index of 60 kg/min is used for all the flights except for the A330 and A340 families where a cost index of 120 kg/min is selected[4]. These values are representative for common operations [19]. To estimate the payload, an 80% of passenger load factor is assumed for A320 and A319 flights, while for long haul flights (A300, A330 and A340) 80% of the total payload is considered (including also freight) [26].

It is assumed that airlines optimize their flight plans considering the cost index in order to minimize the total cost of their flight. Once the flight is optimized, it is considered that, in the current concept of operations, the aircraft flies at its nominal speeds after realizing the delay on ground. In the V_{eq} scenario, as the same fuel as initially planned, even if airborne delay is realized, the total operating cost is maintained as the initially planned by the airline.

It should be noted that only the change of speed during the cruise is considered, therefore, the flight levels are maintained as defined in the original optimal flight plan.

2) On the Ground Delay Programs: In order to simulate the GDPs, it is considered that the centroids of each cluster are representative of their category and therefore are used for the simulations. Only two airport acceptance rates are defined, a reduced one (PAAR), which is considered while the capacity is limited, and a nominal airport acceptance rate used otherwise. For ORD, the AAR is considered to be 112 aircraft per hour and the PAAR 84 aircraft per hour. These values are in accordance with the runway capacities and operations defined by the FAA [27].

From the cluster analysis the GDP definition time, along with the start and ending times, are fixed (see Table I). With these values we compute the time where the airport capacity changes from the PAAR to the AAR (see Fig. 1) in such a way that the end of the GDP (i.e. when the traffic demand is equivalent to the available capacity) corresponds to the time defined by the cluster

It is assumed that once the GDP is canceled, the capacity at the airport is unconstrained. Even if this is not always true, since the GDP has shifted the demand, the natural spread of flights times and schedules seems to allow traffic management to use this criterion quite extensively in practice. This assumption is similar to one of the cancellation policies defined in [10].

The maximum delay that can be recovered is computed assuming that the aircraft that are delayed on ground, at

[4]The CI expresses the ratio between the cost of the flight time and the cost of fuel. By choosing the CI the pilot is changing the ratio of cost between fuel and time and therefore, is determining the speed which minimizes the total cost (Cost = Fuel + CI · Time). It should be noted that the CI value not only affects the cruise speed but determines the whole flight trajectory. This means that the optimal flight level may change and that the climb and descending profiles might also be different for different CI settings.

the cancellation time, can immediately take off and that the airborne aircraft, which are flying at V_{eq}, can speed up immediately to V_0. The recovery of the delay is computed assuming that no extra fuel consumption is produced, thus, the speed is not increased over V_0 once the regulation is canceled.

Finally, the simulations are carried out in wind calm conditions, in order to avoid masking the results with the uncertainty associated to actual wind conditions. The reader is referred to [20] for an assessment of the effect of the wind in the proposed speed reduction strategy.

As stated in [1], for each GDP, there are infinitely many distances that can be selected for the exemption radius. However, the finite set of airports to be included or excluded from the program naturally reduce these possibilities into a discrete set of options. There is no interest in considering an additional distance if it does not encompass a new set of airports. However, for the study undertaken in this paper, three different radii are considered in nautical miles from ORD: 400 NM, 800 NM and 1,200 NM (see Fig. 4). The distance of the flight plan is considered to decide if an aircraft is affected or not by the radius of the ground delay program.

C. Simulation setup

After analyzing and adapting the ETMS traffic, as explained in the section IV-A, the trip distance of each flight is determined. For this purpose, the flight plans, as defined in the original traffic file, are considered. Therefore, the distance from an origin airport might be different for two flights depending on the actual route flown. Then, by using the Airbus PEP suite and the assumed cost indexes and payloads, the nominal parameters for each flight are computed: initial cruise weight, cruise flight level(s) and speed(s) with the required cruise steps if needed.

The initial traffic is simulated twice. In the first simulation the speed and flight levels of the aircraft are maintained to their nominal values computed with PEP. At each step of the simulation the fuel flow is computed according to the Airbus performances of the aircraft. If the minimum cost flight plan computed with PEP requires a step climb, it will be accordingly simulated, considering the weight. The result of this simulation at V_0, is the initial arrival demand at the airport. The application of the GDP to this demand, in order to keep it below the airport capacity, results in the amount of delay assigned to each aircraft.

