ATFM airborne delays without extra fuel consumption in wind conditions

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Abstract—**Air Traffic Flow Management (ATFM) regulations, such as ground holdings, are often canceled before their initially planned ending time. The ground delays impact on the cost of recovering part of the delay if the regulation is canceled, as aircraft are still at the origin airport. In previous publications, the authors have suggested a speed reduction strategy to split the assigned ATFM delay between ground delay and airborne delay. By flying at the the minimum speed that gives the same fuel consumption as initially planned, the airline can maximize the airborne delay without any extra fuel consumption. In this paper, the effect of wind on the amount of airborne delay is assessed and a case study of Chicago O'hare airport is presented. Results show that wind has a great effect on the airborne delay that can be achieved and that, in some cases, even tail winds might lead to an increase of airborne delay.**

I. Introduction

Speed control for ATM purposes has been the subject of several research studies and projects. The majority of the applications focus on a tactical level, where speed adjustments are used to resolve (or mitigate) aircraft conflicts (see for instance [1], [2], [3]). Some other works also propose speed control as a mechanism to enable traffic synchronization strategies [4], [5]. In this context, in [6] en-route speed reductions are proposed to prevent aircraft from performing airborne holding patterns when arriving at the congested airspace. A similar rationale is behind the ATM long-range optimal flow tool developed by Airservices Australia [7], where aircraft within a 1000 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 therefore reducing unnecessary holdings. More recently, a joint FAA/Eurocontrol study, estimated that half the terminal area inefficiency in the system today could be recovered through speed control in the cruise phase of flight, without reducing throughput efficiency [8].

At a pre-tactical level, some research has also been conducted considering speed control as an additional decision variable (in addition to the amount of time of ground holding) to solve the Ground Holding Problem: where aircraft are regulated in such a way that airborne traffic flows do not exceed the available capacity [9], [10]. These measures, however, are difficult to implement with the current concept of operations and therefore, conventional ground delays are still assigned to aircraft at their origin airport as the main pre-tactical air traffic flow management (ATFM) measure. Once airborne, aircraft fly, in the best case, at the nominal flight conditions they would have flown if the regulation had not been in place. But, since controlled times of arrival (CTA) are still not mandated with the current concept of operations, some companies decide to accelerate their delayed aircraft, trying to recover part of the delay previously performed on ground, incurring higher fuel costs and not respecting the assigned arrival slot [8].

Assuming that in the near future, in the context of SESAR and NextGen, CTAs will be effectively enforced on aircraft, the authors have proposed a speed reduction strategy at a pre-tactical level that aims to absorb part of the assigned ATFM delay while airborne, obtaining promising results [11], [12], [13]. Yet, in all of this previous research, aircraft were considered to be flying in calm wind conditions. This assumption was adopted partly for the difficulty of considering winds in the performed simulations, and also due to the fact that actual wind conditions can change greatly on different days, flight altitudes and origin and destination pairs, making it difficult to generalize the results of the speed reduction strategies that were proposed.

This paper presents an initial assessment of the effects of real wind conditions aloft when applying these speed reduction techniques aiming at absorbing ATFM delays. Section II of this paper gives the basic concepts behind the proposed speed reduction concept, while in section III, it is explained how the wind affects the results of airborne delay (AD) that derives from flying slower. Section IV presents a case study, where the principal routes to Chicago O'Hare airport have been analyzed with real wind conditions, and finally, section V concludes this paper.

II. The cruise speed reduction concept

In [12], 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 [13], 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

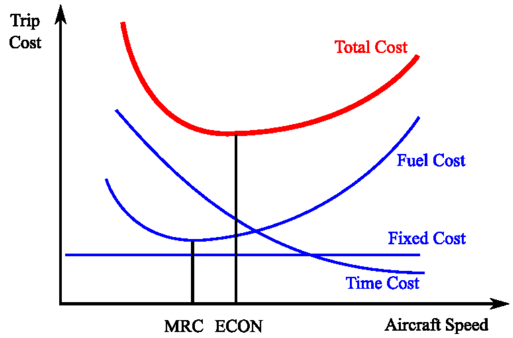


Fig. 1. Aircraft operating costs as a function of the cruise speed

maximum range cruise speed, 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 makes sense if we consider the fact that air traffic management initiatives (or regulations) can be canceled before their initially planned ending time, as is often the case [14], [15]. 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, as showed in [16].

This section gives an overview of the principal concepts that are behind this speed reduction strategy.

