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INITIAL STUDIES OF AN OBJECTIVE MODEL TO FORECAST ACHIEVABLE AIRSPACE FLOW PROGRAM THROUGHPUT FROM CURRENT AND FORECAST WEATHER INFORMATION*

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1. INTRODUCTION

Airspace capacity constraints caused by adverse weather are a major driver for enhanced Traffic Flow Management (TFM) capabilities. One of the most prominent TFM initiatives introduced in recent years is the Airspace Flow Program (AFP) (Brennan, 2007). AFPs are used to plan and manage flights through airspace constrained by severe weather. Aircraft with filed flight plans through the AFP region have the option of rerouting to avoid that airspace or remaining on a route through the AFP region and enduring the assigned AFP delay. An AFP is considered an improvement in managing en route weather impacts over the previous practice of implementing Ground Delay Programs (GDP) at a few select airports in order to reduce en route airspace demand in a region. Moreover, an AFP does not unnecessarily delay flights to an airport that do not pass through the en route region of reduced capacity (Doble et al. 2006).

There are eight predefined AFPs that have been developed to control air traffic demand in the Northeast region of the National Airspace System (NAS) – primarily arrivals to airports in the corridor from DC to NY to Boston - when convective weather reduces en route airspace capacity. A review of AFP usage since its inception in 2006 shows that by far the most frequent AFPs used are FCAA05 and FCAA08 (Figure 1). For all predefined AFPs, including A05 and A08, arrival rate reduction guidelines have been developed through analysis of historical traffic data.

An AFP operates as a strategic air traffic management tool, where “strategic” (i.e., 4 – 6 hour) Collaborative Convective Forecast Product (CCFP) predictions (and other weather information such as current weather impacts) are used to determine key AFP parameters (especially program start time and the time rate profile for the program). The desired lead-time for implementation of an AFP is at least three hours, throughput rates are set for hourly periods, and rates are often revisited during bi-hourly Strategic Planning Teleconferences (SPT).

Although there have been a number of conference papers and FAA documents that discuss the motivation for AFPs and details of the process by which aircraft delays are determined when an AFP is in operation[1], to date there has been little information as to how the key parameters for an AFP (e.g., program start and stop times and the time profile for AFP rates) are determined from weather forecast information[2].

As convective weather continuously evolves, the sector capacity[3] for a region of en route airspace can fluctuate significantly over periods as short as 15-30 minutes (Figure 2). This type of variability in available airspace is common during convective weather events.

It has been operationally difficult to proactively identify the need for (and then implement) tactical adjustments to AFP throughput rates when these programs are in use. Currently, when the actual AFP throughput demand is recognized to be greater than the available airspace capacity, the traffic flow managers and airlines have to reduce demand by ground-holding departures that normally would have transitioned through the AFP

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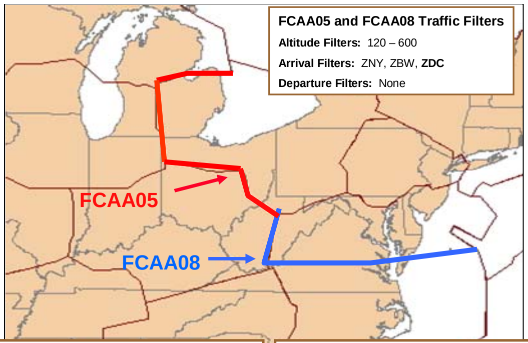
[1] Including how Estimated Departure Clearance Times (EDCT) for individual aircraft are determined when the flight is impacted by both an AFP and other initiatives such as a GDP.

[2] Brennan (2007) notes that critical questions for the use of AFPs include “for what weather conditions, or other congestion events, should AFP’s be employed” and “how should the capacity for an AFP, the rate at which it can accept flights, be established.” However, the answers to those questions are not fully addressed in Brennan (2007) and other literature on AFPs.

[3] Sector capacity, as measured by the number of aircraft in a sector over a given time period (e.g., 15 minutes). This is the metric used in the current TFM system to characterize the workload in a sector.

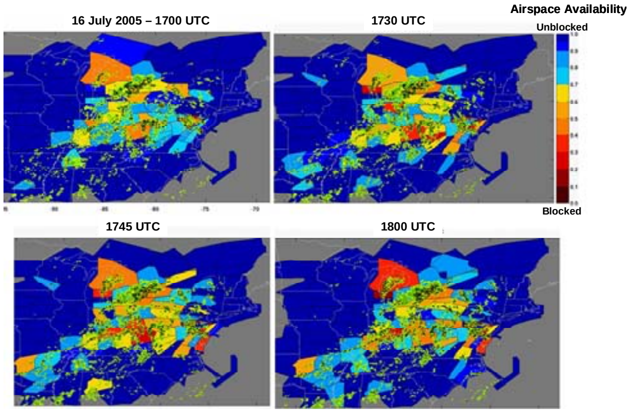
and/or tactically reroute aircraft around the AFP. Another option [used on approximately 50% of the Severe Weather Avoidance Plans (SWAP) events observed in the Route Availability Planning Tool (RAPT) tests (Robinson, et al. 2008)] was to hold departures from the NY airports on the ground so that the NY airport departure airspace could be used to handle the excess arrivals into the Northeast.



FCAA05 Rate Guidelines	
Flow through ZOB:	
Low Weather Impact:	75 – 85 Rate/Hour
Med Weather Impact	65 – 75 Rate/Hour
High Weather Impact	55 – 65 Rate/Hour

FCAA08 Rate Guidelines	
Flow through ZDC:	
Low Weather Impact:	135 – 145 Rate/Hour
Med Weather Impact	125 – 135 Rate/Hour
High Weather Impact	115 – 125 Rate/Hour

Figure 1. Location, traffic filters, and rate guidelines for AFP FCAA05 and FCAA08.


16 July 2005 – 1700 UTC

1730 UTC

1745 UTC

1800 UTC

Figure 2. Variations in en route airspace sector capacities during convective weather on 16 July 2005. Note how rapidly airspace capacity can vary in both space and time. These capacity estimates were computed from CIWS precipitation and echo tops data by the algorithm described in Martin (2007). The colors indicate the estimated reduction in sector throughput, averaged across the jet routes traversing each section.

To help anticipate near-term changes in airspace capacity, tactical forecasts such as the Corridor Integrated Weather System (CIWS) 0 – 2 hour Precipitation and Echo Tops Forecast products are currently presented to traffic managers on a graphical situation display. However, these tactical forecasts are not translated into explicit forecasts of achievable AFP throughput rates.

If the CIWS tactical forecasts could be translated into forecasts of achievable AFP throughput, the question then arises as to what traffic management initiatives (TMIs) might be used to address situations where the projected demand was greater or less than the forecast AFP throughput.

First, we note that the AFP locations are such that major airports are in many cases within 30-60 minutes flight time of the AFP boundary. If the CIWS forecasts could be used to identify excess demand situations one to two hours in advance, it would then be possible to have a more efficient approach to dynamically adjusting the demand through the AFP.

Adaptive adjustments to AFPs are currently under investigation by the FAA Collaborative Decision Making (CDM) Flow Evaluation Team (FET). Examples of “adaptive” adjustments in use or under consideration include:

- Cancelling the estimated departure clearance time for some airports for traffic scheduled to fly through the AFP;
- Modifying AFP rate parameters. This procedure would provide en route capacity benefits analogous to those that will be realized at terminals using “Adaptive Compression”;
- Using Ground Delay Programs (GDP) or Ground Stops (GS) to reduce traffic demand in an AFP airspace region;
- Using overlap AFPs which are portions of a larger AFP that would have different rate parameters (e.g., the northern portion of an AFP could have a percentage reduction in demand that was quite different from the demand reduction for the southern portion of an AFP).

However, the FET has not yet considered in detail the weather forecast information that would be needed for decision support for adaptive AFP adjustments.