In the second simulation, all the aircraft reduce their cruise speed to V_{eq}. As the equivalent speed varies with the weight, at each simulation step (one minute), the equivalent speed is recomputed for all the airborne flights considering their current weight. If a particular aircraft had a change in cruise altitude in the nominal flight, it will also be performed in the second simulation. By doing a comparison of the arrival times between the two simulations, it is possible to compute the maximum airborne delay that each aircraft can realize without incurring extra fuel consumption.

After this, the assigned delay is divided into ground and airborne delay. In the case that a particular flight has assigned

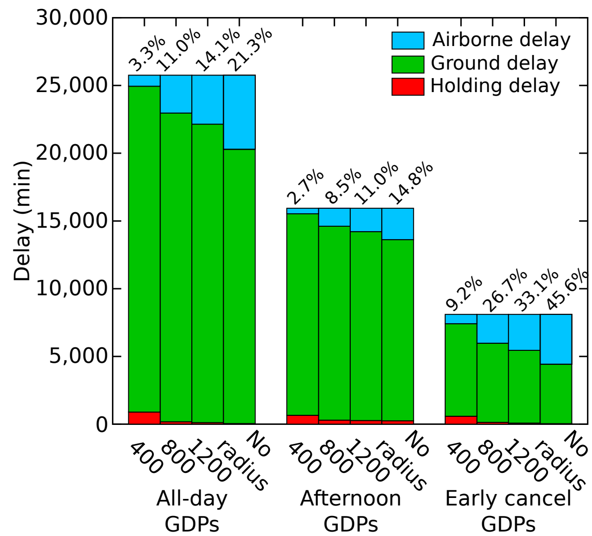


Fig. 5. Division between holding delay, ground delay and airborne delay per simulated GDP. Percentage of airborne delay over the total assigned delay (ground delay and airborne delay)

a delay smaller than the maximum airborne delay realizable by flying at V_{eq}, a new speed (between V_{eq} and V_0) is selected. This new speed is adequately chosen in order to fulfill the CTA, and consequently, for those flights, all the assigned delay is done in the air while saving some fuel with respect to the nominal situation.

It is worth noticing that as the speed is only adjusted during the cruise, it is not necessary to compute accurately the fuel consumption during the climb and descent phases. Consequently, these phases are directly simulated by FACET, which uses the Base of Aircraft Data (BADA) database [28] for the performances of the aircraft.

V. SIMULATION RESULTS

A. Application of ground delay program on traffic

Fig. 5 shows the division between holding delay, ground delay and airborne delay for each of the distances and each of the simulated GDPs. The percentage indicates, for each GDP, the relative value of the airborne delay with respect to the total delay assigned. It is worth noticing that, as expected, the total amount of delay needed to accommodate the demand to the airport capacity is approximately constant, as it was presented in Fig. 1. With the increment of the radius, a transfer of where the delay is served is produced. As stated before, once the holding delay is minimized, an extension of the radius does not reduce any further its value.

For example, in the *All-day* cluster with a 400 NM radius the holding delay is 890 minutes and the assigned delay is 24,867 minutes. If the radius is increased to 800 NM the holding delay required is reduced in 712 minutes that are shifted to assigned delay. The potentially delay realized airborne is increased in 1,977 minutes. If the 400 NM radii are dismissed due to their high holding delay (see Fig. 5), the increment of the radius does not represent a significant reduction on the holding delay.

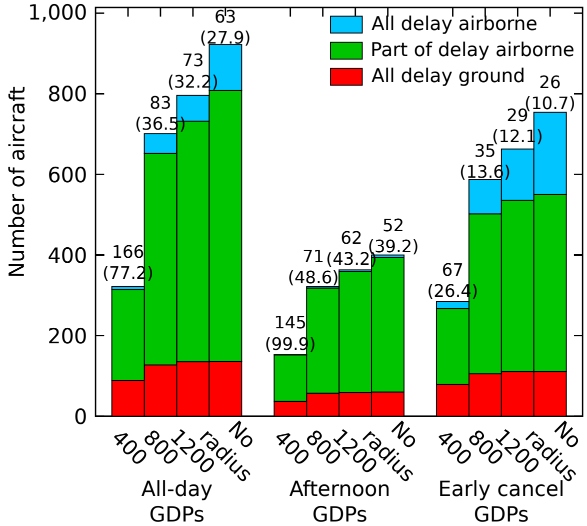


Fig. 6. Aircraft affected by GDP. The value indicate the maximum assigned delay. Between brackets it is presented the average assigned delay