A. Aircraft operating costs

For a given flight, three types of costs are present: fuel consumption, time-dependent costs and fixed costs, which are independent of the time or fuel consumption (such as landing fees or aircraft ground handling). As shown in figure 1, fuel and time-dependent costs are affected by the flight cruise speed.

The optimal speed that gives the minimum fuel consumption for a given flight distance is 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 [17].

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 than 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[1]. 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 minimizes the total cost. This speed is usually

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

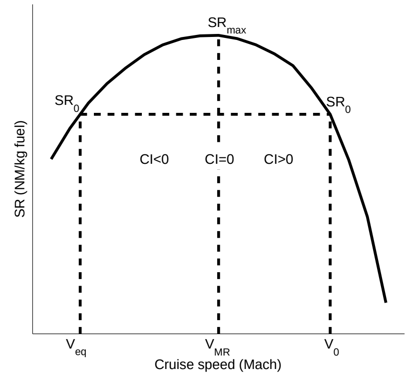


Fig. 2. Typical SR curve and equivalent speed (V_{eq}) definition

called the ECONomic speed and will be denoted as V_0 in this paper (see Figure 1). It should be noted that the CI value not only affects the cruise speed but also 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.

B. The equivalent speed

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 fixed. Figure 2 shows the relationship of the specific range (SR) with the cruise speed. The specific range is defined as the distance that can be flown per unit of fuel burnt, and it is usually measured in NM/kg or NM/lb. As explained before, the maximum SR is achieved when flying at the MRC speed which is the same as minimizing the fuel consumption per unit of distance flown. Since typical operating speeds (ECON speeds) are higher than the MRC speed, the actual specific range will be lower than the maximum one.

In [13] the *equivalent speed* (V_{eq}) was defined as the minimum speed that produces the same specific range (SR_0) as flying at the nominal speed V_0 (see figure 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. As the aircraft flies, fuel is burned and therefore its weight changes leading to changes in the V_{eq} speed. 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[2].

The goal of this strategy is to maximize the airborne delay but without incurring extra fuel consumption. Yet, only a few minutes of delay can be performed in the air by flying at V_{eq} [13] and therefore, this airborne delay will be typically lower

[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]

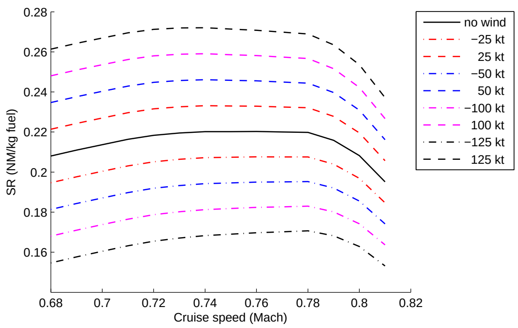
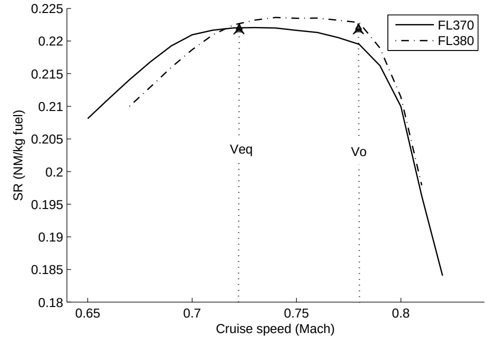
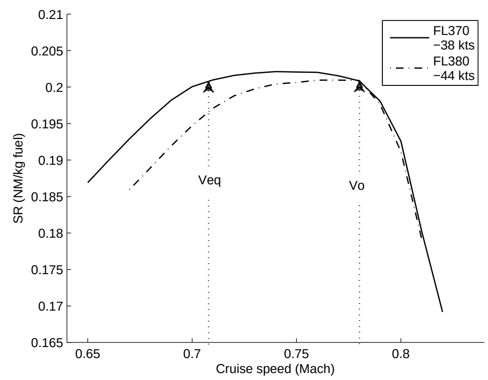


Fig. 3. Typical SR curve with different winds



(a) SR without wind



(b) SR with wind

Fig. 4. Vo and V_{eq} as a function of wind

than the total assigned delay due to an ATFM regulation. Thus, this total delay will be divided between some ground delay at the origin airport plus airborne delay while flying slower. Moreover, long cruise distances are needed in order to obtain practical values of airborne delays from an operational point of view. For this reason, this strategy seems more suitable for North American flights rather than for European flights; as distances between the origin airport and the regulated area are typically shorter in Europe.