To this end, an en route airway blockage-based algorithm, using CIWS tactical forecast information, has been developed in order to objectively estimate achievable flow rates through the FCAA05 and FCAA08 AFP boundaries during convective weather. The model is an adaptation of the weather route-blockage model used in the Route Availability Planning Tool (RAPT) deployed as a demonstration system for NY operations (e.g., Martin, 2007; DeLaura et al. 2008). This model first translated CIWS Precipitation and Echo Tops information into Weather Avoidance Fields (WAF), which represent estimated probabilities of pilot deviations. The WAFs are then used to estimate the weather impact on air traffic operations. The model then identifies a traversable path through WAFs along a route and calculates route availability. Specifically, the Traffic Normalized Fractional Route Availability (TNFRA) – the achievable route throughput – is calculated by combining the route availability with the fair weather traffic demand on each route. Finally, the model estimates the achievable AFP flow rate by summing the achievable flow rates for the individual routes/flows crossing the AFP boundary that are included in the program.

This report describes the results of an exploratory effort to:

a) Achieve an initial understanding of the relationship of AFP rate decision making to the occurrence and severity of actual and predicted convective weather;
b) Assess the ability of the model described above to objectively predict the achievable AFP throughput from CIWS-measured precipitation and echo tops as the convective weather impact varies in time and space during a storm impact event.

2. 2007 FCAA05 USAGE AND OBSERVATIONS

There is a lack of detailed information describing the weather conditions or other congestion events during which an AFP should be employed, and the relationship of the capacity for an AFP to the forecast weather conditions. Therefore, in developing and assessing an AFP throughput capacity model, it was decided that a first step should be to analyze the assigned traffic rates for frequently used AFPs for a number of storm events. The objective here was to gain insights into the relationship between actual and forecast convective weather impacts to the AFP throughput decisions (including "tactical" adjustments to the AFP traffic constraints) in order to better understand which convective weather features were most important for setting AFP throughput rates.

The AFP used most frequently in 2007 to manage en route airspace and mitigate air traffic delay during convective weather was FCAA05. During the five-month period from mid-May to mid-October, FCAA05 was implemented on 20 days (Table 1). AFP parameters (rate restrictions and implementation times) and convective weather characteristics were analyzed for all FCAA05 events. The observed AFP / weather characteristics include:

- FCAA05 issuance, start, and end times
- FCAA05 rates at the time at which the AFP was issued and the rates at the AFP start time for first three hours of AFP period
- FCAA05 rate revisions and use of additional traffic management initiative (TMI) programs to manage en route weather impacts
- FCAA05 convective weather impacts
- Time and location of maximum weather impact
- Dominant type of convective weather organization (e.g., air mass cells, squall lines, etc.)
- CCFP forecasts in FCAA05 region

Table 1. Dates in 2007 that FCAA05 AFP was implemented

Month	Day
May	9, 10, 16
June	11, 13, 19, 27, 28
July	5, 10, 11, 18, 19, 27
August	9, 30
September	7, 26, 27
October	9

These data were analyzed to gain insights into the relationship between observed FCAA05 AFP rates in 2007 (and the need for revisions or supplemental programs) and convective weather organization type, impact location, and the availability of high-confidence forecasts.

These results, presented in detail in this section, identify general circumstances where:

1. Over/under – delivery of air traffic on AFP routes may have occurred
2. Tactical convective weather forecasts translated into explicit statements of en route airspace capacity reductions and reduced traffic throughput could have enhanced AFP operational effectiveness

3. More refined and focused AFP tactics, such as implementing alternative AFPs or managing only subsegmented AFP regions/flows, might have improved airspace usage efficiency

2.1 FCAA05 Implementation and Weather Impact Periods

The mean AFP issuance, start, and end times for the 20 FCAA05 events in 2007 are shown in Figure 4. Included in this Figure are the mean times when convective weather impacting FCAA05 airspace developed and reached maximum coverage and intensity[4]. On average, FCAA05 was implemented 20 minutes prior to the initial development of the AFP storm impact event. An examination of mean FCAA05 rates at the time the program was issued and the time at which the program was started for the first three hours of the AFP (Figure 5) demonstrate how hourly rates are typically set higher in the first hour and then reduced in the next hour. Therefore, if an AFP convective weather event strengthens quickly into a severe storm outbreak soon after initial development; it would appear that the FCAA05 initially over-delivered traffic in its first hour(s) - when the AFP rate had a higher value - given how close the AFP start time was to the weather impact period.

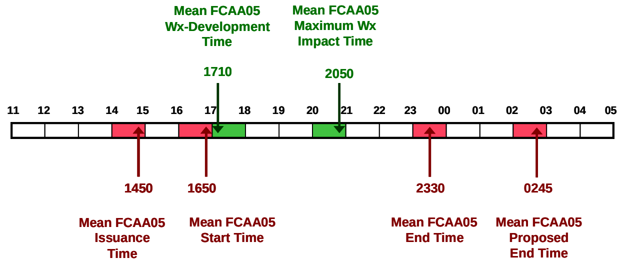


Figure 4. Mean AFP issuance, start, and end times and mean times when convective weather impacting FCAA05 airspace developed and reached maximum coverage and intensity. Times are in UTC.

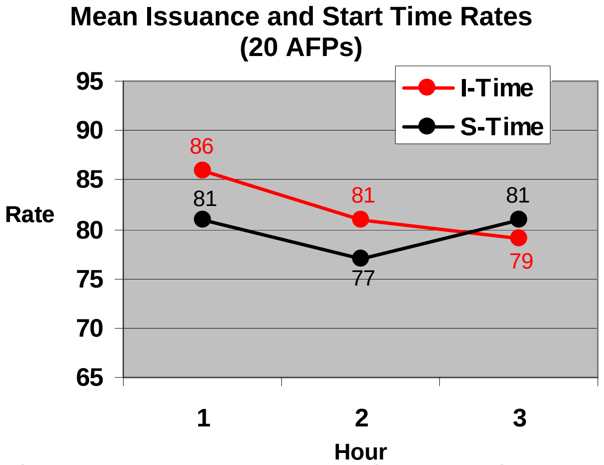


Figure 5. Mean FCAA05 rates in 2007 at issuance (I) time and start(S) time for the first three hours of the AFP.

The average time when the convective weather event impacting the AFP region reached its maximum severity (MaxWx) typically occurred 3.5 – 4 hours after the initial weather development and FCAA05 start time. Inspecting each FCAA05 event individually shows that MaxWx occurred between 2000 – 2200 UTC on 14 of 20 FCAA05 days (70%). Knowing that the period of MaxWx often occurred during this two-hour window may prove useful as justification for operational AFP planners to set lower initial rates for this period when the most significant airspace constraints are anticipated.

More detailed discussions on the AFP implementation and weather impact periods, in the context of traffic rates and weather organization, are discussed in the following sections.

2.2 FCAA05 Rates at Time of Most Significant Weather

The mean FCAA05 rate (R) at the time of MaxWx for 19 AFP events in 2007 was 74 aircraft/hour.[5] Though on average the time of MaxWx occurred four hours after that start of FCAA05 (see Figure 4), 70% of all convective weather events on FCAA05 days in 2007 strengthened to MaxWx within 3 hours of the AFP start time. The actual AFP rate issued at start time for the third AFP hour was less than or equal

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[4] CIWS VIL precipitation data were used to determine periods of initial convective weather development and maximum severity. The initial storm development period occurred when two or more level 5+ precipitation cells first appeared in the airspace region east of the FCAA05 boundary. Maximum severity of the weather event was defined to occur when the areal coverage of level 5+ CIWS VIL within the AFP region was at its peak.

[5] Though FCAA05 was implemented on 20 days in 2007, MaxWx on 09 May occurred before the start of the AFP and therefore R(MaxWx) was not available for that event.

to the lowest hourly rate setting of any AFP hour, at the time of implementation, on 15 of 20 FCAA05 events. This suggests that when the AFP was implemented, the third hour of the program, often occurring near 2000 UTC, was often anticipated to have the most severe capacity constraints caused by weather. However the average AFP throughput rate at the time of MaxWx was reduced by an additional 9% (81 to 74/hr). This in turn suggests that expectations for the effective AFP capacity at the time of MaxWx were roughly 10% too high when the FCAA05 AFP was implemented. Moreover, this 10% R(MaxWx) capacity overestimation is likely a conservative measure, given that demand was often coincidentally reduced by Ground Stop (GS) and Ground Delay (GDP) programs also implemented to address airspace capacity loss caused by thunderstorms in en route airspace (see Section 2.4). These results suggest that an objective AFP throughput prediction model may help refine FCAA05 throughput rates set at AFP start time, and provide explicit guidance for rate reductions (or needed traffic management initiatives) that may be subsequently required as the anticipated airspace capacity constraints worsen between the time of initial weather development and the time of MaxWx.

