

WEATHER FORECAST REQUIREMENTS TO FACILITATE FIX-BASED AIRPORT GROUND DELAY PROGRAMS

Bob Hoffman, Ph.D.¹ Jimmy Krozel, Ph.D.² and Ray Jakobovits, Ph.D.³
Metron Aviation, Inc., Herndon, VA, 20170

1. INTRODUCTION

A Ground Delay Program (GDP) in Air Traffic Management (ATM) is a mechanism to control the take off time for each aircraft bound for a common airport. When convective weather or some other capacity-reducing event is expected to occur at or near an airport, then the flow rate of arriving aircraft is reduced to match the expected (forecasted) airport acceptance rate (AAR), to safeguard the safe landing and taxiing of aircraft.

In the future, we expect that a new type of GDP – a fix-based GDP – can be used when more precise weather forecast information is achieved. A fix-based GDP analyzes how the convective weather is expected to affect each metering fix arrival rate around an airport (typically, there will be 4 metering fixes), not just the airport arrival rate in general. The question is: what weather forecast accuracies are required to perform this new ATM control strategy? In order to perform this analysis, we must be able to accurately evaluate how the forecasted weather is going to affect not only the metering fix locations, but also the jet routes leading to these airport metering fixes.

This analysis evaluates the performance of fix-based GDP procedures relative to current airport-based GDPs under a range of weather forecasting capabilities. We compare current airport-based GDPs to future airport fix-based GDPs, with weather forecasting requirements expressed in terms of various temporal and spatial forecast errors relative to a baseline perfect forecast. A general modeling framework is developed for studying weather impacts on airport GDPs and is applied as a single-day case study of Chicago O'Hare International Airport (ORD). The analysis demonstrates the payoff for using more precise fix-based GDP flow control mechanisms to exploit improved weather forecasting capabilities expected in the future. The results indicate the weather forecast requirements to achieve a particular airport GDP performance level.

2. BACKGROUND

A Strategic Plan of Operations (SPO) for managing flows during severe weather events in the National Airspace System (NAS) takes into account reduced Airport Acceptance Rates (AARs) due to weather constraints. Long range weather forecasts such as the Collaborative Convective Forecast Product (CCFP) (Figure 1) are currently used to predict the future arrival capacity of an airport. If the predicted

capacity (number of aircraft that the airport can safely land in a given time period) falls short of scheduled demand (number of aircraft that wish to land at an airport in a given time period), traffic flow managers may implement a ground delay program (GDP). Effective use of GDPs, implemented through collaboration between the FAA's Air Traffic Control System Command Center (ATCSCC) and the airlines, continues to be a vital component of the overall management of capacity^{1, 2, 3, 4}.

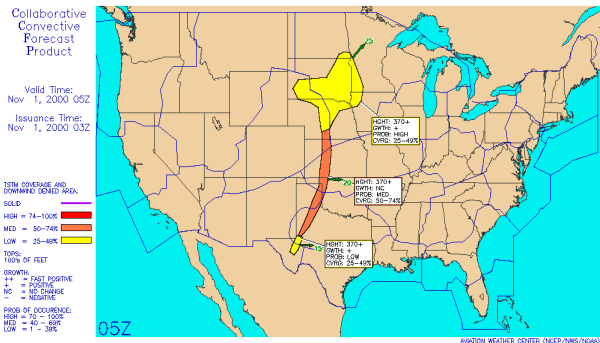


Figure 1: CCFP (Aviation Weather Center website).

Current GDP algorithms assign flights to a sequence of arrival slots created in accordance with the expected arrival capacity. Since this requires that flights be notified prior to departure, a GDP is often implemented hours in advance of its start time – where the start time marks the earliest time at which arrivals need to be postponed. For each hour of the program, a set of virtual arrival slots is created in accordance with the capacity for that hour (e.g. a 30-flight capacity in one hour would yield 30 two-minute slots). Flights are then assigned to arrival slots in a manner about to be described.

The net effect of ground delays is to stretch out the flow of arrivals over time, as in Figure 2. For a given flight, the amount of ground delay tends to grow linearly with the number of minutes into the program that the flight is estimated to arrive, but total delay over all flights tends to grow quadratically. As shown in the figure, before the GDP, 60 aircraft per hour are planned to arrive at the airport. The GDP plans for only 30 aircraft per hour to arrive at the airport so that the reduced capacity (perhaps due to adverse weather) is not exceeded.