The benefits arise in the case that the regulation is canceled while the aircraft is already in the air. With the current concept of operations, the aircraft would perform the total delay on ground. Therefore, if the crew decide to recover part of the delay (because the regulation is no longer in place), it will be necessary to speed up over V_0 leading to the use of a lower specific range and therefore to 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 some delay (once the regulation is canceled) 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 [16].

III. Influence of wind on the maximum airborne delay

Let x be the distance flown, t the time and F the fuel burnt by the aircraft. Then, the specific range (SR) is defined as:

$$SR = \frac{\mathrm{d}x}{\mathrm{d}F} = \frac{\mathrm{d}x}{\mathrm{d}F}\frac{\mathrm{d}t}{\mathrm{d}t} = \frac{GS}{FF} = \frac{TAS + w}{FF} = SR_{air} + \frac{w}{FF} \tag{1}$$

where FF is the fuel flow, GS and TAS are the aircraft ground and true speeds, respectively; and w is the wind component in the direction of the flight.

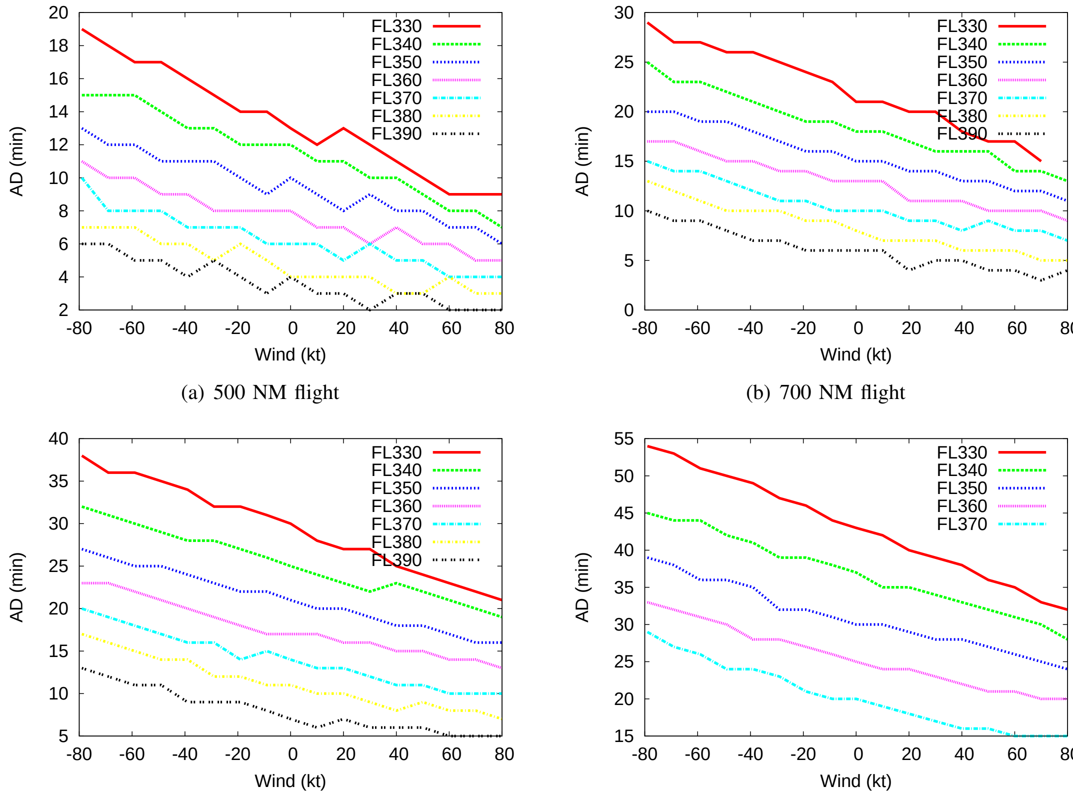
In no wind conditions, the SR will be determined only by the aerodynamic and propulsive characteristics of the aircraft. In a windy environment, the shape of the SR curve will vary due to the $\frac{w}{FF}$ term, which is not a constant value as FF depends on the TAS. Therefore, if all the parameters are fixed, the margin between V_0 and V_{eq} will also vary with the wind.

Figure 3 shows an example of a typical SR curve with different winds. As expected, negative winds (head winds) will lead to a reduction of the SR and positive winds (tail wind) will result in a larger distances flown per unit of fuel. Besides that, it is worth noticing how the shape of the curve is also modified due to the wind. Therefore, for a given V_0, the V_{eq} will change as a function of the wind.