The location and organization-type of the convective weather event, at the time of MaxWx, was identified for each FCAA05 day in 2007. The MaxWx location was quantized into three FCAA05 regions: West, East ZOB, and ZNY. The types of convective weather organization were distributed into four primary categories:

1. Line – linearly organized convection that often persists for several hours
2. Cluster – collection of storm cells organized into larger convective entities that exhibit common motion and evolution
3. Embedded – weak, disorganized convection embedded in broader regions of non-convective precipitation
4. Unorganized Cellular – disorganized storm cells that develop and propagate in a chaotic manner (e.g., air mass convection)

The mean R(MaxWx) for FCAA05 was significantly higher when the AFP MaxWx was located in the West AFP region, and the rate was lowest when MaxWx occurred in ZNY (Figure 6). The 10-15% reduction in AFP rate when MaxWx occurs in ZNY (rather than in ZOB) is likely a statement of the increased traffic flow impacts, as a result of increased airspace limitations, that occur when thunderstorms are present in NY airspace.[6] Figure 6 also shows that AFP MaxWx occurred within ZNY on 13 of 19 FCAA05 days in 2007 (68%). This suggests that the significant weather impact on perhaps 2 out of 3 FCAA05 events may have been more directly managed by an FCAA01 AFP (Figure 7), where the stated "likely weather for use" is for when storms are in ZNY and closing in on the NY terminals (rather than for convection present in the Ohio Valley, as is stated for FCAA05).

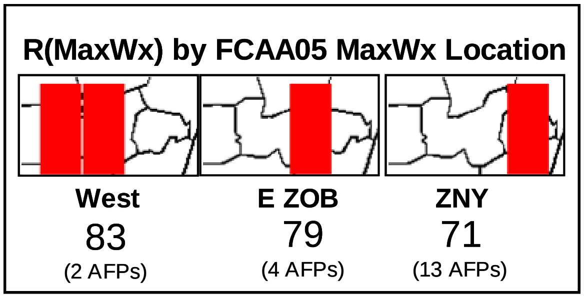

Figure 6. Mean R(MaxWx) by FCAA05 MaxWx location. The number of AFP days when MaxWx occurred at each of the three locations is provided in parentheses.

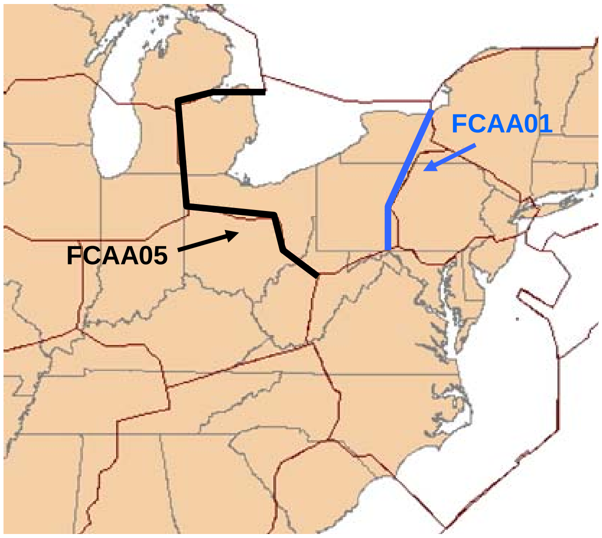

Figure 7. AFP boundaries for FCAA01 and FCAA05.

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[6] An operational ARTCC traffic manager interviewed on this subject suggested that the impact on traffic flow doubles when convective weather crosses from ZOB into ZNY airspace.

A breakdown of R(MaxWx) by convective weather organization type reveals that FCAA05 rates were set significantly lower when the AFP weather was organized (and thus typically more severe and disruptive) vs. unorganized (Figure 8). The most prevalent mode of FCAA05 MaxWx organization was linear convection (9 of 19 events – 47%).[7] These results suggest that the operational AFP decision makers were clearly accounting for the increased airspace constraints and reduced capacity common with more organized and widespread weather events. However, it is unclear from examining only R(MaxWx) statistics if a reduction in 13 aircraft/hr across the FCAA05 boundary when MaxWx was organized as a solid squall line vs. organized as permeable air mass cells (see Figure 8) sufficiently reduces en route traffic given the relative airspace availability constraints.[8] The likelihood that the AFP may have over-delivered traffic during line storm (and ZNY) MaxWx events becomes more apparent when the use of additional programs and FCAA05 rate revisions are analyzed (see Sections 2.4 and 2.5).

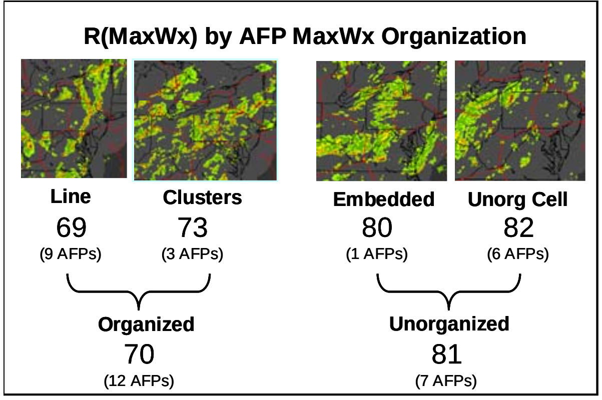

Figure 8. Mean R(MaxWx) by FCAA05 weather organization type. CIWS Precipitation product images provide examples of each type of storm organization category. The number of AFP days when MaxWx was organized as line, clusters, embedded, or unorganized cellular (then as organized or unorganized) is provided in parentheses.

2.3 FCAA05 Rates at AFP Issuance and Start Times

On average, FCAA05 programs began two hours after the initial AFP issuance notice (see Figure 4). It is stated in S2K+7 CDM Industry Training for AFPs that “a minimum of three hours notice must be provided prior to activating an AFP.” This criterion was met on 10 of 20 FCAA05 events in 2007. Given that 50 % of the time the need for an AFP to manage en route capacity loss was apparently recognized amongst all FAA and Industry decision-makers two hours (or less) before the start of the program underscores the potential importance of high-quality 0 – 2 hour tactical convective weather forecasts for initial AFP decision-making. Moreover, the frequency of these shorter lead time AFP issuances suggests that (a) the longer-range (2 – 6 hr) forecasts had difficulty predicting thunderstorm activity in the AFP airspace regions and/or (b) the severity of the anticipated weather impacts on available capacity may not be readily apparent without more explicit translations of weather forecasts into objective forecasts of the time-varying arrival capacity loss.

The mean AFP rate for the first two hours of the 2007 FCAA05 programs was typically reduced by 5% between Issuance (I) time and Start (S) time (See Figure 5). Since the weather affecting the AFP region generally did not develop until soon after AFP S-time, it is logical to conclude that the actual weather impacts changed little between I-time and S-time. If the weather impact remained largely unchanged during the two-hour (on average) interval between AFP issuance and implementation, why was the AFP rate often adjusted prior to the program start time?

A National Traffic Management Officer (NTMO) at the Air Traffic System Command Center (ATCSCC) was interviewed about AFP usage and we asked why more restrictive AFP rates were not used at I-time (or even at S-time) on days when the CCFP predicted (with high confidence) significant weather impacts or, more generally, the operational TFM community, recognizing the potential scenario, “knew” that thunderstorm impacts on en route airspace were going to be severe. The NTMO admitted that there is substantial pushback by the NAS customers on AFP rate setting for almost every AFP under consideration for implementation. In the opinion of the NTMO, the customers prefer to “wait and see”, since they don’t trust the accuracy and interpretation of the CCFP forecasts and they may be skeptical that advertised delay mitigation

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[7] MaxWx for 8 of the 9 FCAA05 line storm events in 2007 occurred within ZNY airspace.