¹ Manager, Research and Development, 131 Elden Street, Suite 200.

² Chief Scientist, Research and Development, 131 Elden Street, Suite 200, AIAA Associate Fellow.

³ Sr. Analyst, 131 Elden Street, Suite 200.

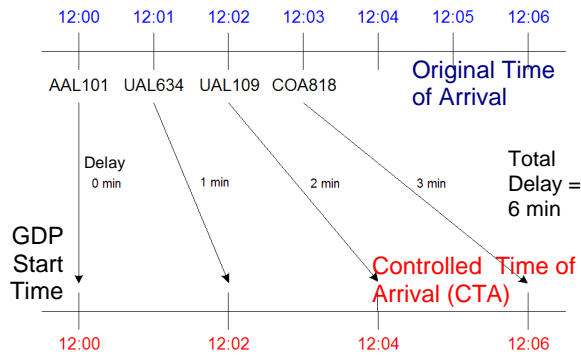


Figure 2: The net effect of ground delays is to stretch out the flow of arrivals over time.

Because these algorithms model arrival flow as a single queue processed by a single server, traffic managers are limited to only two options. Either they slow all of the incoming aircraft at a common rate while detailed modeling of flows over fixes or they slow the incoming traffic over one fix while ignoring the other fixes and the overall airport picture. The traffic flow management (TFM) community is now considering more advanced flow control capabilities. One of those is a *fix-based GDP*, in which a flow control rate can be set for each of the airport arrival fixes, independently of the others.

To see why a fix-based GDP would be effective, consider the following scenario, which occurred at Newark Airport (EWR) on July 9 of 2002. At 15:51Z, a GDP was issued for flights scheduled or estimated to arrive at EWR between 18:00Z to 01:59Z. This was based on a 15:51Z forecast of weather approaching EWR from the west. An ordinary GDP would apply delays to all EWR arrivals. But, as seen in **Figure 3**, arrivals from the south are not affected by weather and they need not be affected by the GDP.

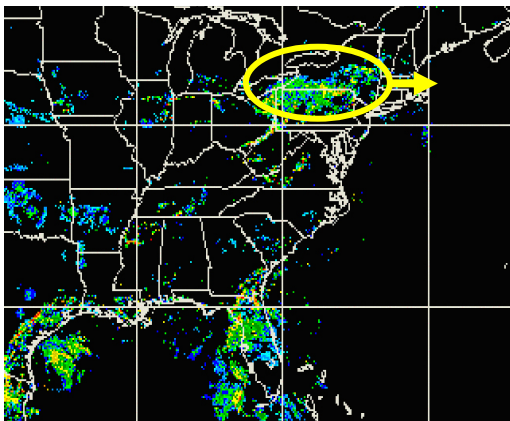


Figure 3: Weather impacting flights into EWR from the West, but not from the South (7/9/02).

A fix-based GDP would allow traffic managers to apply delays over only those fixes where the weather is causing a problem (the east and west, and to avoid delaying traffic coming from the south and north).

In this paper, we devise a formal research

framework to investigate the relationship between GDP algorithms and weather forecasting requirements. As part of the modeling effort, two innovations are developed. First, we show how to characterize complex weather patterns by three parameters, which correspond to the location, timing, and severity of weather, respectively. Weather forecast errors can then be represented by deviations of these parameters from forecasted parameters. This avoids the need to create weather scenarios in full detail when assessing the potential impact of forecast errors. The second innovation is a delay estimation model that can measure the impact of weather and arrival fix capacities on each of the airport arrival flows. These innovations are combined to show that significant benefit can be derived by extending the single-flow control policy used in today's GDPs to flow control over each of the multiple airport arrival flows. This provides valuable guidance to TFM policy makers in the future development of TFM techniques and weather forecasting requirements.

3. MODELING

In order to systematically study the impact of variable weather conditions on airport arrival flow control, a formal GDP research framework was developed for Chicago O'Hare International Airport (ORD). ORD was chosen for its size, complexity, amount of weather, and high frequency of GDPs. The framework and techniques apply equally well to other major airports.