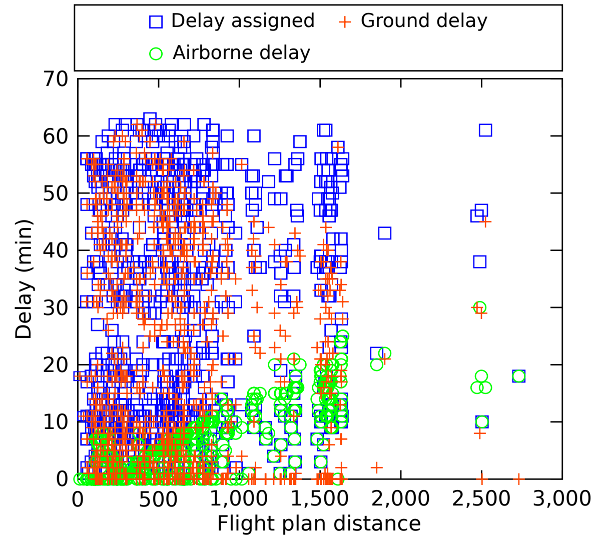


Fig. 7. Airborne delay and division between ground and airborne delay as a function of the flight plan distance for the *All-day* cluster

Thus, for ORD a radius of 800 NM already minimizes of the holding delay.

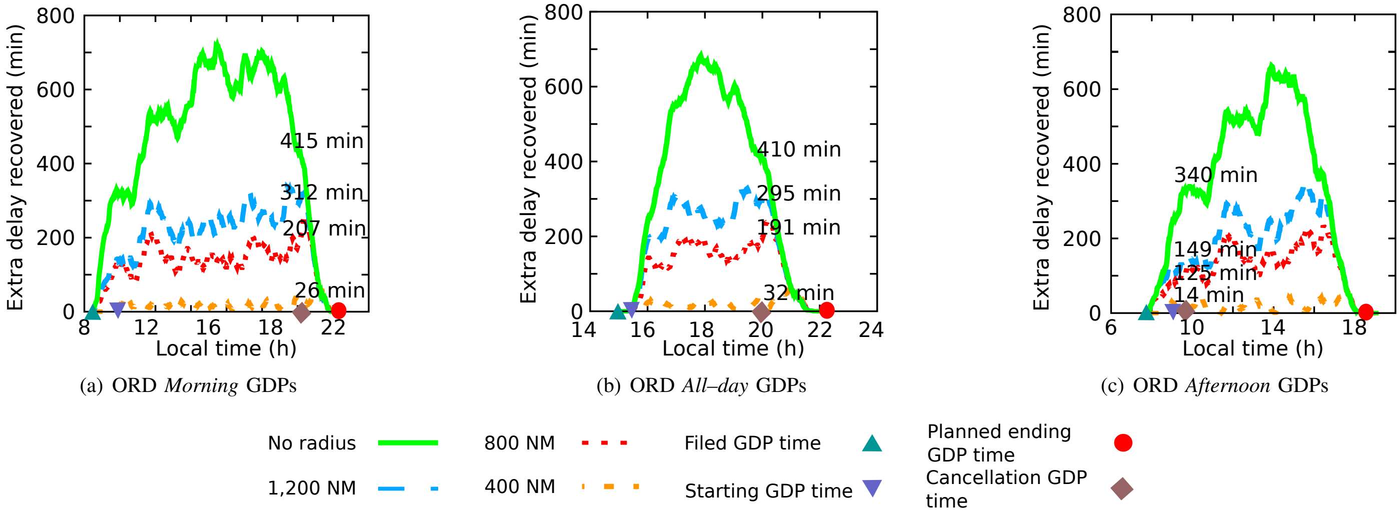
The rest of the delay (ground and airborne delay) would be realized completely on ground if the speed reduction technique is not applied. However, if the cruising speed is adapted to V_{eq}, it is possible to realize part of that delay while airborne without incurring fuel consumption. As commented before, the amount of airborne delay realized in this manner, with respect the ground delay increases with the radius. For average radii lengths, the amount of airborne delay varies between 9% and 15% of the total assigned delay, but it is possible to observe that if the whole NAS is used the airborne delay is around 20% , being able to reach up to almost 50% in some cases. As an example, for the *Afternoon* GDPs, the ground delay and the airborne delay assigned for the 400 NM radius is 14,876 minutes and 408 minutes respectively (2.67% of the total assigned delay can be realized airborne), for the 800 NM 14,317 minutes and 1,326 minutes (8.48%), for the 1,200 NM 13,946 minutes and 1,726 minutes (11,01%) and 13,374 minutes and 2,317 minutes when no radius of exemption is defined (14.77%).