[8] Similarly, it is unclear from R(MaxWx) statistics by storm organization type if AFP rates used during unorganized, commonly less-severe, weather events may have been too low, perhaps resulting in an under-delivery of traffic across the AFP boundary and/or requiring too many flights to route out of the AFP region.

expectations of proposed AFPs can be achieved or that they are in the best interest of their individual business models. Instead, the NTMO said that the customers may believe that if severe capacity restrictions do materialize, the reactive TMIs (Ground Stops, Ground Delay Programs, expanded Miles-in-Trail (MIT) restrictions, Playbook reroutes, etc.) may serve to alleviate demand/capacity imbalances just as effectively as an AFP. Hence, by waiting and reacting to the convective weather, customers still hold their "free pass" should the forecasts be incorrect and the significant weather disruption never develops.

The NTMO said that in order for an agreement to be reached among all collaborating FAA and industry parties on implementing an AFP, ATCSCC almost always starts the AFP with higher rates early in the program and then reduces the rates further with subsequent AFP updates. Unfortunately, this may result in traffic over-deliveries before the AFP rates can be further reduced and once this occurs, it is often difficult to correct this demand/capacity imbalance without implementing additional restrictions and programs such as "GDP in support of SWAP" (the very program that AFPs were designed to replace).

A "hidden" impact of over delivering arrival demand into AFP05 airspace is that departures from the Northeast may be impacted adversely. During the 2007 RAPT operational evaluation, it was observed that the arrival demand into the Northeast exceeded the tactical arrival capacity, in turn leading ATC to use the NY departure airspace to handle arrivals (Robinson et al. 2008). In fact, NY/PHL departure airspace was closed at times to accommodate deviating arrivals during *50% of the convective weather impact days* observed in 2007.

More realistic (and restrictive) AFP rates might be more easily negotiated (and implemented) during AFP planning discussions if all collaborators were provided with an objective, explicit model-based forecast of the anticipated capacity losses caused by convection in the AFP airspace region. Improving the operational accuracy of initial AFP rates may lessen the need for cascading NAS initiatives that were frequently used later in the AFP usage period (see Section 2-4).

The mean FCAA05 I-time and S-time rates for the first three hours of the AFP program were also analyzed to see how they vary as a function of the actual convective weather characteristics (Figure 9). The results show that I-time and S-time AFP rates were set 1-5% lower when convective weather initially developed in the eastern AFP airspace (ZOB/ZNY boundary eastward into ZNY). Also, AFP rates were set significantly lower (~5-15%) when the FCAA05 weather event was (a) organized (vs. weaker, unorganized convection) and (b) accompanied by a high-confidence CCFP forecast east of the FCAA05 boundary at the time of AFP issuance. As with the R(MaxWx) statistical comparison for separate weather organization types (see Figure 8), these results again suggest that AFP rate decision makers are implicitly cognizant of the capacity impacts and air traffic throughput variability given expectations for weather severity, forecast certainty, and region of impact. However, the differences in AFP I-time and S-time set rates for varying weather, and the often negligible hour-to-hour rate adjustments – particularly during the first three hours of the AFP, when weather first develops and often strengthens to MaxWx – suggests that improved tactical estimates of explicit weather-capacity constraints and the subsequent recognition of opportunities to modify AFP rates might increase the AFP operational effectiveness.

2.4 Use of Ground Stop / Ground Delay Programs with FCAA05 Events

The goals of an AFP are to:

- Reduce en route air traffic demand where capacity is limited due to en route weather constraints;
- Distribute delays caused by en route weather impacts more equitably to all users of the constrained airspace.

In essence, AFPs were designed to replace "GDP in Support of SWAP" procedures, where en route demand was reduced at a few select airports in order to manage en route airspace capacity losses well-removed from these terminals. In 2007 however, FCAA05 and GDP and GS programs were often used simultaneously to reduce traffic demand on weather-impacted en route airspace.

In this analysis, a GDP or GS was considered a TMI to combat only *en route* convection if (a) no storms were present within the airport TRACON when the program was implemented and (b) no ATC issues pertaining to limited ceiling/visibility or strong terminal winds existed. In the subsequent discussion, we refer to these GDPs and GSs as "en route" GDPs or GSs. The scope of these en route programs was typically all arrivals into the pertinent airport.

In 2007, an en route GS or GDP for metro-NY (i.e., EWR, LGA, JFK) or PHL arriving traffic was implemented on **15 of 20 FCAA05 days (75%)**.[9] The pertinent weather and AFP traits for the five FCAA05 events where NY/PHL en route GS's or GDP's were not used were as follows:

- 09 May 2007: Western ZOB weather; MaxWx occurred before AFP S-time
- 11 Jun 2007: Unorganized weather of limited spatial coverage; AFP lasted < 3 hrs
- 18 Jul 2007: Limited weather coverage; NY terminal weather event
- 07 Sep 2007: Western ZOB unorganized weather; AFP lasted < 2.5 hrs
- 26 Sep 2007: ZOB weather; limited weather coverage; AFP lasted < 3 hrs

In short, en route GS's or GDP's were not used on those events where the weather coverage was limited, thunderstorms were unorganized, and/or the weather impact occurred in western-AFP airspace. In fact, given that AFPs were implemented for less than three hours on three of the FCAA05 days with these weather characteristics suggest that an AFP may not have even been needed on those days ("under-delivery").

The pervasive use of en route GS's and GDP's during FCAA05 events may have been a factor in the early termination (on average) of AFP events in 2007 (see Table 1). When an aircraft is subject to both an AFP and a GDP or GS, the GDP or GS takes priority.[10] In these situations where many aircraft passing through the AFP are being controlled by GS's and GDP's, the operational utility of the AFPs was probably reduced so much that the AFP was cancelled early.

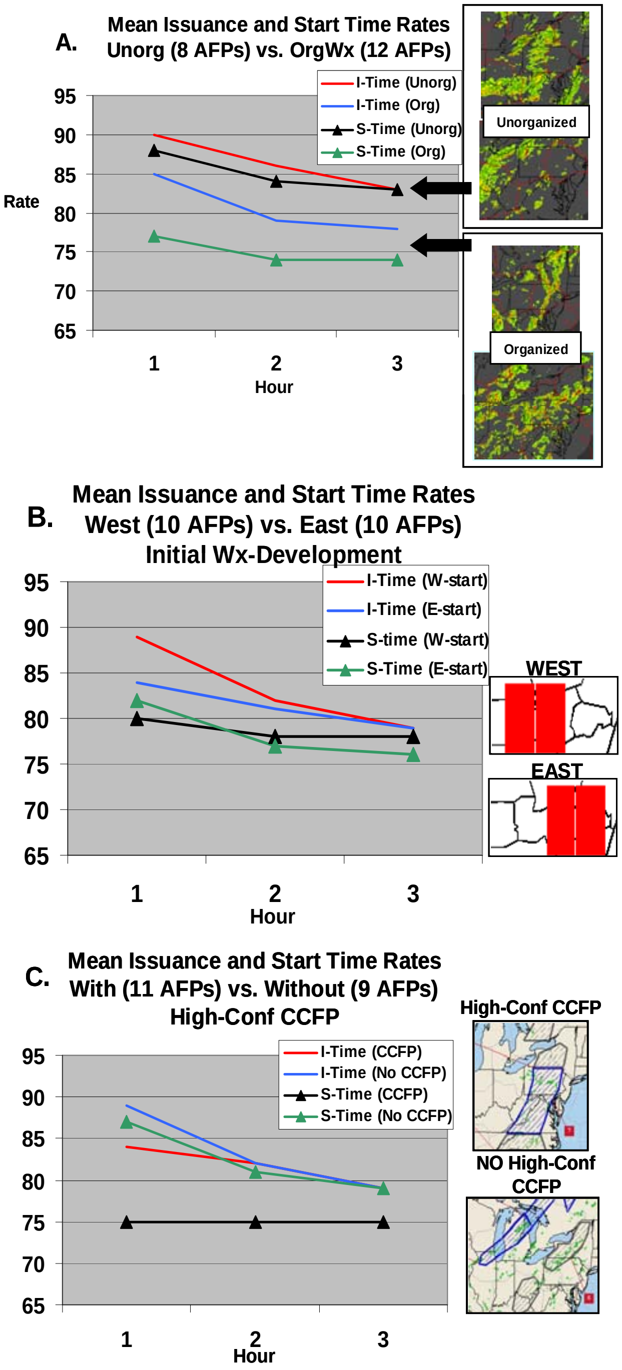

Figure 9. Mean AFP I-time and S-time rates for first three hours of FCAA05 programs, partitioned by (A) weather organization type, (B) location where AFP weather initially develops, and (C) the presence of a high-confidence CCFP forecast within the AFP region at the time of AFP issuance.

