AIAA Guidance, Navigation, and Control Conf., Providence, RI, Aug., 2004.

Potential Benefits of Fix-Based Ground Delay Programs to Address Weather Constraints

Bob Hoffman, Ph.D.* Jimmy Krozel, Ph.D.† and Ray Jakobavits. Ph.D.‡
Metron Aviation, Inc., Herndon, VA, 20170

The objective of this analysis is to evaluate the performance of increasingly precise airport ground delay program (GDP) procedures under a range of weather forecasting capabilities. The GDP procedures include both current (airport-based) programs and future (airport arrival fix-based) programs. The weather forecasting capabilities assume various temporal and spatial forecast errors relative to a baseline forecast. A general modeling framework is developed for studying weather impacts on GDPs and is applied as a single-day case study of Chicago O'Hare International Airport (ORD). The framework includes a weather severity index used to aggregate weather impact. The analysis demonstrates the payoff for using more precise GDP flow control mechanisms than are used today to exploit improved weather forecasting capabilities expected in the future.

Nomenclature

AAR	=	*Airport Acceptance Rate*
ADL	=	*Aggregate Demand List*
ATCSCC	=	*Air Traffic Control System Command Center*
CCFP	=	*Collaborative Convective Forecast Product*
CTA	=	*Controlled Time of Arrival to an Airport*
dBZ	=	*Decibels*
ETMS	=	*Enhanced Traffic Management System*
GDP	=	*Ground Delay Program*
NAS	=	*National Airspace System*
NWS	=	*National Weather Service*
S_{ave}	=	*Average Speed*
S_{eff}	=	*Effective Speed*
SPO	=	*Strategic Plan of Operations*
T_A	=	*Time crossing Boundary at Point A*
T_B	=	*Time crossing Boundary at Point B*
TFM	=	*Traffic Flow Management*
WSI	=	*Weather Severity Index*
Z	=	*Zulu Time*

I. Introduction

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

---

* Manager, Research and Development, 131 Elden Street, Suite 200.
† Chief Scientist, Research and Development, 131 Elden Street, Suite 200, AIAA Associate Fellow.
‡ Sr. Analyst, 131 Elden Street, Suite 200.

(ATCSCC) and the airlines, is currently and will continue to be a vital component of the overall management of capacity [1, 2, 3, 4].

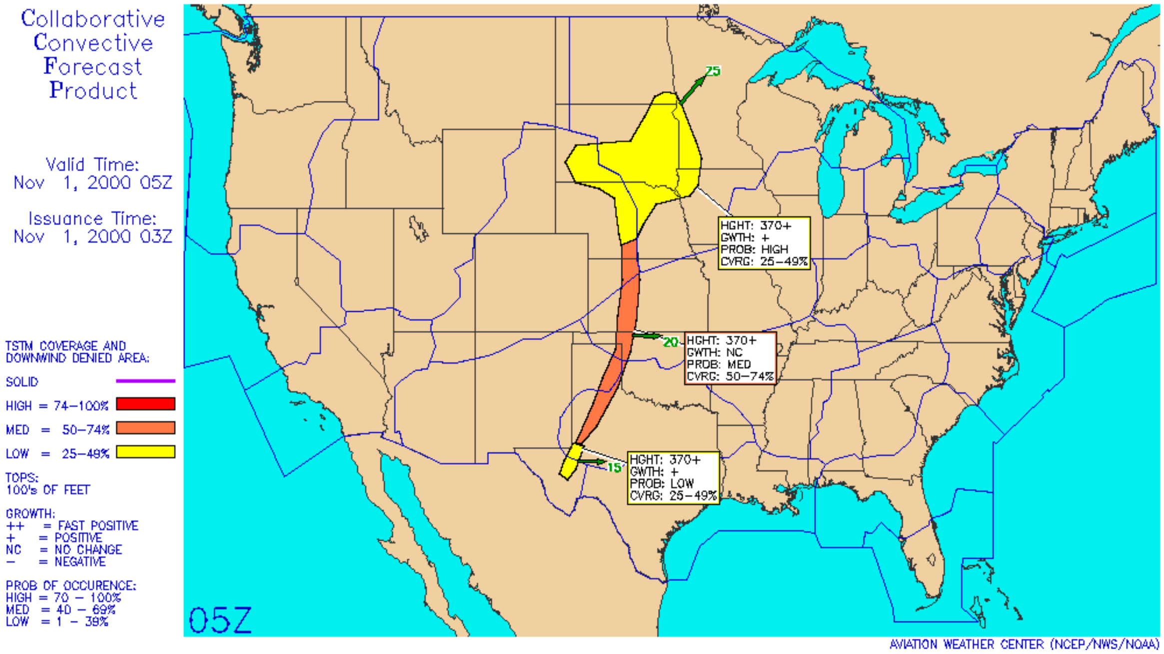


Figure 1: CCFP from Aviation Weather Center website.

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.

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.