There are two primary modeling efforts. The first effort models the relationship between weather and en route delays using as input actual weather data in the National Weather Service (NWS) standard reflectivity format and Enhanced Traffic Management System (ETMS) data. This provides an estimate of the delay that an arriving flight will experience as a function of weather encountered in the vicinity of its arrival fix plus other quantifiable factors associated with the airport at the time of arrival of the flight.

Using the weather-related delay estimates as input, the second effort determines the optimal airport-based and fix-based ground delay performances that could take place under weather-related delay estimates based on forecast weather. Optimal performance means minimization of ground plus airborne delay by setting appropriate arrival rates for the GDP. Historical aggregate demand list (ADL) data, derived from ETMS, is used to generate airport arrival demand.

Next, we discuss the most innovative components of the research framework.

3.1 Weather Severity Index

Historical weather information was used both in planning GDPs and in assessing the performance of GDPs. In the former case, we needed to associate particular weather geometries with planning parameters – GDP start time, GDP duration, and airport or fix-based AARs. In the latter case, we needed to compute performance metrics for arriving

flights based on the weather encountered in the vicinity of the airport.

Historical weather data was compiled into a series of snapshots, each five minutes apart. The data was aggregated into cells (two by two nautical miles) labeled with one of the seven NWS weather levels shown in **Table 1**. Commercial aircraft will generally fly through NWS level 2 and below, but avoid level 3 and above⁵. We needed a simple way to parameterize the overall severity of the weather in a given region of airspace. A Weather Severity Index (WSI) was defined as the percent of cells in the region that are categorized as NWS Level 3 or above. A WSI was computed for the airspace around each airport arrival fix (KRENA, KUBBS, BEARZ, and PLANO) using a 30-degree wedge centered on the fix (see **Figure 4**). Each of the four indexes represents the relative severity of weather encountered by an aircraft passing through the respective arrival fix. In addition, a WSI was computed for a circular region surrounding the airport itself. The radius was set so that the circle would have an enclosed area equal to the area of each of the arrival fix wedges.

As an example, **Figure 5** illustrates weather severity on June 26, 2002 for ORD, a notoriously difficult traffic flow management day. High WSI values indicate the presence of weather. Reading left to right (chronologically), the data indicate how the weather passed through ORD from the north and northeast, hitting KRENA first and then passing through KUBBS, the airport, PLANO and finally BEARZ.

In computing the WSI values, NWS weather levels 3 and above were all weighted equally. In the delay model described below, we allowed the weights to be determined by the regression algorithm. Realized weather data was available for our test days but we did not have the forecasts that would have been used to support TFM decision-making in anticipation of the weather events. To generate mock forecasts, we shifted the realized weather data in space and time to simulate the effect of forecast errors. Temporal variations were achieved by re-assigning the timestamp on each weather snapshot. Timestamps were varied in 5-minute increments, up to a maximum of ± 30 minutes. This amounts to translating the WSI curve forward or backward in time.

Spatial variations for weather were accomplished by scaling up or down the severity of the individual weather cells. A bi-directional “wildfire” algorithm (implemented in 4- or 8-neighbors on a weather grid) expands each weather cell by a fixed percentage, assigning overlapping regions a maximum value (more severe weather) of merging weather cells. The process is illustrated in **Figure 6**. The end result is that in order to examine temporal and spatial changes in the weather, we need only translate and/or scale the WSI curves.

Table 1: NWS Standard reflectivity levels and weather classifications.

NWS Level	Color	Rainfall (mm/hr)	dBZ	Type
0	None	<0.49	dBZ<18	None
1	Light Green	0.49 - 2.7	$18 \leq$ dBZ<30	Light Mist
2	Dark Green	2.7 - 13.3	$30 \leq$ dBZ <41	Mod.
3	Yellow	13.3 - 27.3	$41 \leq$ dBZ <46	Heavy
4	Orange	27.3 - 48.6	$46 \leq$ dBZ <50	Very Heavy
5	Deep Orange	48.6-133.2	$50 \leq$ dBZ <57	Intense
6	Red	>133.2	$57 \leq$ dBZ	Extreme

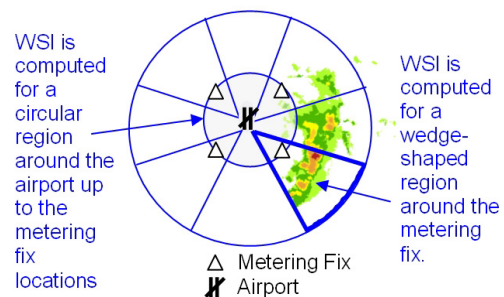


Figure 4: Weather Severity Index (WSI) is determined by a region of airspace around an airport.