The increment of the radius leads to more flights in the pool of aircraft which can potentially have delay assigned and that can realize part of that delay airborne, as depicted in Fig. 6. Those aircraft will also come from further distances and therefore can potentially realize higher amounts of airborne delay during their longer cruise. The flights that absorb part of their delay while airborne are the ones which can potentially recover part of their assigned delay without incurring extra fuel consumption by speeding up to their nominal speed once the ground delay program cancels.

Another effect of the increment of the radius of exemption is that the maximum and the average delay are reduced as the total amount of delay is divided between more flights. As a consequence, the number of flights that can realize all their assigned delay airborne, i.e. flying at a speed between V_0 and V_{eq} and therefore saving fuel, increases. Fig. 6 also shows these tendencies. For example, in the *All-day* GDPs, the maximum assigned delay decreases from 166 minutes to 83 minutes by setting a radius of exemption of 800 NM instead of 400 NM. The average delay assigned by aircraft also decreases, from 77.2 minutes to 36.5 minutes. This reduction in the maximum and average assigned delay facilitates the absorption of delay airborne. Thus, when the average delay is only of 10.7 minutes, as in the No radius case of the *Early cancel* GDPs, 45.6% of the total assigned delay can be realized while airborne by flying at V_{eq}. It is worth noticing that there is a direct relationship between the type of traffic an airport generally has and the amount of aircraft which are able to realize all their assigned delay airborne. The aircraft types and average flight length are as important as the arrival demand.

The increment on the amount of airborne delay done with the length of the radius is a tendency but it is not proportionally related. The underlying reason is that in order to increase the amount of airborne delay realized, it is needed to increase the pool of aircraft with delay assigned, and as it was commented previously, the increment of the radius has only an interest if the number of airports from where the flights originates also increases. In Fig. 7, it is presented for the *All-day* ground delay program, the assigned delay and the division between ground, and airborne delay for all the affected aircraft as a function of their flight plan distance. As the flight plan increases, the maximum airborne delay realizable increases too. For example, for flight shorter than 1,000 NM, the maximum airborne delay realizable is almost always below 10 minutes. As the slot assignation is based on the estimated time of arrival it is distributed independent on the flight plan length. For this reason, the longer the radius of exemption the higher the potential airborne delay realizable.

Due to the location of ORD, there is a progressive inclusion of airports as distance increases, see Fig. 4 and Fig. 7. Thus,



(a) ORD *Morning* GDPs (b) ORD *All–day* GDPs (c) ORD *Afternoon* GDPs

Fig. 8. Extra delay recovered as a function of cancellation time and radius of exemption. Value the amount of extra delay at the cancellation time according to the centroids of each GDP

the increase of the radius of the GDP implies a smooth increment of airports and therefore, aircraft which can potentially realize airborne delay, leading to a gradual increment on the proportion of airborne delay over the total.

B. *Delay saved if ground delay canceled*

For each simulated GDP, the amount of delay that is recovered if the regulation is canceled before planned, and the aircraft flying at V_{eq} speed up to V_0 is computed. If all the delay is realized on ground, the recovered delay can only be the one that is not accrued yet. For a given flight, see Fig. 3, the delay recovered will be all the initially assigned delay if the cancellation time is before the flight's estimated time of departure (ETD). It will be the difference between the cancellation time and the controlled time of departure if the GDP cancels between the ETD and the CTD. If the flight has already taken off, however, no delay is recovered for that flight since it is assumed that the flight cruises at V_0. With the speed reduction strategy, the recovered delay is increased by the time that can be gained by speeding up to V_0 (i.e. not using extra fuel) for the aircraft that are already flying at V_{eq} when the GDP is canceled.

Fig. 8 shows the difference between the delay recovered if the speed reduction technique is implemented and the nominal case where all the delay is realized on ground if the ground delay program is canceled at each simulation step. Therefore, it is indicating the delay that is extra recovered by the aircraft airborne. In each plot it is also indicated the amount of extra delay recovered at the cancellation time according to the GDP clusters defined in table I.