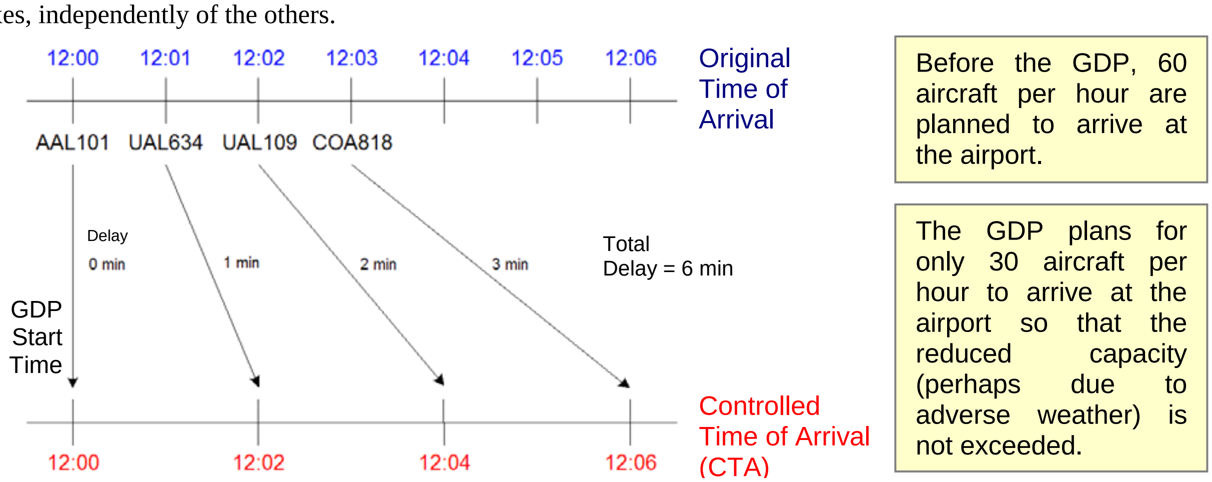
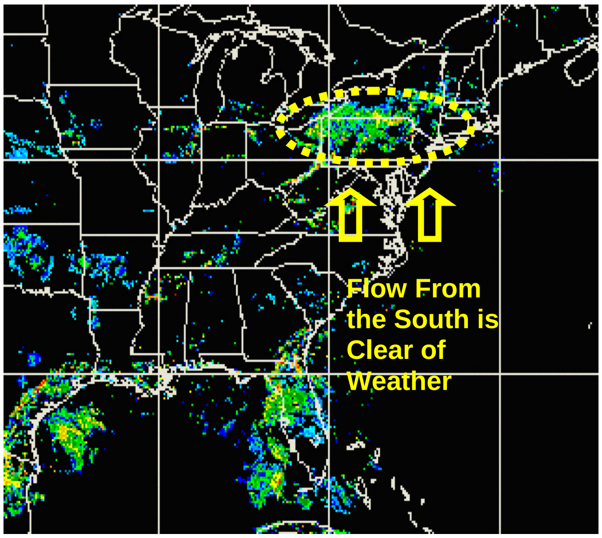


Figure 2: The net effect of ground delays is to stretch out the flow of arrivals over time.

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 need not be affected. A fix-based GDP would have allowed traffic managers to apply delays over only those fixes where the weather is causing a problem. Additional benefits may be gained by allowing flights to switch arrival fixes (corner post swaps).




```
Date:  07/09/2002  15:51  Advn:  29  Origin:
ATCSCC  Facid:  EWR/ZNY   Title:  CDM  GROUND
DAY PROGRAM

AIRPORT: EWR
ADL TIME: 15:47Z
PROGRAM TYPE: RBS PP
ARRIVALS ESTIMATED FOR: 091800Z - 100159Z
PROGRAM AAR: 37
ALL  CENTERS  ARE  INCLUDED  IN  THE  PROGRAM.
THE FOLLOWING SHALL APPLY
FA DELAYS:
(NoWest+CZY_AP) ZAU ZBW ZDC ZFW ZHU ZID ZJX
ZKC ZMA ZME ZMP ZNY ZOB
ZTL CYHZ CYOW CYUL CYYZ
EXEMPTED AIRPORTS: NONE
MAXIMUM DELAY: 87
AVERAGE DELAY: 42
REASON: WEATHER, SUPPORT OF SWAP
REMARKS: NONE
```

Figure 3: Weather impacting flights into EWR from the West, but not from the South (7/9/02) and the GDP planned for the weather event.

In this paper, we devise a formal GDP research framework to investigate the relationship between GDP algorithms and weather forecasting capabilities. 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 tools.

II. 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 and high frequency of GDPs. The framework and techniques apply equally well to other major airports. **Figure 4** shows a schematic of the approach we developed.

There are two primary modeling efforts, represented by the upper and lower halves of **Figure 4**, respectively. The first effort (upper half of **Figure 4)** 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 (lower half of **Figure 4**) 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, which are highlighted in **Figure 4.**