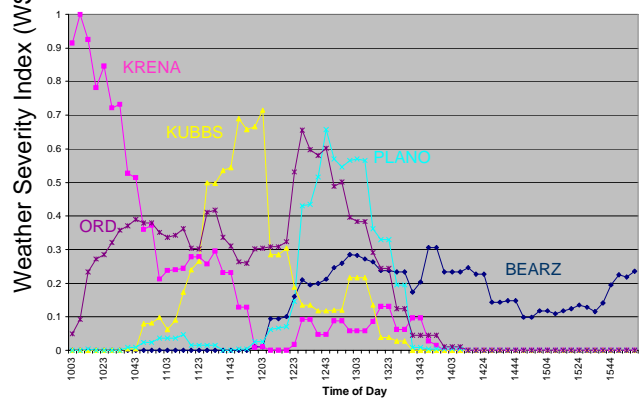


Figure 5: WSI values for 10:00 - 16:00 on June 26, 2002.

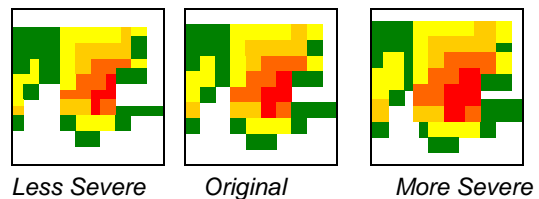


Figure 6: A weather severity variation manipulated by a wildfire algorithm.

3.2 Vectoring Delay Computation

En route delays are due to either speed changes or spatial deviations (vectoring). Speed changes are harder to detect in historical data than delays

associated with vectoring. However, we were able to capture vectoring delays by examining recorded flight tracks. Consider an aircraft that was observed to traverse a sector in T minutes, using points A and B as entry and exit points, respectively, as in **Figure 7**. Let d be the distance between points A and B , let $d + \Delta d$ be the distance actually traversed by the aircraft in the sector, and let V be the observed average velocity of the aircraft in the sector (where all distances and velocities are relative to the ground). Then we define the *vectoring delay* of the aircraft to be the increased travel time across the sector resulting from having traveled Δd miles more than was necessary, assuming an average velocity of V . This delay can be computed as the difference of observed transit time minus hypothetical transit time, which reduces algebraically to

$$\text{Vectoring Delay} := \left(1 - \frac{d}{d + \Delta d}\right) T.$$

The algorithm processed 258 flights arriving at ORD between 10:00z and 16:00z on June 26, 2002. The delay computed for each flight consisted of all vectoring delay occurring within 100 nautical miles of ORD, with the exception of delays that were identified by the algorithm as “landing delays” associated with maneuvers necessary for landing. About 3 min/flight of vectoring delay is typical, not including landing delay minutes. About 75% of the flights experienced vectoring delays of less than 2 minutes. The longest vectoring delay was 37 minutes.

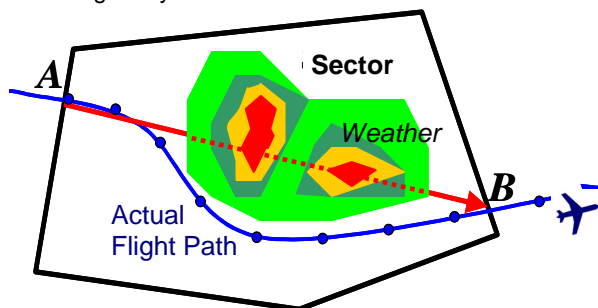


Figure 7: Delay is determined by comparing the direct distance to the flown distance.

A sample of the computed vectoring delays is presented in **Figure 8**. Each point is plotted according to the times at which the flight *would have* arrived at the fix, had it not experienced vectoring delay prior to reaching the fix. The largest vectoring delays coincide with the largest WSI values, strongly suggesting that there is a relationship between weather severity and vectoring delay.