The total number of aircraft affected in the ground delay programs applied to ORD is high, but due to the large capacity of the airport, the average delay per aircraft is relatively small for long radius of exemption. This produces that the amount of aircraft realizing part of the assigned delay airborne is very high, as presented in Fig. 6. Therefore, if the regulation is canceled before initially planned, there are a significant amount of aircraft in the air which can potentially increase their speed to their nominal one and recover part of the delay. Thus, the airborne delay recovered can be up to 717 minutes.

As expected, the longest is the radius of exemption, the more airborne delay is recovered. As commented in the previous section, the increment of airborne delay as a function of the radius, depends on the traffic and location of the airport, for Chicago O'Hare the benefit of using the speed reduction strategy increases gradually with the length of the radius of exemption, see Fig. 7 and Fig. 8. For example in the *Morning* GDPs case, the extra delay recovered thanks to this technique increases from 26 minutes to 207 minutes, 312 minutes and finally 415 minutes, as the radius of exemption increases from 400 NM to the whole NAS.

From these results, it could be concluded that the FAA should always define a radius of exemption the longest as possible in order to maximize the extra recovery. However, when deciding the optimal radius for a given GDP, the total delay saved when canceled before planned should be considered (ground and holding delay that are not realized), as it is stated in [1]. In general a long radius implies less delay recovered as aircraft have already serve delay then the regulation is canceled.

Fig. 9 presents the total delay recovered if the ground delay programs are canceled at their cancellation time according to their clustering. As depicted, the extra airborne delay recovered can represent up 60% of the total ground delay recovered. As a direct implication of the use of an exemption radius, the longer the radius, the lower is the holding delay, and therefore, less holding delay is recovered if the GDP is canceled ahead of planned. Similar behavior is appreciated for the ground delay, as more ground delay is accrued with a longer exemption

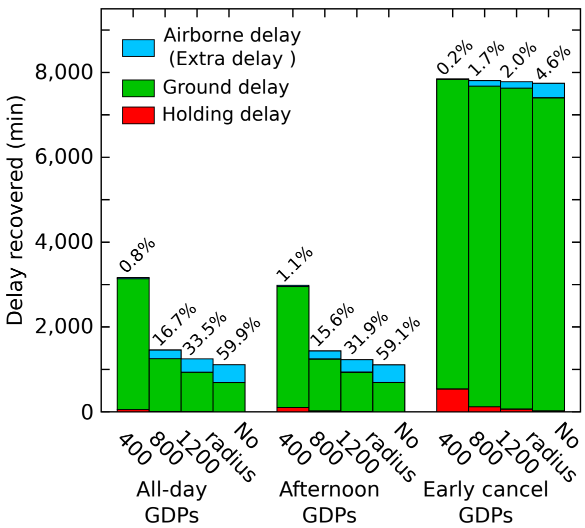


Fig. 9. Results at cancellation time according to the centroids. The percentage indicate the saved airborne delay with respect the ground saved delay

TABLE II. AGGREGATED EXTRA DELAY SAVED FOR ALL GDPS DURING ONE YEAR PER RADIUS OF EXEMPTION

400 NM rad (min)	800 NM rad (min)	1,200 NM rad (min)	No Radius (min)
3,246	23,168	34,753	48,685

radius due to the longer flight distance the aircraft need to fly to attain their assigned slots, delay that can not be recovered. Thus, there is a trade-off between the holding delay realized and the amount of delay that can be recovered at the cancellation time.

VI. DISCUSSION OF THE RESULTS

The aggregate extra delay saved using the speed reduction strategy is computed for each radius and presented in table II, considering that the extra delay saved is realized per each GDP of each of the categories. At this aggregate level values are significantly high even if for a single GDP the extra delay recovered is relatively small.

If the benefit of using the speed reduction strategy in terms of extra delay recovered is relatively small for short GDPs radii, the use of this technique has an interesting benefit: the difference in recovered delay when the regulation is canceled beforehand is reduced between two consecutive studied radii. For example, as depicted in Fig. 9, if no speed reduction technique is implemented the difference between the delay recovered with a 400 NM radius in the *All-day* GDPs and a 800 NM radius is of 1,885 minutes. In the speed reduction scenario, the distance between them is of 1,704 minutes (181 minutes less). In the *Afternoon* case, the difference between the 800 NM and the 1,200 NM radius is 309 minutes if all the aircraft fly at their nominal speed and 205 minutes if the speed reduction strategy is implemented (a reduction of 104 minutes). This behavior is found in all the cases studied.