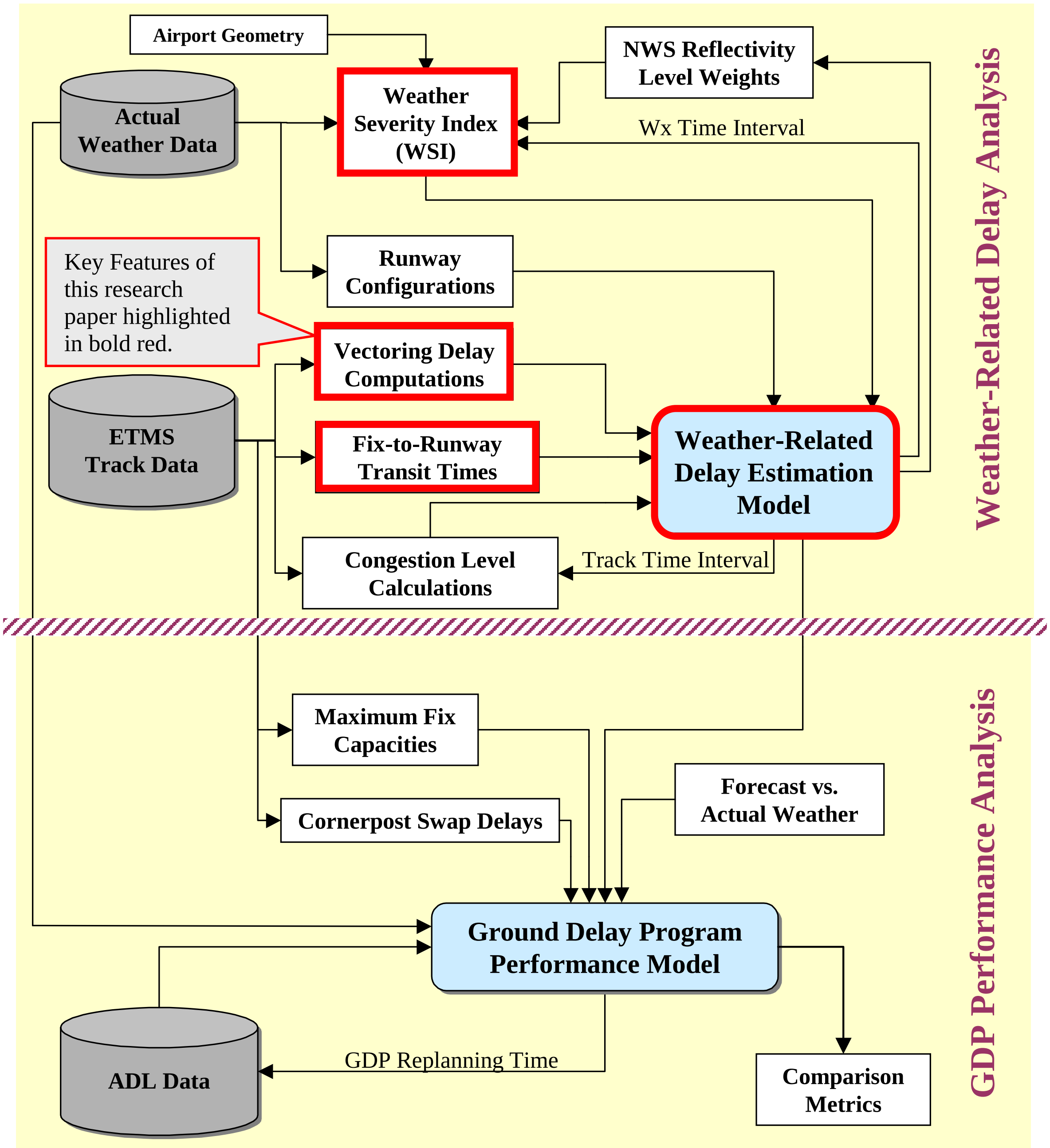


Figure 4: GDP Research Framework.

A. 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 above[5]. 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 5**). 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.

Table 1: NWS Standard reflectivity levels and weather classifications.

NWS Level	Color	Rainfall Rate (mm/hr)	Reflectivity (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

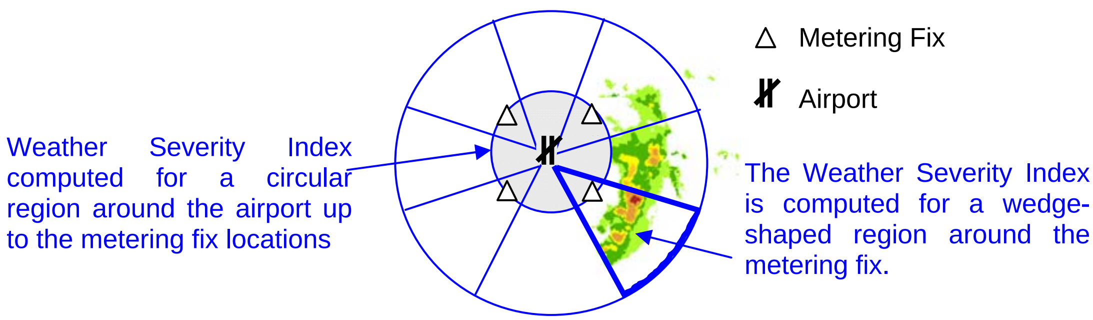


Figure 5: Weather Severity Index (WSI) is determined by a region of airspace around an airport.

As an example, **Figure 6** illustrates weather severity on June 26, 2002, a notoriously difficult traffic flow management day. 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.