One of the main characteristics of wind is that it changes with altitude. Therefore, for a given route, the optimal flight level might change if wind conditions are different at different altitudes. For example, in tail wind conditions, it is possible to obtain higher SR at altitudes that are not optimal from an aerodynamic and/or propulsive point of view.

An example of this change of optimal flight level is presented in Figure 4. If no wind is present, with the current characteristics of weight and V_0, the optimal flight level is FL380 as it is the one which has the higher SR (see figure 4(a)). However, if a head wind is present on the route, with speeds of 38 kt and 44 kt respectively for FL370 and FL380, the FL370 will have a higher SR for the same V_0. Therefore, FL370 will be more optimal than FL380. By flying at FL370 the airline will obtain a similar SR than flying at FL380, but the equivalent speed will be lower at FL370 than at FL380. Thus, if $(V_{eq}|_{FL380} - V_{eq}|_{FL370}) > (w|_{FL370} - w|_{FL380})$, more delay would be done in the air with the same fuel consumption as in the nominal flight.

In general, head winds will represent an increase in the cruise flight *air* distance and therefore, more time will be



(a) 500 NM flight

(b) 700 NM flight

(c) 900 NM flight

(d) 1300 NM flight

Fig. 5. Airborne delay as a function of flight level and wind (constant wind during the cruise)

available for airborne delay. Conversely, tail winds represent a reduction of the *air* distance and flight time and, consequently, a reduction in the airborne delay. However, as has been shown in figure 4, actual wind conditions might lead to a different optimal flight level that will represent an increase in the distance between V_0 and V_{eq} and therefore an increase of the airborne delay.

A. Constant wind approximation

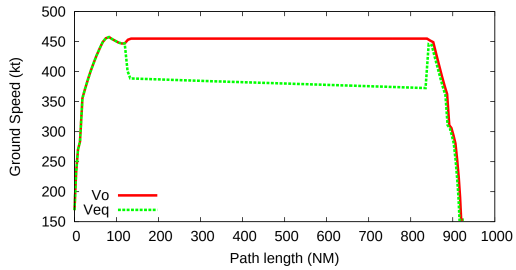
As a first approximation, some simulations with constant wind magnitudes during the cruise phase have been performed. An Airbus A320, with a typical commercial load factor of 80% [19] was used. Moreover, the nominal cost index was set to 60 kg/min, corresponding as well to a typical setting for this aircraft type [17]. Cruise performance data has been obtained from databases contained in Airbus' *Performance Engineers Program* (PEP) software suite. Different flight distances with seven different altitudes and constant cruise winds from -80 kt to 80 kt have been computed. Flight distances (500 NM, 700 NM, 900 NM and 1300 NM) correspond to the whole flight and therefore, the cruise distance will vary as a function of the simulated flight level. Figure 5 presents the results of the obtained airborne delay for each simulation.

As expected, the stronger the head wind, the higher the airborne delay that can be done. For example, around 10 minutes of airborne delay can be performed in a 500 NM flight, flying at FL370 with a constant head wind of 80 kt (see Figure 5(a)). For the same altitude and the same distance, but with 80 kt of tail wind, only 4 minutes of airborne delay can be done. From Figure 5(c) we can see how, for a 900 NM trip, if no wind is present, the aircraft will be able to perform around 15 minutes of airborne delay by flying at FL370. As we have previously seen, an increase of tail wind will lead to a reduction of the airborne delay. It is worth noting that, in the presence of winds, the optimal flight level might change. Therefore, as it can be seen in the figure, depending on the resulting optimal flight level it might be possible to have more than 15 min of airborne delay, even with tail wind.

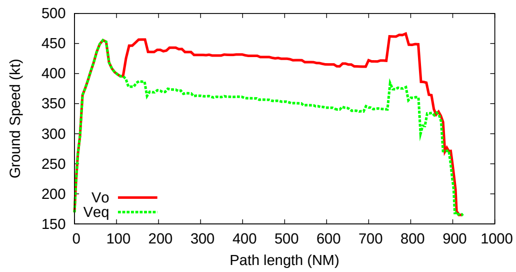
From this tables, the aircraft operator could get a quick approximation of the airborne delay that can be done by reducing the cruise speed without using extra fuel for a given flight. The actual airborne delay an airline can do on a given flight will depend on the wind present at different altitudes. Knowing that wind profile, it will be possible to determine what the optimal flight level is and, therefore, by using these tables determine what the airborne delay is.