3.3 Fix-to-Runway Transit Times

In order to associate hypothetical weather impact on arriving flights, it is necessary to model when a flight would have reached (or come close to) an arrival fix. Arrival fix crossing times are not formally recorded but can be back-computed from the runway arrival times available in the ETMS data.

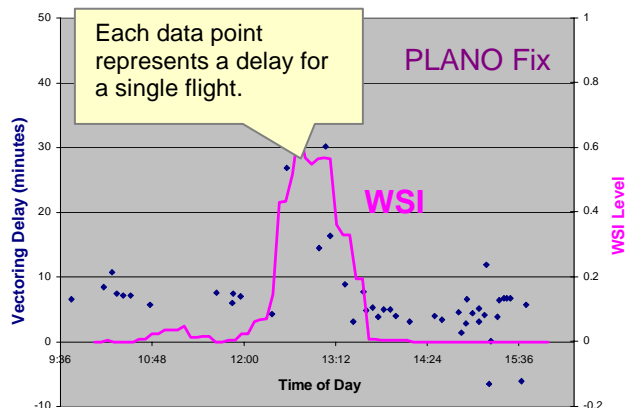


Figure 8: Vectoring Delays vs. WSI for the ORD PLANO Arrival Fix on June 26, 2002.

The problem with using actual runway arrival times is that they are tainted by realized weather events and traffic controller directives. For our modeling purposes, we require the time the aircraft *would have* neared the arrival fix under a hypothetical set of conditions. So, rather than using actual runway arrival times as a base, we use the time at which the flight was supposed to reach the runway under the GDP plan (its controlled time of arrival, or CTA). In order to translate a CTA to a fix-crossing time, we subtract from the CTA the average transit time from the planned arrival fix to the runway. In our analyses, we used the median time for each fix to adjust assigned landing slot times to fix-crossing times. For the June 26, 2002 experiment, the median values are as illustrated in **Table 2**.

Table 2: Metering fix to ORD Transit Times.

Arrival Fix	Median Transit Time (min)
BEARZ	11
KRENA	13
KUBBS	6
PLANO	14

3.4 Weather-Related Delay Estimation Model

In order to relate the WSI to flight delay, a regression analysis was performed with the vectoring delay as the dependent variable and with three independent variables: arrival fix WSI_{Fix} , airport WSI_{ORD} , and arrival rate at the time of arrival. WSI_{Fix} and WSI_{ORD} represent the maximum WSI levels at the arrival fix and airport, respectively, over the 15-minute period immediately preceding the time that a flight reaches its arrival fix. One regression was performed for each of the three arrival-rate data ranges identified above. The weights on NWS Levels 3 – 6 were allowed to vary, as well as the number of 5-minute weather snapshots to use in associating weather level with each arriving flight. The results were as follows:

- As expected, low-arrival and high-arrival rate data ranges did not yield any identifiable relationship between weather level and vectoring delay. This is because aircraft are generally

spared from weather effects close to the airport by TFM controls in low-arrival rate situations, and because there is little or no weather present in high-arrival rate situations.

- For medium-arrival rate situations, however, we found predicted delay to be an increasing function of arrival rate and weather severity. In modeling a relationship, the weights on the NWS Levels comprising the WSI values were: 0.01, 0.02, 0.15, and 0.82 for NWS Levels 3-6. Thus, as expected⁵, the regression analysis placed most of the weight on the two highest NWS Levels. This relationship explained about half the variance in the vectoring delay times.

The results presented in this section demonstrate that there is a payoff for using more precise flow control mechanisms to exploit improved weather forecasting capabilities.

4.1 Airport-based vs Fix-based GDPs

Current GDP procedures have a serious limitation in their flexibility: all of the arrival fix flows must be uniformly slowed or only one of the arrival fix flows must be slowed. This is appropriate only if the overall airport capacity is reduced or if weather affects just one fix. However, weather patterns often affect a combination of the arrival fix flows. The fix-based GDP would offer traffic managers the ability to implement a different flow control level at each of the arrival fixes for an afflicted airport; this section compares the fix-based GDP to a standard airport GDP under a common set of weather conditions.