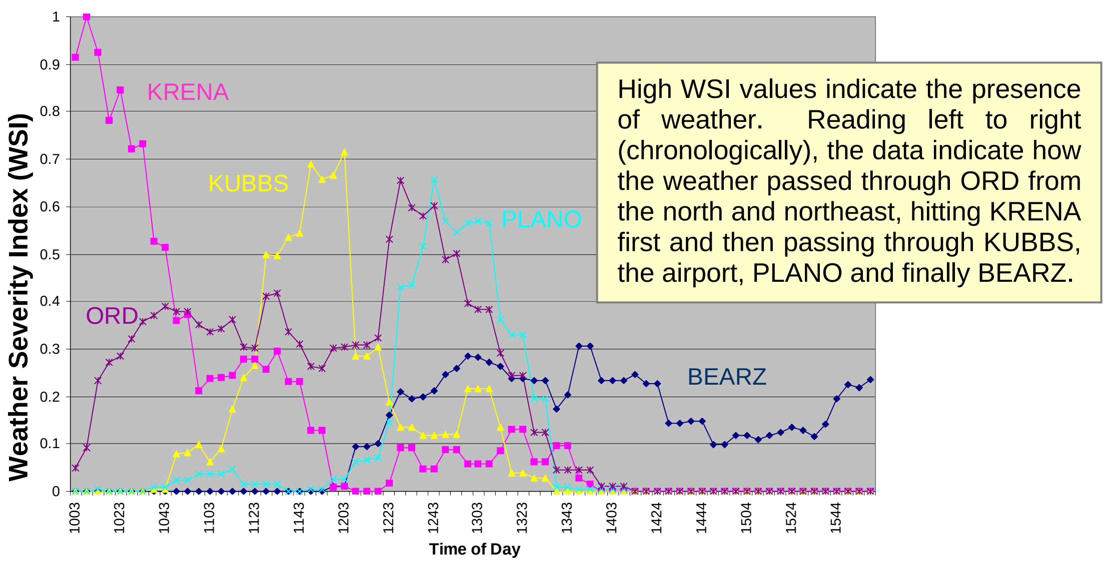


Figure 6: Weather Severity Index (WSI) Values for 10:00 to 16:00 on June 26, 2002.

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-neighbors 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 7**. 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.

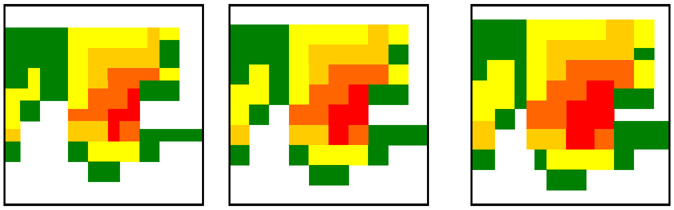


Figure 7: A weather severity variation manipulated by a wildfire algorithm.

B. Vectoring Delay Computation

En route delays are due to either speed changes or spatial deviations known as vectoring. Speed changes are harder to detect in historical data than delays associated with vectoring. However, we were able to capture vectoring delays by using an algorithm designed to detect and measure delays due to en route deviations from a planned flight track. *Sector Delay* is represented using the notion of effective speed across a sector. As illustrated in **Figure 8,** the ratio of effective speed (S_{eff}) to average speed (S_{ave}) of a flight crossing the sector determines if the flight incurred any delay in the sector:

$$S_{eff} = \frac{DirectToDist}{T_B - T_A} \qquad S_{ave} = \frac{FlownDist}{T_B - T_A}$$

$$Delay = \frac{S_{eff}}{S_{ave}}(T_B - T_A)$$

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.

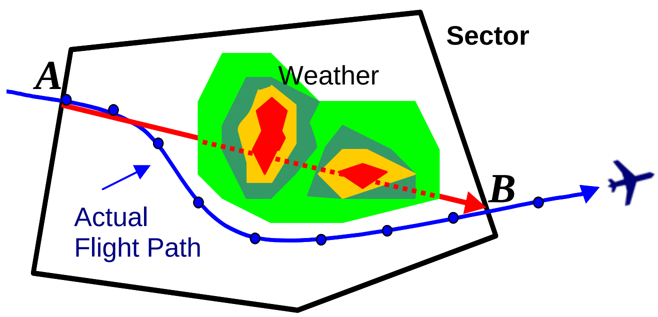


Figure 8: Delay is determined by comparing the direct distance to the flown distance.

A sample of the computed vectoring delays is presented in **Figure 9**. 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.

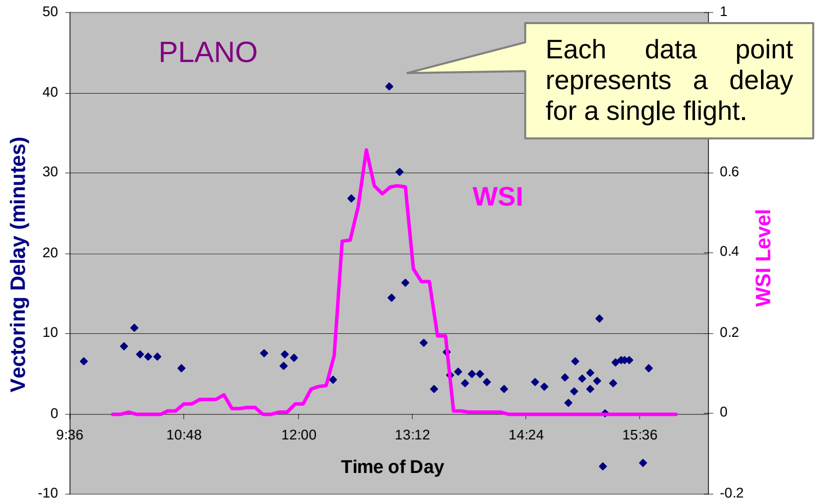


Figure 9: Vectoring Delays vs. WSI for the ORD PLANO Arrival Fix on June 26, 2002.

C. 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. 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

D. 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:

- Low-arrival and high-arrival rate data ranges did not yield any identifiable relationship between weather level and vectoring delay. During periods of low arrival rates, vectoring delays tended to be small, regardless of the weather. Periods of high arrival rates did not coincide with periods of bad weather.
- In the medium arrival rate data range, a relationship was identified that explained about half of the variance in the vectoring delay times.