B. Influence of real wind conditions

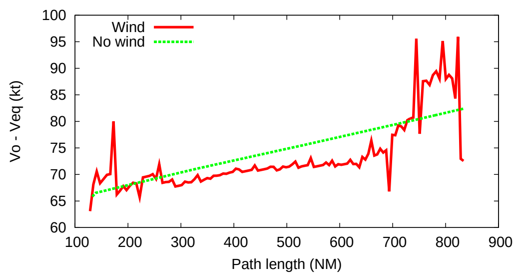
In a real flight, the aircraft will constantly face different winds. Therefore, the V_{eq} will not only change because the weight loss but also because of wind variations. Figure 6 shows the ground speed of an Orlando International - Chicago



(a) V_0 and V_{eq} without wind



(b) V_0 and V_{eq} with wind



(c) $V_0 - V_{eq}$

Fig. 6. MCO - ORD flight at FL360

O'Hare (MCO - ORD) flight with an Airbus A320 at FL360. In figure 6(a) the flight is presented without wind. In the nominal flight, the speed (V_0) increases until it reaches the cruise speed. At that time it remains constant, the ground speed will be the same as the true air speed because no wind is present. As the weight of the aircraft decreases V_{eq} reduces its value.

When wind is present, we can appreciate that even if the TAS is constant in the nominal flight, the GS changes due to wind variations, as seen in figure 6(b). Finally, figure 6(c) represents the margin between V_0 and V_{eq}. As the weight of the aircraft is lower, V_{eq} is slower, this reduction is linear in the no-wind scenario, with wind, a similar tendency is observed but the effect of the wind leads to more abrupt changes. The airborne delay is determined by the distance between the nominal speed V_0 and the equivalent speed V_{eq}. Therefore, the higher this margin is the higher the airborne delay can be performed with the same fuel consumption as in the nominal flight.

IV. Case Study

In order to study the effect of wind on a real case scenario, the flights to Chicago O'Hare airport (ORD) have been simulated using the Future ATM Concepts Evaluation Tool (FACET) developed by NASA-Ames [20].

TABLE I
Flights to ORD performed by A320 aircraft types within 1200 NM radius

Airport	NM	Num. routes	Num. flights	Aggregated %
LGA	660	3	25	10.5
DFW	715	3	18	18.0
BOS	760	3	12	23.0
MCO	925	3	12	28.0
MSP	300	3	12	33.1
ATL	560	3	11	37.7
PHL	620	2	9	41.4
BDL	720	2	8	44.8
DCA	550	2	8	48.1
DEN	800	5	8	51.5
DTW	215	2	8	54.8
EWR	650	2	8	58.2
IAH	830	3	8	61.5
STL	230	2	8	64.9
CYYZ	380	2	7	67.8
MCI	365	1	7	70.7
TPA	915	1	7	73.6
AUS	890	1	6	76.2

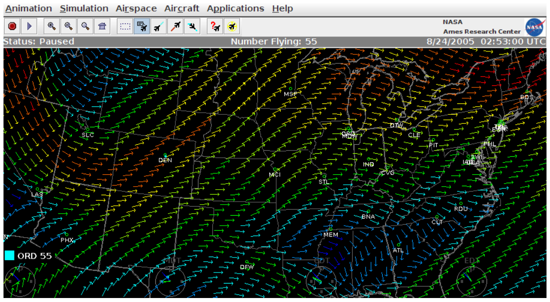
A. Scenario setup

From all the flights arriving to ORD on August 24th, 2005[3]. We have analyzed those that originated at an airport inside a 1200 NM radius centered at ORD and that where flown by A320 aircraft or by an aircraft with similar performance (B737-400, B737-800, B737-900 and MD-80). As in previous examples, all flights have been simulated with a cost index of 60 kg/min and a commercial load factor of 80%. Table I contains these flights. The table also shows the number of different routes that were used that day between each particular origin-destination pair. The eighteen airports with more traffic represent more than 75% of all that traffic.

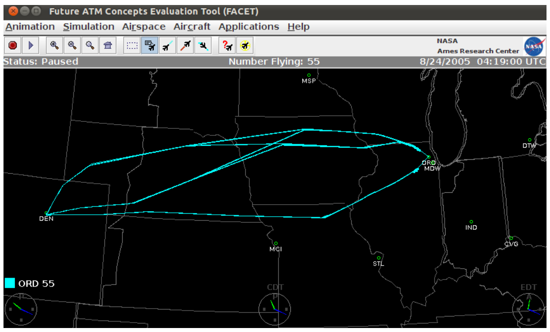
If a ground delay program (GDP) is defined, a radius of application typically is set. Therefore, the aircraft close to the airport are the ones that are more affected. Moreover, it is interesting to study short and medium flights as they are the ones which, without wind, are able to perform less airborne delay. Finally, by setting this 1200 NM filter, it is not necessary to simulate changes in altitude during the cruise as all the flights are short enough to not need a climb step. Once again, Airbus performance databases have been used.