The study scenario assumes that a GDP would be in effect from 10:00z to 16:00z on June 26, 2002. When an airport-based GDP was put into effect (modeled), the delay-minimizing sequence of AARs produced a total ground delay of 20.9 hours, an estimated total vectoring delay of 60.2 hours, and a total weighed delay of 141.4 hours, with 357 total arrivals during the GDP.

With fix-based planning, the total ground delay is 22.5 hours, the estimated total vectoring delay is 57.3 hours, and the total weighted delay is 137 hours. The number of arrivals during the GDP is also 357. Thus fix-based planning decreases total weighted delay by about 3%.

The advantage of fix-based planning becomes more pronounced when the intensity of the weather increases. Conversely, when the intensity of the weather is diminished, any advantage accruing to fix-based planning disappears. **Figure 9** illustrates the results for the two AAR sequences shown above under weather prediction accuracy temporal and/or intensity variations.

The results of variations in weather prediction accuracy are as follows. If the realized weather is twice as severe as expected (underpredicted), then the total weighted delay increases by 30 – 40%. If the realized weather is half as severe as expected (overpredicted) then total weighted delay decreases by 15 – 20%. Temporal variations in the weather prediction accuracy may turn out to be better or worse than the forecast, so the results of systematic

changes in the arrival time of the weather are not monotonic. Also, since the WSI is the weighted average of a large number of weather cells in a fixed geographic region, WSI levels change relatively slowly with time as cells move in or out of that area. Thus, temporal weather prediction errors generally cause less problems than spatial errors, and temporal weather prediction errors are less significant when the actual weather arrives less severe than the planned weather (which is as expected). As shown in **Figure 9**, the advantage of fix-based planning over airport-based planning reaches a maximum of about 9% when the weather intensity is doubled and the weather is shifted by 30 minutes.

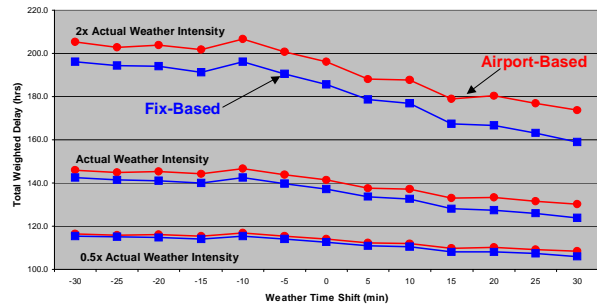


Figure 9: Comparison of GDP plans under variations in weather forecast accuracy (positive weather time shift denotes forecast weather later than actual weather).

4.2 Airport-based GDPs vs Fix-based GDPs with Cornerpost Swaps

One means of reducing anticipated en route delays due to over-demand at a particular arrival fix is to redirect traffic to an alternate fix (cornerpost swapping). While fix-based GDPs tend to severely restrict flows across metering fixes in response to severe weather forecasts, use of a cornerpost swapping tactic may enable overall arrival rates into an airport to be increased, and ground delay minutes reduced, without significant increases in en route delays. However, in order to minimize disruption to flight plans and to avoid congested traffic lanes that converge near the airport, corner post swap decisions are generally made en route while a flight is 200 or more nautical miles from the airport.

As an illustration, we examine what actually happened during the time period of the ORD case study. Flight data extracted from ETMS data shows that 36 out of 285 flights (12.6%) arriving between 10:00 and 16:00 used actual arrival fixes that differed from their filed arrival fixes. In each case, the filed fix was changed to an adjacent fix. In most cases, by the time the redirected traffic crosses the 200 nmi range ring, it is already being vectored to a swapped fix. Thus, in order to dynamically swap arrival fixes based on weather forecast information, swap decisions need to be made an hour or more before the scheduled arrival times.

Corner post swapping is performed today on a tactical level but is severely limited by the complex arrival and departure patterns near the airport. More proactive rerouting around arrival-fix weather

anomalies (e.g. pre-departure) could greatly increase the number of corner post swaps. The net effect is to increase the airport arrival capacity.