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[9] En Route GS's or GDP's were also implemented for IAD, DCA, BWI, and BOS airports during several FCAA05 events.

[10] The AFP Operational Concept (issued by the FAA System Operations Service, Version 1, October 2005, by Mark Libby, James Buckner, and Michael Brennan) states: If conditions at an airport require that a GDP be applied, the control times assigned by the GDP will take precedent over any AFPs with which the flights may be involved. This may disrupt the flow in an AFP and traffic managers should inspect all AFPs after a GDP action to see if an adjustment to the AFP is required. Any AFPs imposed while a GDP is in effect will treat GDP-controlled flights as exempt, and not change their delay status.

NTMO's interviewed at ATCSCC suspect that the increased load factors on commercial aircraft during summer 2007 made airlines much more reluctant to cancel flights which in turn kept en route traffic demands unexpectedly high (compared to historical expectations of cancellations and subsequent demand adjustments during similar en route weather impact events). They added that this persisting demand for weather-reduced capacity increased the need for additional demand reductions through the use of GS's and GDP's. However, the NTMO's admitted that AFP rates being set higher at the start of the program than was actually perceived as achievable (to ensure AFP buy-in among all planning collaborators – see previous Section) likely resulted in traffic over-delivery situations from which it was difficult to recover; thus requiring additional demand reductions by way of metro-NY and PHL GS's and GDP's – the very programs that AFP's were designed to replace for en route convective weather concerns.

It is not clear why NY and PHL GDPs were used as opposed to aggressive modifications to AFP parameters. One possible explanation is that the convective weather impacted arrival airspace used only by select airports. If that was the case, we do not understand why the scope of almost all en route GDPs on AFP days in 2007 included the majority of U.S. airports, despite our observation that there were some airports with opportunities to depart traffic to GDP airports on routes unimpeded by convective weather.

The need for additional en route traffic management programs on most AFP weather days, even when FCAA05 rates were further reduced through program revisions (see Section 2.5), also suggests that either convective weather forecasts were insufficient or incorrect or the true impact of en route weather on airspace capacity was not fully anticipated or understood.

2.5 FCAA05 Rate Revisions

AFP rates were revised after implementation during 8 of 20 FCAA05 events in 2007 (40%). Of these 8 revised events, AFP rates were reduced six times. We suspect that rates would have been reduced for even more FCAA05 events had demand not already been reduced by en route GS's or GDP's employed during 70% of the AFP days in this study.

On each of the six FCAA05 days where the AFP rate was lowered after the AFP start time, the MaxWx was organized and located within ZNY airspace (i.e., the most severe en route weather impact possible within FCAA05 airspace – see Section 2.2).[11] Even with the reduced AFP throughput rates, en route GDP and GS programs were implemented at metro-NY airports to further reduce traffic demand. This suggests that (a) AFP reduced-rate revisions were perhaps implemented too late, (b) the rate reduction was still not sufficient given the significant loss of capacity due to weather, or (c) there may have been other factors which were being considered.

There were only three FCAA05 events, with organized MaxWx located in ZNY, where AFP rates were not revised lower:

1. 16 May 2007: FCAA05 rate set to 65 at S-time; convection weakened and the AFP rate was increased two hours after S-time.
2. 28 Jun 2007: FCAA05 rate set to 75 at S-time
3. 09 Oct 2007: FCAA05 rate set to 75 at S-time

High-confidence four to six hour CCFP forecasts accurately predicted (at the time the AFP was issued) the location of the AFP weather impact on four of six of the FCAA05 events where MaxWx was organized within ZNY and for which the AFP throughput rates were subsequently reduced. However, all four of the "verifying" high-confidence strategic forecasts predicted only sparse convective weather coverage. Given the high variability in the actual weather that occurs when the CCFP predicts "sparse coverage" (Kay et al. 2006), it is unclear how one would set an AFP with confidence based on these forecasts.

3. TESTS OF AN INITIAL TACTICAL AFP THROUGHPUT FORECASTING MODEL

The analysis of FCAA05 AFP usage in 2007 showed that tactical changes to AFP hourly throughput were required on many occasions and/or GS's and GDP's were put into effect to further adjust the en route demand. Hence, the results suggest a need for a tactical AFP throughput forecast model.

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[11] In fact, five of the six weather impact events located within ZNY on days in 2007 when FCAA05 rates were revised lower were strong squall lines. The sixth weather event was organized as numerous, strong convective cell clusters covering large areas of the Northeast.

In this section, we describe an initial model to forecast AFP rates from CIWS forecasts and analyze the model's ability to correctly predict the potentially achievable FCAA05 and FCAA08 AFP throughput during three weather event case studies, given the actual, three-dimensional (3-D) convective weather characteristics.[12]

3.1 Description of AFP Throughput Model Components and Methodology

3.1.1 Assessing Convective Weather Impacts on AFP Arrival Rates

Weather impacts used in the estimation of AFP rates are based on the application of a route blockage model to the AFP arrival routes (inbound to Boston, New York and Washington DC airports). Route blockage is defined as a number between 0 and 1 which represents the likelihood that a pilot will traverse convective weather encountered along the route. The rate of traffic throughput achievable (Traffic Normalized Fractional Route Availability, or TNFRA) on a given route at a particular time is estimated as

$$\mathrm{TNFRA}(t) = (1 - \mathrm{RB}(t)) * \mathrm{FWT}(t),$$

where RB = route blockage and FWT is the average fair weather traffic along the route (Martin, 2007). The fair weather traffic used in this study was the average of traffic counts from ETMS data from three storm-free days. The route blockage algorithm will be summarized briefly and then its application to the estimation of AFP arrival rates will be described in greater detail.

Route blockage is a function of the route width, route 'segment length' and the weather avoidance field (WAF), which gives the probability at each pixel that a pilot will deviate around the pixel due to convective weather encountered there. WAFs can be calculated for any flight altitude from vertically integrated liquid water (VIL) and echo tops, using a statistical convective weather avoidance model (CWAM) (DeLaura et al. 2008). Figure 10 illustrates the WAF calculation. Route widths are defined for AFP arrival routes that are representative of the bounds of observed weather-avoiding maneuvers and that ensure minimal overlap between adjacent, roughly parallel airways (40 km, centered on the airway). The route 'segment length' is the distance in the direction of travel over which an aircraft may be expected to make a maneuver to avoid convective weather. The segment length used in this study is 55 km, approximately 4 minutes flight time at 500 knots.

Figure 11 illustrates the blockage algorithm. The 'traversable paths' – those that pass through the minimum WAF in traversing the route segment - are found for each route segment of the route. At each boundary between adjacent segments, the 'traversable width' – the intersection of the cross-sections of the traversable paths of each route segment – is calculated. The 'choke point' – the location of the minimum traversable width along a traversable path that runs the full length of the route – is determined for each traversable path. The preferred traversable path is the one with the widest choke point.