As wind might change during the day, from each origin we have selected the take off time of the first flight of the day. By using the forecast wind of November 28th, 2007 from Rapid Update Cycle (RUC) files taken from the National Oceanic & Atmospheric Administration[4], we have been able to compute the average wind of all the flight levels of all the routes that were used between the two airports. This information has been used to compute the cost of each possible route and flight level and determine the nominal route, flight level, speed (V_0) and weight. Figure 7(a) shows an example screen-shot of FACET with the wind loaded. It should be noted that RUC data format has been chosen in this study because it offers a very realistic set of meteorological conditions that are easy to integrate with FACET simulations. In a real operational implementation, the

[3]data gathered from the Enhanced Traffic Management System (ETMS)
[4]http://ruc.noaa.gov/



(a) Wind vectors at isobaric level 425 mb



(b) Different routes simulated from DEN to ORD

Fig. 7. Example of FACET simulator screen-shots

best available wind forecast at the creation of the flight plan would be used instead.

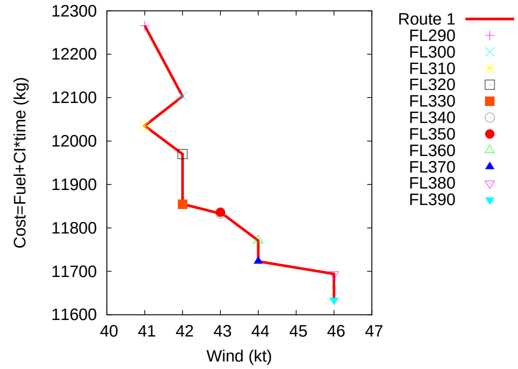
In the simulations, the dynamics of the climb and descent phases have been simulated by FACET. Once the aircraft is in cruise at each step of the simulation the fuel flow, weight and V_{eq} have been computed. Figure 7(b) shows a moment of the simulation with flights from Denver (DEN) to Chicago (ORD). In this figure it is also possible to see that there exist more than one possible route for the same flight.

B. Characteristic results

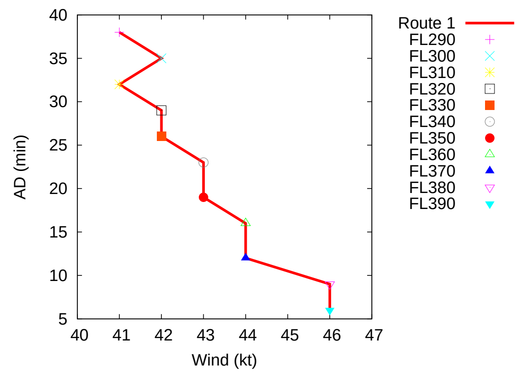
In general, the main wind streams in North America are west - east flows. By its geographical position, Chicago has flights that have different types of wind. The flights coming from airports located west of Chicago usually have tail winds and, in general, are medium-long flights. On the other hand, the flights from the east coast are shorter flights but with heavy head winds. Finally, the flights from the south have roughly cross wind. In this section, the results of three different flights, one from each of these locations, are presented with more detail. The airports studied are Austin-Bergstrom International Airport (AUS), Washington Dulles International Airport (IAD) and Orlando International Airport (MCO).

From each origin two different graphs are presented. The first one shows the cost of each simulated route and flight level. The airline will choose the route and flight level which minimizes its total cost[5]. The second one presents the airborne delay that can be done with respect to each nominal flight, which depends on the route and flight level.