In order to assess the impact of combining en route corner post swaps with fix-based GDP planning, we ran an excursion in which swaps were included as decision variables in determining the delay-minimizing sequence of arrival fix AARs. In comparing ADL flight information at the 10:00z data time used for GDP planning, we found that only 9 of the 36 corner post swaps were already recorded in the ADL data (and therefore included as part of all of the GDPs described in previous sections of this paper). Five of those flights had already departed, four of which were within one hour of arrival and one within two hours of arrival. The other four flights were scheduled to arrive much later. For this excursion, we started with the ADL data and assumed that any additional swaps were possible, as long as they were made between adjacent fixes (i.e. no swaps between BEARZ and KRENA or between KUBBS and PLANO). The maximum fix capacity was set at 45 aircraft per hour, although acceptance rates did not reach that level in the results.

Figure 10 shows the delay curves for fix-based GDP planning with corner post swaps compared with the base case airport-based GDP. The separation between the two types of GDP plans is greater than previous results, and as noted on the figure, the number of arrivals with fix-based planning is also about 4% higher than with airport-based planning. The overall reduction in delay per arriving flight is in the range 11 – 14% for perfect weather predictions, and 16 – 20% for more severe weather. A total of 41 flights had fixes swapped in the fix-based plan.

4. CONCLUSION

The results of studying GDP strategies demonstrate that there is a payoff for using more precise pre-departure flow control mechanisms to exploit improved weather forecasting capabilities of the future. The modeling approach used in this work should give weather researchers some indication of the type of forecasts needed in the future for effective GDP planning. Specifically, GDP modeling and planning improvements could be made, if forecasts can be made specific enough to distinguish between impact at individual airport arrival fixes, versus the general airport region. Such forecasts would need to be translated, with the help of ATM researchers, to be phrased in terms of air traffic impact. The weather severity index developed in this paper showed enough promise that it could perhaps be extended to a notion of weather porosity for aircraft.

The potential deviations of realized weather from forecasted weather were used in this paper as a way of gauging effectiveness of refined GDP planning under varying weather realizations. This tells us

something of the robustness of the GDP planning benefits. But, more generally, there is a need to develop GDP planning that takes these potential weather deviations into account in advance. This would have to be accompanied by weather forecasts targeting pie-slice-like regions around airports, with associated likelihood of occurrence and timing.

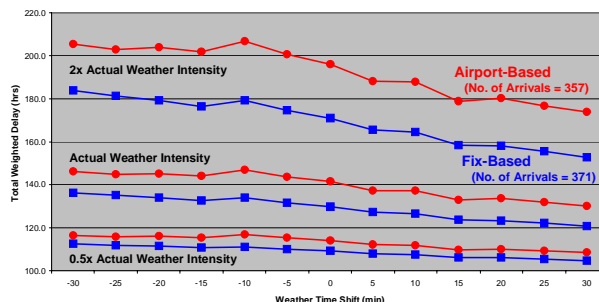


Figure 10: Comparison of Airport-Based and Fix-Based GDPs with cornerpost swaps (positive weather time shift denotes forecast weather later than actual weather).

6. ACKNOWLEDGMENTS

This research was funded by NASA Ames Research Center under contract NAS2-02075.

7. REFERENCES

- Ball, M.O., Chen, C.-Y., Hoffman, R., and Vossen, T., "Collaborative Decision Making in Air Traffic Management: Current and Future Research Directions", in *New Concepts and Methods in Air Traffic Management*, Bianco, L, Dell'Olmo, P, and Odoni, A., Editors, Springer-Verlag, Germany, 2001.
- Ball, M.O., Hoffman, R.L., Knorr, D., Wetherly, J., and Wambsganss, M., "Assessing the Benefits of Collaborative Decision Making in Air Traffic Management," in *Air Traffic Systems Engineering*, Donohue, G.L., and Zellweger, A.G., Editors, AIAA Press, Reston, VA, 2001.
- Wambsganss, M.C., "Collaborative Decision Making in Air Traffic Management," in *New Concepts and Methods in Air Traffic Management*, Bianco, L, Dell'Olmo, P, and Odoni, A.R., Editors, Springer-Verlag, Germany, 2001.
- Wambsganss, M.C., "Collaborative Decision Making through Dynamic Information Transfer," *Air Traffic Control Quarterly*, Vol. 4, pp. 107-123, 1997.
- Rhoda, D.A., and Pawlak, M.L., "The Thunderstorm Penetration/Deviation Decision in the Terminal Area", *American Meteorological Society's 8th Conference on Aviation, Range, and Aerospace Meteorology*, Dallas, TX, 1999, pp. 308-312.