Once the choke point is found, the route blockage is calculated as the inverse-distance-weighted average of all WAF pixels in the two route segments on either side of the choke point whose WAF value is greater than or equal to the maximum WAF value encountered in the traversable path. Since the WAFs are probabilities with values between 0 and 1, the route blockage will also be a number between 0 and 1. The route blockage has two desirable properties. It requires no *a priori* definitions of blockage thresholds (e.g., "maximum penetrable WAF probability", or "minimum passable width") and the blockage value gives some estimate of the severity of the weather that a flight may encounter in following the route, since blockage is guaranteed to be >= the maximum WAF value that the flight must penetrate in order to stay on the route.

3.1.2 Assessing Weather Impacts on Traffic Throughput in AFP Airspace

Weather impacts on an AFP of interest are not confined to weather events intersecting or near the AFP line. In fact, AFPs may be issued to manage en route weather impacts well-displaced from the actual flow constrained area (FCA) segment defining the AFP entry point (see Section 2; Figure 6). In order to account for upstream and downstream weather impacts on the AFP crossing rate at any given time, route blockages are calculated for four different time offsets along the arrival route: ten minutes prior to AFP crossing, at the time of AFP crossing and ten and twenty minutes after the AFP crossing. Each of these time offsets corresponds to a different portion of

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[12] In a follow-on study, we will consider the accuracy of the throughput forecasts using actual CIWS forecasts.

the arrival route (Figure 12). The maximum of the four route blockages is used in the estimation of the AFP crossing rate for that route at the given time. For the purposes of this study, the actual weather (not the forecast weather) was used in the route blockage calculation. The estimated throughput for each route at a given time is the TNFRA value calculated from the route blockage and the fair weather traffic on the route at the time. The AFP rate at that time is simply the sum of the throughputs for each AFP crossing route.

For example, in order to estimate the throughput on J546 crossing FCAA05 between 1155 UTC and 1205 UTC, it is necessary to calculate the route blockage on route J546 in region A (see Figure 12) at 1150 UTC, in region B at 1200 UTC, in region C at 1210 UTC and in region D at 1220 UTC. The blockage for J546 at 1200 UTC is assigned the maximum of these four blockages. The estimated traffic throughput is the product of the blockage and the fair weather average number of aircraft crossing AFP005 between 1155 UTC and 1205 UTC.

Finally, the boundary of FCAA05 has been modified for this analysis to run due north through the middle of ZOB rather than to the west and north along the ZOB boundary. This was done to make the AFP flow rate estimations more consistent with the location of weather impacts in Eastern Ohio and Pennsylvania that typically motivate AFP initiation. The modified boundary allows for a more flexible approach to tactical AFP flow rate adjustments; for example, flow rates across FCAA05 could be increased by releasing departures from airports within ZOB. The operational validity of the modified FCAA05 boundary was confirmed in discussions with air traffic managers from ZOB.

3.2 Model Results

Estimates of the impact of the actual convective weather on AFP throughput have been calculated for three convective weather events that occurred 01 June 2006, 27 July 2006, and on an AFP implementation day occurring 27 June 2007. These events had widespread impacts on the NAS and affected major flows across both the FCAA05 and FCAA08 lines.

Figure 13 depicts color maps of route availability (1 – route blockage) for the FCAA05 and FCAA08 AFP during an example time of peak storm impact on air traffic (1900 UTC, 27 June 2007). These route availability estimates indicate significant reductions across both FCAA05 and FCAA08 domains. The TNFRA model was used to estimate a moving 15-minute average traffic throughput across each AFP boundary at each minute of the 24 hours spanning each event. The TNFRA estimates are compared to the fair weather traffic average and the observed traffic throughput for each event (time series plots in Figures 14 and 15). The figures also show throughput estimate error histograms (estimated throughput – observed) for each route. Two sets of histograms are shown: one for all weather impacts (RA<1) and one for severe weather impacts (RA<0.5). The histograms suggest that the modeled impacts and estimated throughputs are in generally good agreement with observed data; the median error is 0 and well over half of the estimates are within +/- two aircraft.

Figures 14 and 15 also illustrate an alternative form of TNFRA (MAX_TNFRA), where the achievable traffic throughput is estimated by multiplying the route availability on each route by the maximum fair weather traffic on the route rather than by the fair weather traffic at the time of blockage. MAX_TNFRA may be viewed as an upper bound on AFP throughput.

When model estimates of throughput are less than the observed traffic:

1. weather impacts or route blockages are overestimated by the model,
2. AFP-delivered traffic demand exceeds the fair-weather demand used by TNFRA, or
3. some combination of the two occurs.

When model estimates of throughput are greater than the observed traffic:

1. weather impacts or route blockages are underestimated,
2. weather or volume impacts outside the analysis domain are reducing traffic demand,
3. under-utilized capacity exists within the domain, or
4. some combination of the three has occurred.

Examination of the FCAA05 and FCAA08 time series indicate that the TNFRA model for estimating impacts on AFP throughput (red) compares well to the observed trend in actual AFP throughput (green). Only in the 27 June 2007 case involving FCAA08 do we see a prolonged interval (1700 – 0400) of the TNFRA model overestimating the weather impact on throughput across the AFP.

In that case, actual traffic compares better with MAX_TNFRA which, as noted, is a measure of maximum achievable throughput. It is postulated that, in this case, the prolonged increase in actual throughput is the result of more traffic being directed south of weather impacts affecting FCAA05, consequently increasing the traffic directed through the FCAA08 domain. An inspection of the coverage, location, and severity of convection during the 27 June 2007 event shows that, given the dearth of available airspace in the A05 region, nominal FCAA05 traffic would have had to route through FCAA08 airspace, increasing observed A08 traffic throughput during this event.

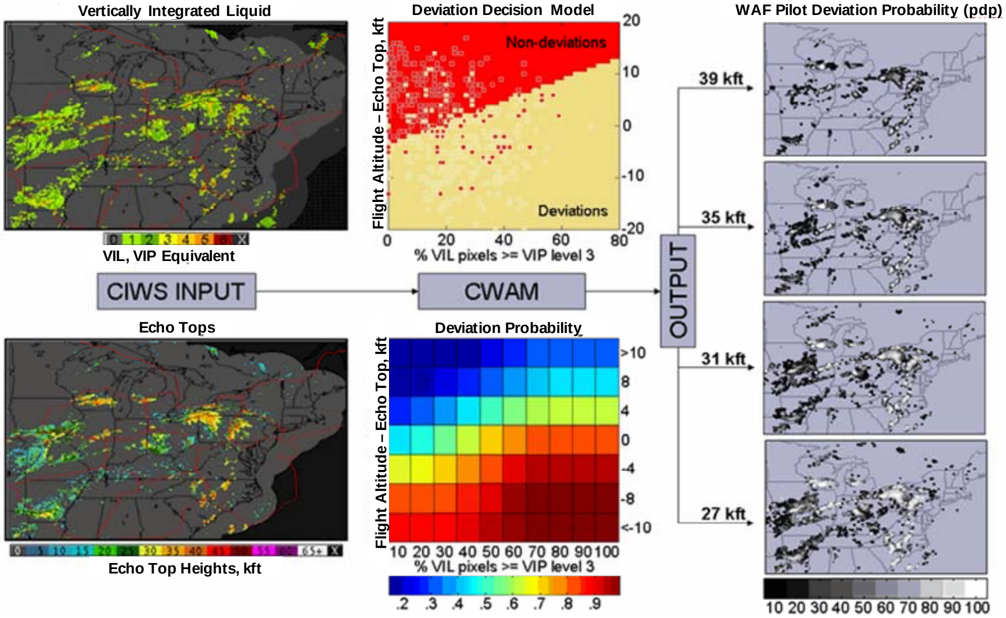


Figure 10. Illustration of weather avoidance field (WAF) calculation, using the convective weather avoidance model (CWAM).