In the latter arrival-rate range, predicted delay was found 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 expected[5], the regression analysis placed most of the weight on the two highest NWS Levels.

Figure 10 plots predicted delay versus actual vectoring delays for each flight. Perfect predictions (predicted = actual) fall on the diagonal line, while under-predictions (predicted < actual) lie above the diagonal and over-predictions (predicted > actual) lie below the diagonal. The fact that so much of the variance in the vectoring delay values remains unexplained by the model indicates that there are additional significant factors still to be identified.

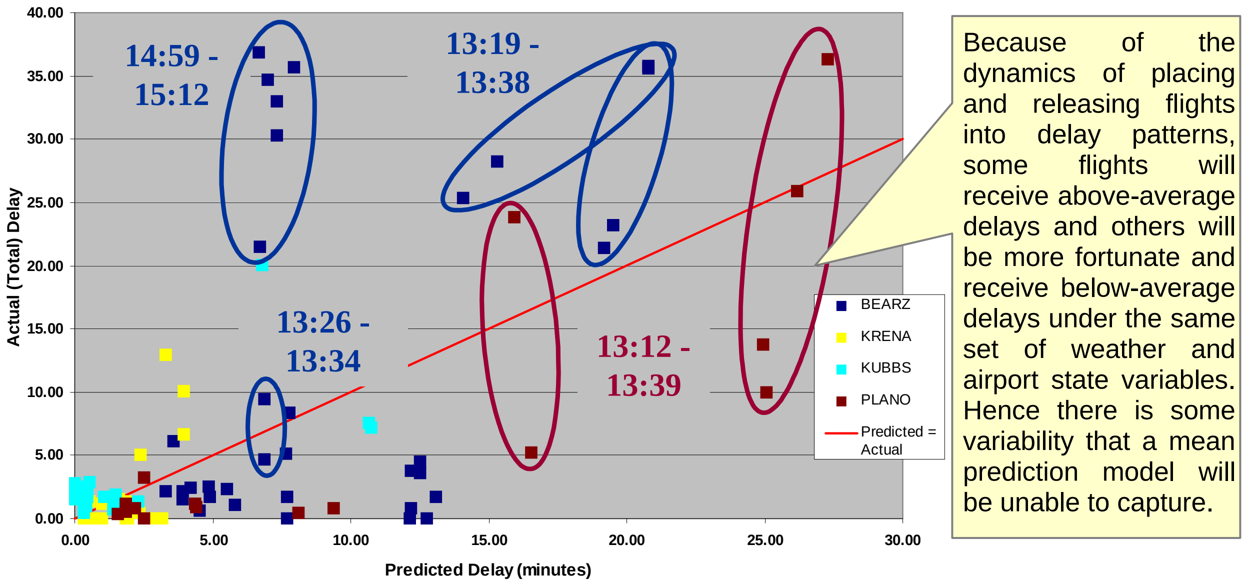


Figure 10: Predicted vs. Actual Vectoring Delays, ORD June 26, 2002.

In order to explain some of the predictive model deficiencies, **Figure 10** clusters select flights by comparable arrival time (after adjusting for delays incurred prior to reaching the fix). Of the seven flights that arrived at BEARZ between 13:19 and 13:38, two flights experienced delays that were well predicted by the predictive model (diagonal line), but the other five were under predicted. ORD was experiencing significant departure congestion at this time; the GDP arrival rate was about to be revised downward and there may have been additional delays imposed on arriving flights in an attempt to maintain the arrival rate before the decision was made to revise the GDP. The six flights arriving at PLANO between 13:12 and 13:39 probably illustrates the dynamics of managing reservoirs of delayed flights, as highlighted in the figure. Lastly, the six flights arriving at BEARZ between 14:59 and 15:12 had delays falling significantly above the prediction line. The weather had improved, but there are no entries in the TFM log files to suggest any reason why these flights should have been held. Finally, the flight having both the highest actual and highest predicted vectoring delay was investigated; this flight was held in a tight pattern just inside the 100-nautical mile range ring prior to crossing PLANO and heading directly for the runway.

The model obtained here illustrates the concept of relating weather, airport operations, and en route delays. Examination of additional data sets, as well as future research on this project developing weather-related aircraft trajectories should greatly improve our understanding of those relationships.

III. GDP Performance Results

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.

A. 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. The scheduled demand for ORD ramps up during that period from 26 aircraft during the first hour to 100 aircraft during the final hour. At the same time, the weather was most severe between 11:30 and 13:30, slightly before the peak demand period. When an airport-based GDP was put into effect (modeled), the delay-minimizing sequence of AARs is shown in **Figure 11**. The maximum AAR of 80 is maintained until 14:00, and then reduced for the final 2 hours of the program. That 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.