Moreover, if the 400 NM radius GDPs are dismissed due to their high holding delay, in general, selecting a longer radius of exemption with the speed reduction technique leads to the same amount, or even more, of delay recovered than doing a smaller radius without speed reduction. As an example, in the *All–day* GDP cluster, only 2 extra minutes of delay are saved with an 800 NM radius and no speed reduction implemented with respect a 1,200 NM exemption radius where the cruise speed reduction technique is realized (see Fig. 9). In the *All–day* GDP cluster 172 extra minutes of delay are recovered if the whole NAS is used with the speed reduction technique with respect the total delay recovered with a 1,200 NM radius and no speed reduction.

VII. CONCLUSION

The use of a radius of exemption has implications on the GDPs and on the use of the speed reduction strategy suggested in this paper. When defining a GDP with a radius of exemption, the network manager has to consider the associated trade-offs. On one hand, it is better to define a small radius as the unrecoverable delay is minimized. Thus, if the regulation is canceled before planned, more delay can be recovered. On the other hand, a large exception radius ensures a reduction of the maximum and the average assigned delay as the pool of affected aircraft is increased. This leads to a fairer and less costly solution and the expensive and undesired holding delay is minimized as more delay is realized on ground[5]

In this paper, it has been shown that airborne speed reduction allows using higher radii of exemption minimizing the negative impact on the total amount of delay recovered. Therefore, this technique allows the radii to be increased – having similar benefits in terms of delay recovery like with shorter radii and without the speed reduction technique – and reducing the difference in delay recovered between different radii. This has the additional advantage that the average delay assigned is smaller as the total delay is divided between more aircraft. Therefore a less costly and a fairer ground delay program is implemented.

Considering the speed reduction strategy, the bigger the radius the more distance is available to realize airborne delay by the aircraft and therefore more delay can be absorbed during the cruise phase without incurring extra fuel consumption. Moreover, more aircraft realizing airborne delay implies that the number of flights which can potentially recover extra delay by speeding up during their cruise if the regulation is canceled is maximized. Finally, as higher radii imply lower average assigned delays, the number of aircraft that can realize all their assigned delay in the air, and by doing it save some fuel with respect their initially planned flight plan, is also maximized.

It is worth remembering that the effects of the use of a radius of exemption are airport and demand dependent. The location

[5]As stated in [1]: "the total ground delay and the total cost may not be related in a simple manner. As the delay assigned to a flight increases, it becomes more likely that passengers will miss connections, that crews will timeout, that the delayed availability of aircraft will cause delays on subsequent flights, etc. Thus, the cost to an airline of 20 flights each incurring 15 minutes of delay, as a rule, is less than the cost of 5 flights each incurring 60 minutes of delay".

of Chicago O'Hare airport leads to a proportional increment of the airborne delay realized as a function of the radius length. For other airports this behavior might be different and should be studied. The use of more realistic scenarios including wind should also be considered because, as presented in [20], wind in general represents an increment on the amount of airborne delay realizable. Thus, the benefits of this strategy will even be increased.

In this paper only the cruise speed has been modified as it is easier from an operational point of view. However, in [9] it was shown that if the flight level is optimized in order to maximize the airborne delay realizable the values of airborne delay increase significantly. Therefore, instead of just adjusting the cruise speed, a whole trajectory optimization could be considered to increase the airborne delay while maintaining the fuel consumption.

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Author Biography

Luis Delgado is an Aeronautical engineer from the National School for Civil Aviation (École Nationale de l'Aviation Civile, ENAC) located in Toulouse (France). He also holds a degree in Computer Science Engineering from the Technical University of Catalonia (Universitat Politècnica de Catalunya, UPC). He received is Ph.D in Aerospace Science and Technology from the UPC in 2013. Since 2007 he is assistant professor at the UPC.

Xavier Prats is an Aeronautical Engineer from the National School for Civil Aviation. He holds a degree in Telecommunications Engineering from the Technical University of Catalonia (Universitat Politècnica de Catalunya, UPC). He earned both degrees in 2001. He received his Ph.D in Aerospace Science and Technology from UPC in 2010. He is currently an assistant professor at the School of Telecommunications and Aerospace Engineering of Castelldefels (EETAC).