[5]Total cost (C) is computed as a function of the trip fuel (TF), Cost Index (CI) and trip time (TT) as $C = TF + CI \cdot TT$



(a) Cost of the flight

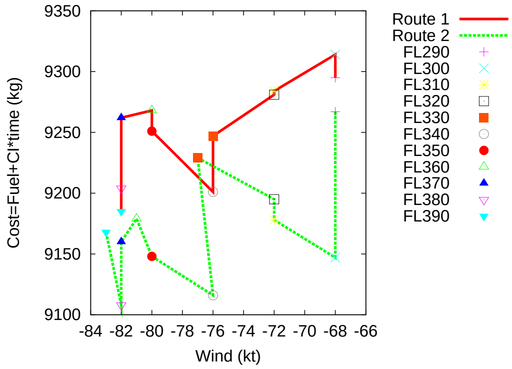


(b) Airborne delay

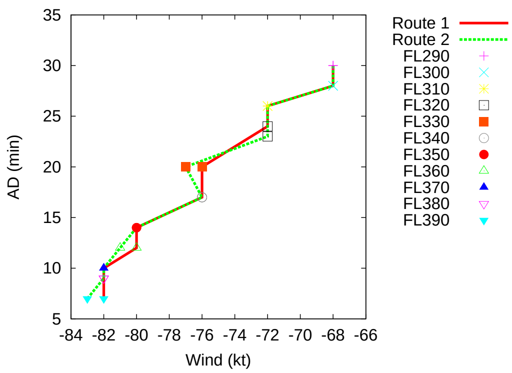
Fig. 8. AUS to ORD flight

As can be seen in figure 8, only one route was flown that day from Austin to Chicago. Figure 8(a) represents the cost and average wind of flying at each flight level. As can be observed, the flight level with lower cost is the FL390, where an average tail wind of 46 kt is present. With that flight level, figure 8(b) shows that 6 minutes of airborne delay can be performed without extra fuel consumption. The Austin flight is a 890 NM flight. If that flight is done without wind, the optimal flight level will be the FL370 and it would be possible to do 14 minutes of airborne delay. Therefore, for this flight the wind is reducing the possibility of doing airborne delay by 8 minutes. If the flight is done without wind but at FL390, 7 minutes of airborne delay can be performed, only one minute of difference from the wind scenario. Knowing the optimal flight level and the wind, it is possible to use the graphs from figures 5(b) and 5(c) to get an approximation of the 6 minutes of airborne delay.

In the second flight (IAD-ORD), there are two different routes. From figure 9(a) it can be deduced that the second route is more efficient than the first one, and that the FL380 is the one with a lower cost. At this flight level, 9 minutes of airborne delay can be performed. If no wind is present the optimal flight level is a different one (FL370) and in this case the airborne delay would be 7 minutes. In this case, the head wind increases the flight time and therefore results in higher airborne delays. Moreover, if the same flight level is

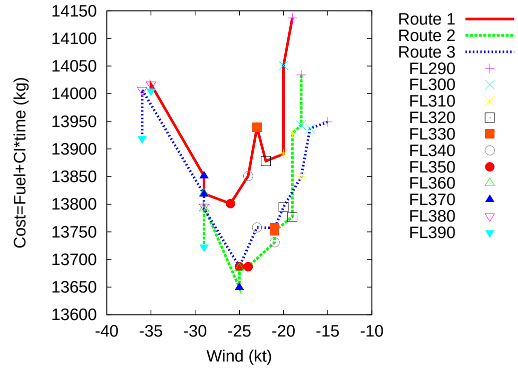


(a) Cost of the flight

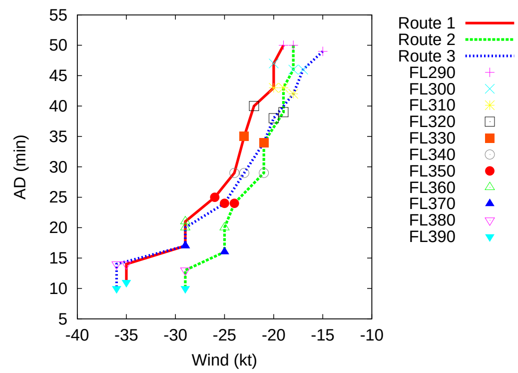


(b) Airborne delay

Fig. 9. IAD to ORD flight



(a) Cost of the flight



(b) Airborne delay

Fig. 10. MCO to ORD flight

kept (FL380) but no wind is present, it is only possible to do 5 minutes of delay. In this case, the head wind leads to almost twice as much delay as without wind.

Finally, for the Orlando - Chicago flight, there were three different routes. The one with the lowest cost was the second route using FL370 (see figure 10(a)). In this case, the amount of airborne delay that could be done is 16 minutes (see figure 10(b)). If no wind is present, a different route is more adequate (route number three) and only 8 minutes of airborne delay can be done. If the same route and flight level is kept, 15 minutes of airborne delay can be done. This flight shows how, if wind is low and the route and flight level is kept the same, the impact of wind on the airborne delay is small. However, even relatively low wind might produce a change in the optimal flight level and/or route, leading to a big increase of airborne delay (from 8 minutes to 16 minutes in this case).