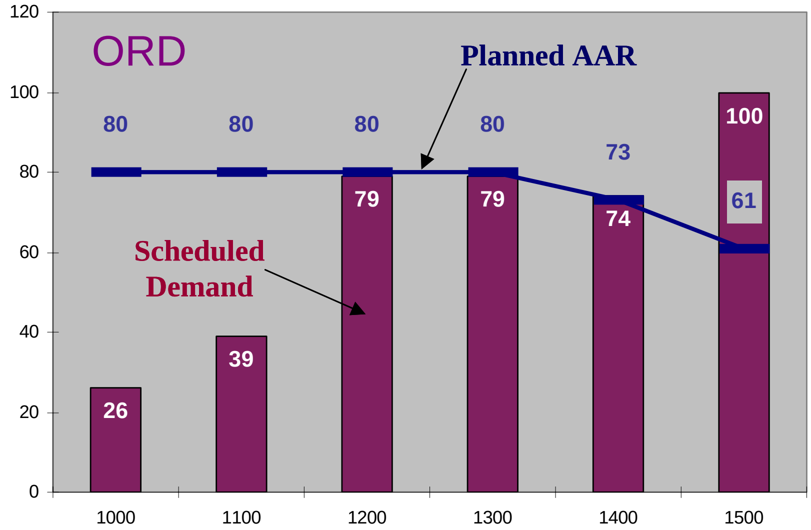


Figure 11: Minimum Delay Airport-Based AAR Sequence.

With fix-based planning, the delay-minimizing set of AARs is as shown in **Figure 12**. 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 13** illustrates the results for the two AAR sequences shown above under weather prediction accuracy temporal and/or intensity variations.

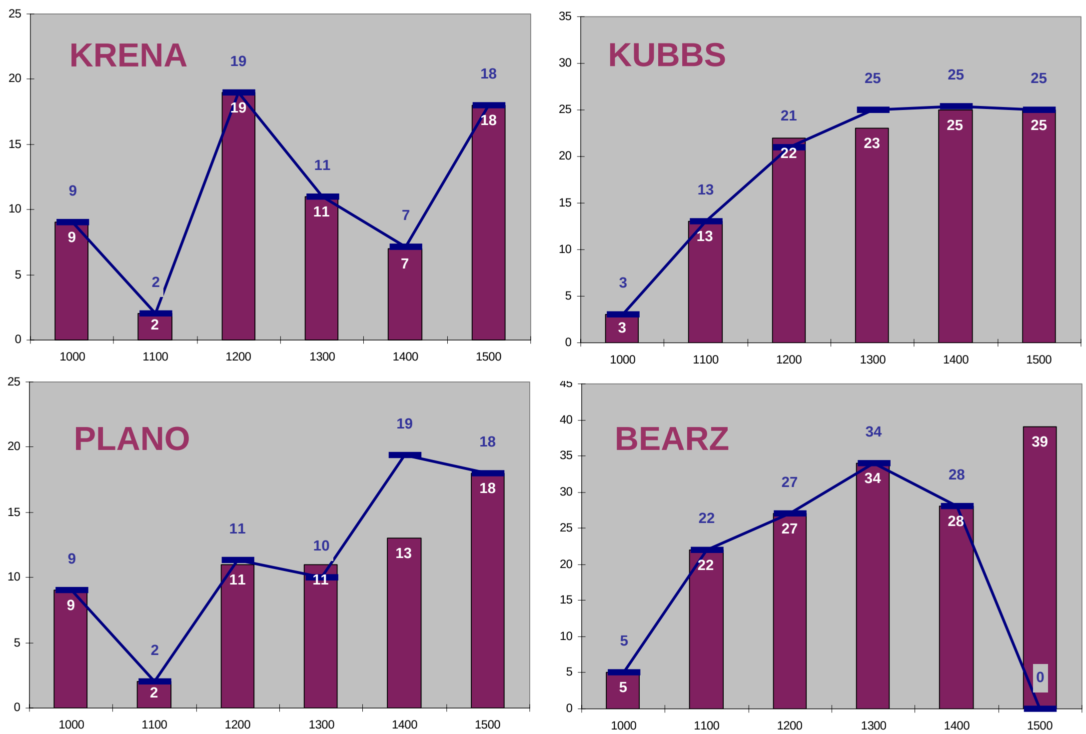


Figure 12: Minimum Delay Fix-Based AAR Sequence.

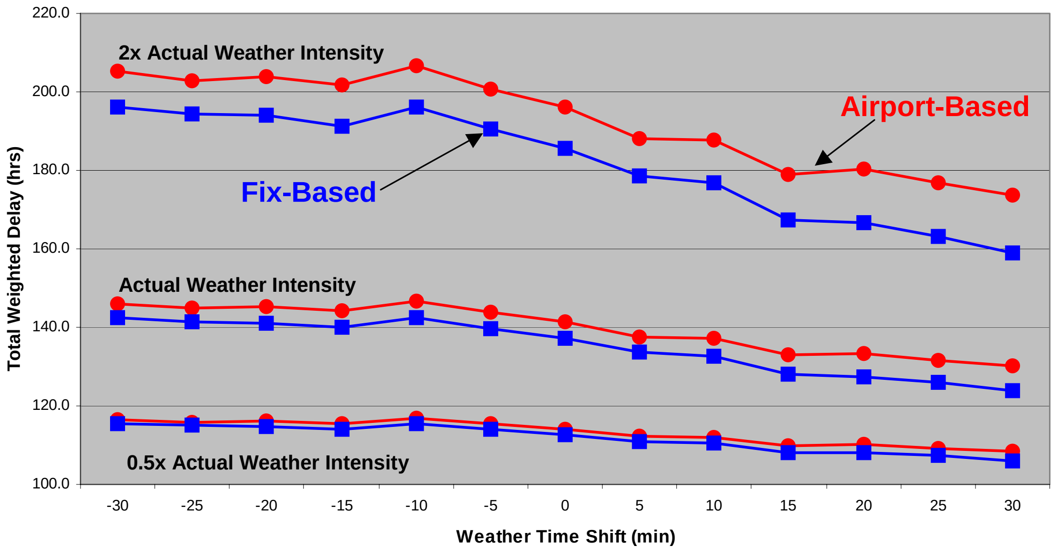


Figure 13: Comparison of GDP plans under variations in weather forecast accuracy (positive weather time shift denotes forecast weather later than actual weather).