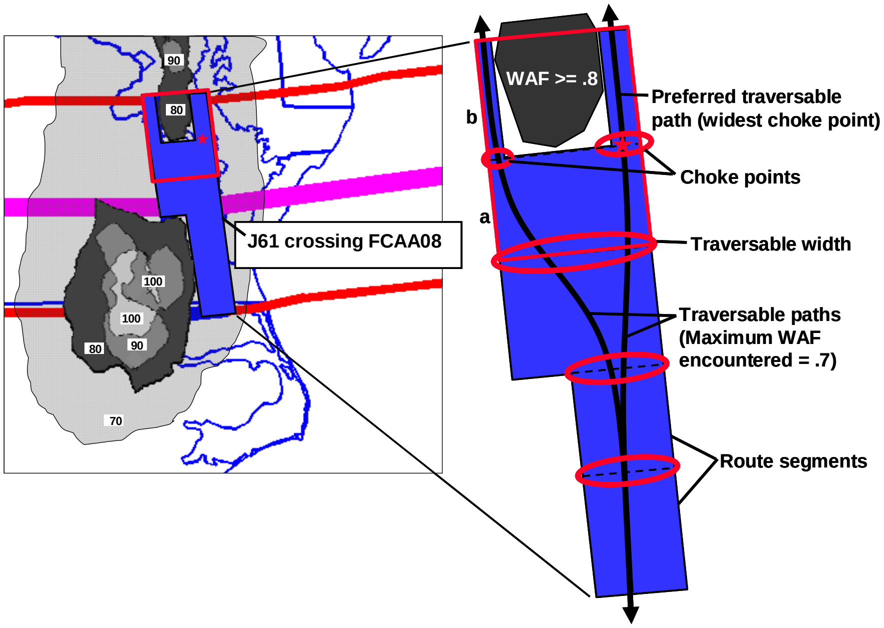


Figure 11. Illustration of the route blockage algorithm. The route blockage is calculated as the inverse-distance-weighted average of all WAF pixels >= 0.7 (the WAF value that the traversable path must

penetrate to traverse the route) in route segments a and b; the blockage is guaranteed >= 0.7. WAF values from 70% to 100% probability of pilot deviations are shown in regions shaded in gray. The airspace boundary for AFP FCAA08 is shown by the thick magenta line. The red lines mark approximately 10 minutes of total en route flight time on J61 as it crosses the AFP boundary.

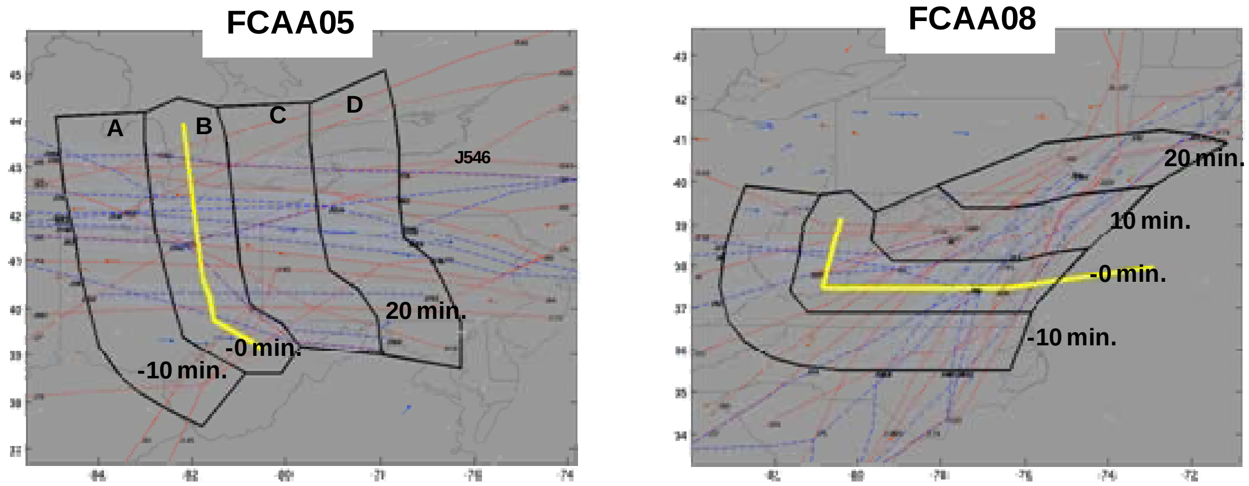


Figure 12. Illustration of FCAA05 and FCAA08 boundaries, showing the time-offset regions for estimating impacts of weather upstream and downstream of the boundaries (see explanation in section 3.1.2). Labels A, B, C, D and J546 are referenced in the illustrative example in the text.

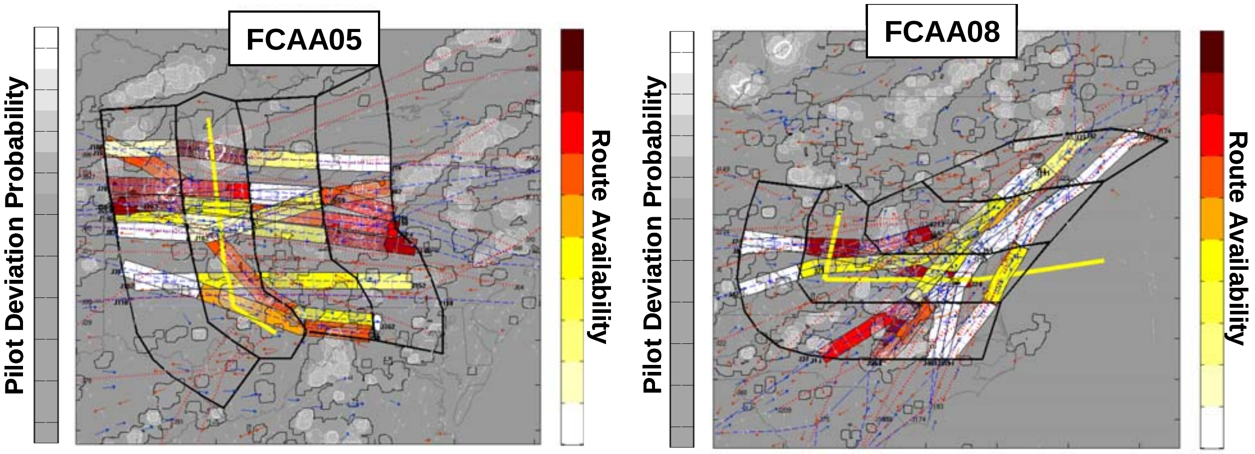


Figure 13. FCAA05 and FCAA08 AFP route availability at 1900 UTC on 27 June 2007. Low impacted routes are colored in white, deepening from yellow to shades of red for highly impacted routes. A muted grayscale overlay of WAFs for flight altitude of 35 kft (low WAF pilot deviation probabilities in gray, high deviation probabilities in white) and the 100% WAF contour (thick solid white contour) are also shown.