C. Simulation results

Following the same principle as in the previous section, the best route and flight level, and airborne delay, have been computed for all the flights listed in table I. The results are presented in table II. Two origins which are not in table I have been added, Louis Armstrong New Orleans International Airport (MSY) and Salt Lake City International Airport (SLC). They have been added because MSY follows a route with an average wind which is almost perpendicular to its track, and SLC is an airport with heavy tail winds and a longer route.

TABLE II
RESULTS: AIRBORNE DELAY IN WIND CONDITIONS (WITHOUT WIND BETWEEN BRACKETS)

Origin	Optimal FL	Optimal Route	Wind (kt)	Airborne Delay (min)	Δ Airborne Delay (min)
LGA	390 (380)	1 (1)	-100	10 (8)	2
DFW	390 (380)	2 (1)	26	5 (8)	-3
BOS	390 (380)	1 (1)	-95	13 (9)	4
MCO	370 (390)	2 (3)	-26	16 (8)	8
MSP	320 (340)	1 (1)	92	4 (4)	0
ATL	370 (370)	1 (1)	-43	9 (8)	1
PHL	340 (390)	1 (1)	-86	20 (5)	15
BDL	390 (380)	1 (1)	-98	12 (9)	3
DCA	390 (370)	1 (1)	-82	7 (7)	0
DEN	380 (380)	4 (4)	103	6 (10)	-4
DTW	Too short - no cruise				
EWR	380 (380)	1 (1)	-107	13 (7)	6
IAH	370 (380)	3 (3)	5	12 (10)	2
STL	300 (300)	1 (1)	16	3 (4)	-1
CYYZ	380 (380)	1 (1)	-105	5 (3)	2
MCI	320 (360)	1 (1)	101	5 (4)	1
TPA	310 (380)	1 (1)	-22	43 (11)	32
AUS	390 (370)	1 (1)	46	6 (14)	-8
IAD	380 (370)	2 (2)	-83	9 (7)	2
MSY	390 (390)	1 (1)	8	6 (6)	0
SLC	380 (380)	1 (1)	110	10 (14)	-4

In general, head winds represent a higher airborne delay, the only exception is the flight from Reagan National Airport (DCA), where the airborne delay is the same with and without wind. The reason is that the flight level used without wind is different than with wind. If the same flight level is kept without wind, 3 more minutes of airborne delay can be done with wind than without. On the other hand, when a tail wind is present, in general, less airborne delay can be performed than without wind. However, this is not always the case, for instance from Kansas City International Airport (MCI) even with 99 kt of average tail wind, more airborne delay can be done with wind than without wind, again, the change on the optimal flight level is the cause, in this example, the wind leads to a situation similar to the one shown in figure 4.

V. Conclusion and Further work

In this paper we have given a first assessment of the effects of realistic wind conditions in the reduction of cruise speeds aiming at performing airborne delays without incurring extra fuel costs. In general terms the longer the flight the higher the maximum airborne delay can be. Consequently, head winds will lead to increases in airborne delay and, in general, tail winds will mean a decrease in the maximum airborne delay. The variations in airborne delay with respect flying without wind are due to the fact that the flights are longer or shorter but also because the specific range function is changed by adding a term depending on the wind. Besides the effect on cruise time, the wind has another important effect because it is not the same at different altitudes: it might change the optimal flight level and route for a given flight, even for small winds variations. These changes may produce situations where airborne delay can be increased, with respect to the non wind case, even in tail winds conditions.

The values of airborne delay that we have obtained for flights in a radius of 1200 NM with forecast winds are consistent with the airborne delay we obtain if we assume an average constant wind during the whole cruise. This means that by knowing the average wind it is possible to get a good approximation of the airborne delay that can be done without needing the detailed wind profile the aircraft will face.

The values of airborne delay found in these simulation are representative enough to suggest that this speed reduction technique might be useful in a real operational scenario. Finally, as further work, the simulations need to be extended to include flights with changes in cruise altitudes and different aircraft types, payloads and cost indexes. In addition, the constant wind approximation will be further assessed in order to obtain an analytical model which will not require from simulations.

Acknowledgment

The authors would like to thank Dr. Banavar Sridhar, Mr. Alex Morando, Dr. Avijit Mukherjee and Dr. Hok Kwan Ng from NASA Ames Research Center for their comments and help with the use of FACET; and Airbus for the use of PEP program, which allowed us to undertake realistic aircraft performances simulations.

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