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 that 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 13**, 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.

B. Distance-Based GDPs

Traffic managers commonly exempt from ground delay those flights originating at airports beyond a certain distance from the GDP airport. The distance is chosen through a combination of experience, intuition, and negotiation. The net effect is to shrink the set of flights that will absorb the total delay necessary to control the airport flow. **Figure 14** illustrates the cumulative distribution of flights arriving at ORD on June 26, 2002 sorted by flight length. Exempt flights are allowed to use their last filed arrival fix. Thus, in terms of fix-based planning, there is less flexibility in adjusting fix acceptance levels to limit vectoring delays, since the number of exempt flights passing through a fix in a given hour imposes a lower bound on the fix acceptance rate. Since we are not considering the effects on specific air carriers as part of this research, airport-based planning is unaffected by distance-based exemptions. To illustrate the impact of distance-based exemptions, a 500-nautical mile exemption cut-off was explored.

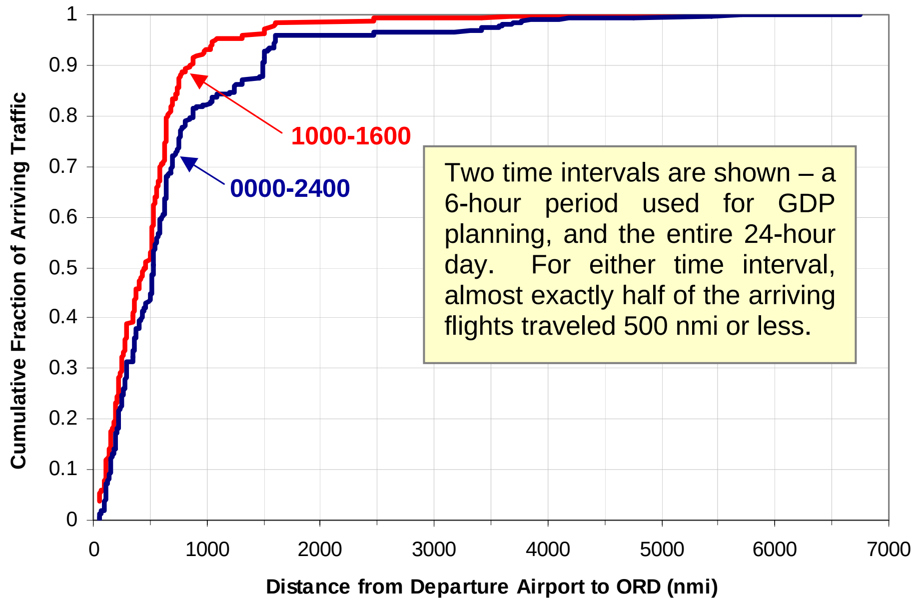


Figure 14: ORD Arrivals vs. Flight Length on June 26, 2002.

The net result of reduced flexibility is that the use of distance-based exemptions reduces some of the advantage derived from fix-based planning. Those gains might be recovered through the use of corner post swaps (see below), but in the absence of such swaps, some fixes must be utilized more than the delay-minimizing plan would require. **Figure 15** presents the delay graphs for this case. The airport-based graphs are the same as those shown in **Figure 13**, while the fix-based graphs reflect the constraints on fix acceptance rates that result from the 500-nmi exemption rule. While there is little to separate the two sets of delay graphs, we note that the number of arriving aircraft in the GDP time horizon under the fix-based GDP is 372 (versus 357 under the airport-based GDP), so there is still an advantage to fix-based planning, it is just not as pronounced as in the no-exemption case, where the number of arrivals was 376 with the same overall delay.

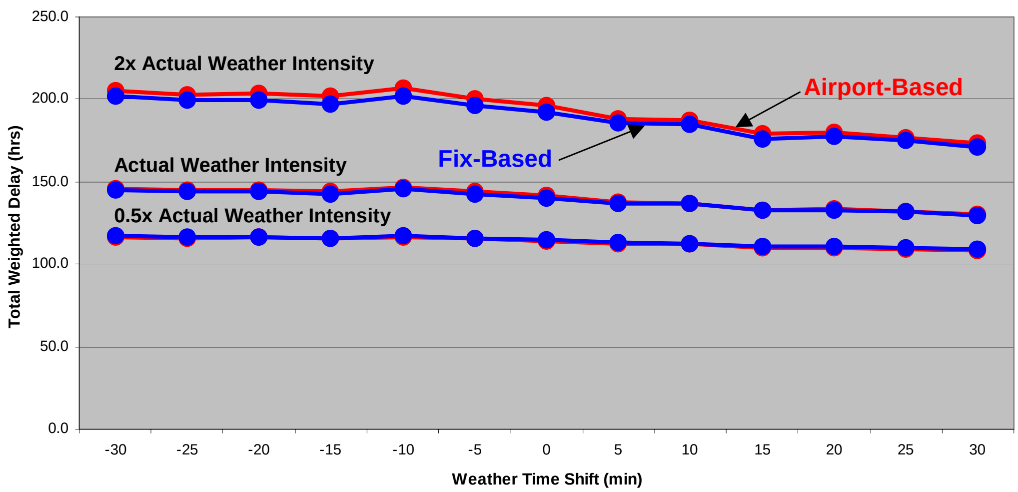


Figure 15: Comparison of Airport-Based and Fix-Based GDPs using Distance-Based Exemptions (positive weather time shift denotes forecast weather later than actual weather).

Note that the loss in efficiency associated with distance-based GDPs is entirely predictable and consciously traded off by traffic flow managers in favor of more equitable delay distributions. The reasoning is that if the GDP were canceled prematurely, then long-haul flights would receive a high amount of unrecoverable (and unnecessary) ground delay. Equity issues being highly subjective and less relevant to future capacity increases, we have kept investigation of distance-based GDPs to a minimum.

C. 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. While fix-based GDPs tend to severely restrict flows across metering fixes in response to severe weather forecasts, use of this corner post swap 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 16 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.

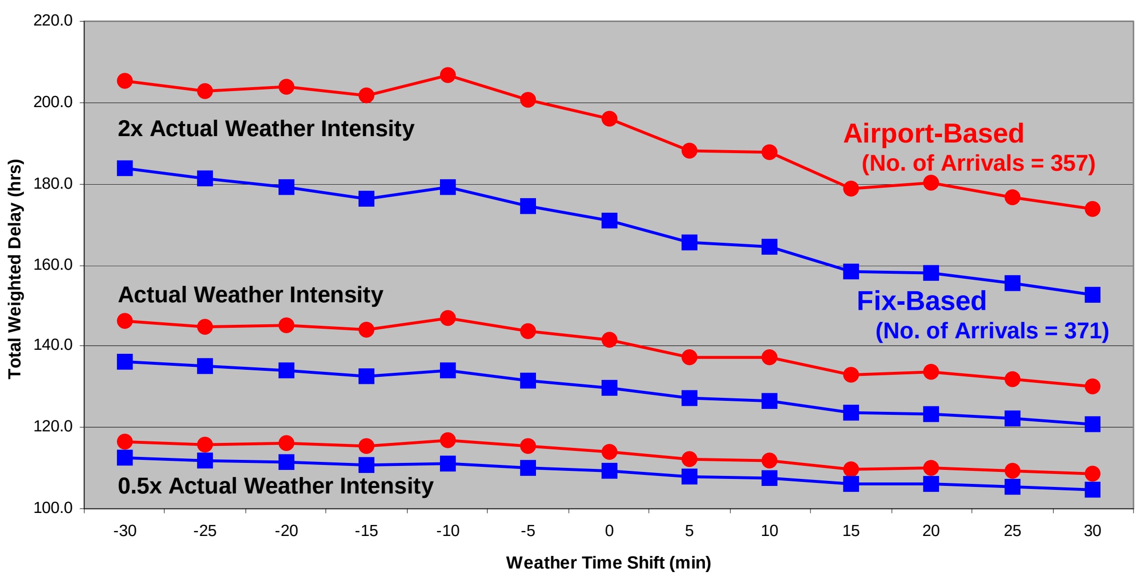


Figure 16: Comparison of Airport-Based and Fix-Based GDPs with cornerpost swaps (positive weather time shift denotes forecast weather later than actual weather).

One limitation of the current analysis is that there was no delay penalty assessed for corner post swaps, while it is clear from the flight tracks analyzed for the case study that such flights travel extra distance. Future research should enable those penalties to be determined on a flight-by-flight basis.

IV. 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. In the scenario chosen for this study, fix-based GDP planning reduced delay costs anywhere from 3% to 20% over airport-based GDP planning, depending upon the severity of the weather, the relative levels of demand and airport capacity, and the use of corner post swaps in conjunction with ground delays. In terms of GDP related weather forecast accuracy, if the realized weather is twice as severe as planned by the GDP (under-predicted), then this increases the overall weighted delay levels by 30 – 40%. If the realized weather is half as severe as planned by the GDP (over-predicted), then this reduces overall weighted delay levels by 15 – 20%. Temporal variations in the weather prediction accuracy may turn out to be better or worse that the forecast, so the results of systematic changes in the arrival time of the weather are not monotonic. Temporal weather prediction errors generally cause fewer problems than spatial errors, and temporal weather prediction errors are less significant when the actual weather arrives less severe than the planned weather.

Acknowledgments

This research was funded by NASA Ames Research Center under contract NAS2-02075. We are greatly appreciative to our NASA Technical Monitor, Matt Jardin, Ph.D., for his guidance, which helped focus the effort. Finally, we appreciate the financial support of the sponsor of the research, NASA Ames Research Center and the Virtual Airspace Modeling and Simulation (VAMS) Project Manager, Mr. Harry Swenson.

References

[1]Ball, M.O., Chen, C.-Y., Hoffman, R., and Vossen, T., “Collaborative Decision Making in Air Traffic Mangement: Current and Future Research Directions”, in New *Concepts and Methods in Air Traffic Management*, Bianco, L, Dell’Olmo, P, and Odoni, A.R., Editors, Springer-Verlag, Germany, 2001.

[2]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 A*ir Traffic Systems Engineering*, Donohue, G.L., and Zellweger, A.G., Editors, AIAA Press, Reston, VA, 2001.

[3]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.

[4]Wambsganss, M.C., “Collaborative Decision Making through Dynamic Information Transfer,” *Air Traffic Control Quarterly*, Vol. 4, pp. 107-123, 1997.

[5]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.