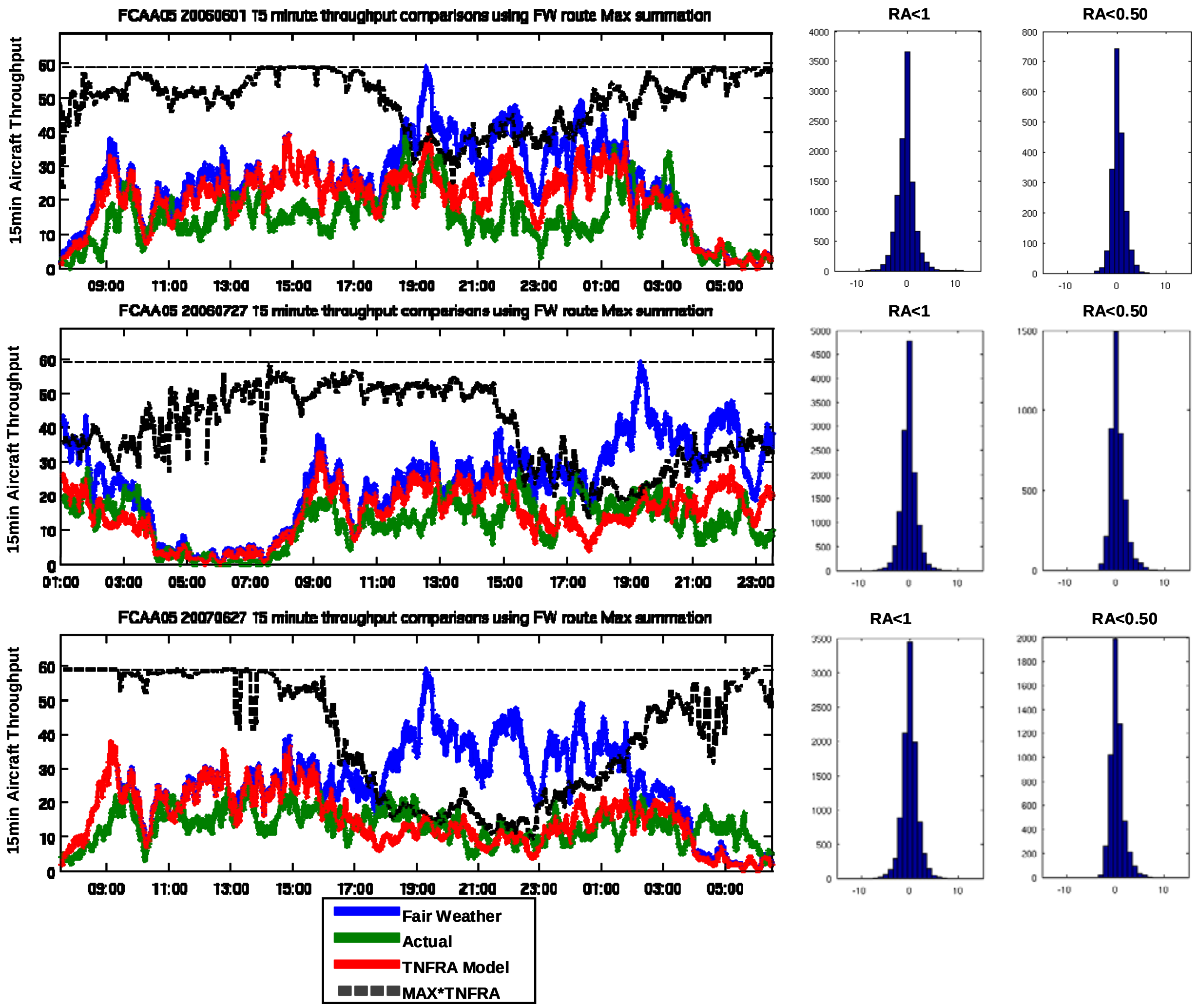


Figure 14. AFP throughput estimates compared to the actual 15 minute throughput across FCAA05 for the three high impact weather events: 01 June 2006, 27 July 2006, and 27 June 2007. The green line represents the actual 15 minute AFP filtered throughput that occurred on each of the three weather impacted days. The blue line represents the AFP filtered fair weather throughput estimate derived by summing the 15 minute route maximum of the three fair weather days centered at each one minute time step. The red line in the time series represents the TNFRA reduction of the fair weather estimate and is the model for assessing weather impact. The thick black dotted line is the TNFRA reduction relative to the single value maximum observed fair weather throughput (thin dashed line) and is meant to represent a measure of potential achievable capacity given weather impacts in the AFP domain. The histogram bin amplitudes represent the number of times the difference between a route's actual throughput and the route availability estimate is observed. The positive side of the histogram indicates that the route availability overestimated the weather impact on a route's throughput at any given time; the negative side of the histogram indicates the underestimate. The first column of histograms (left side) shows the occurrence distribution of these differences over all instances where route availability indicates weather impact (RA<1.0). The second column of histograms (far right) compares the differences of a smaller set of instances with greater weather impact (RA<0.50).

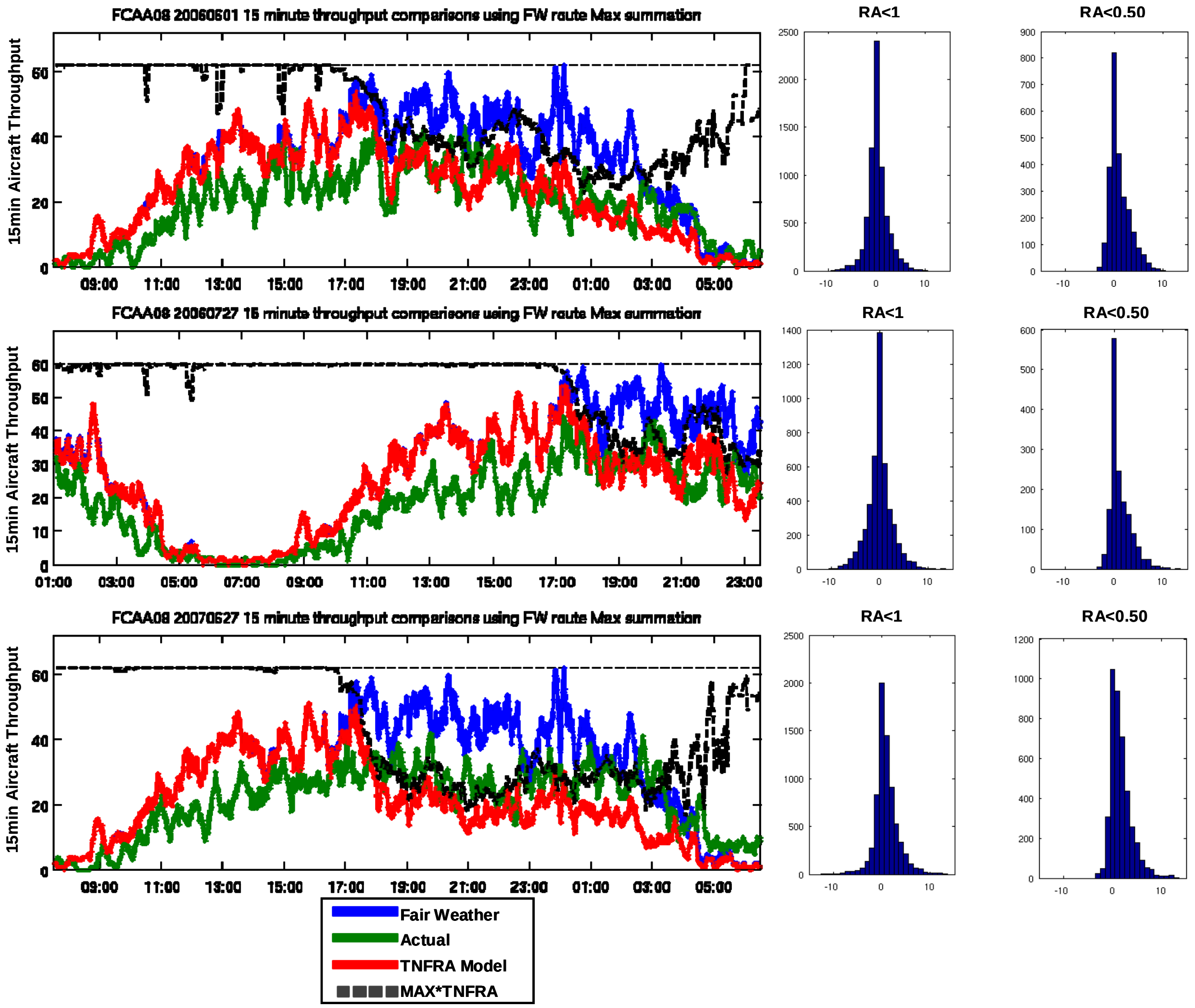


Figure 15. As in Figure 14, except for FCAA08.

3.3 Example Application of AFP Throughput Model Using Actual Weather

Given the unbiased nature of the route availability algorithm when using actual weather (see histogram results in previous Section), it may be possible to use the model throughput estimates to search for underutilized route capacity within an AFP domain. Figure 16 shows the specific eastbound arrival flows (through the FCAA05 AFP region) associated with major airports in Boston, New York, Philadelphia, and the D.C. area. The model-estimate and actual throughput comparisons for these major flow regimes across FCAA05 during the 27 June 2007 high impact event are each calculated individually. It appears that underutilized capacity existed in the system later in the time series (from roughly 2300 UTC onward) for the NY and DC flows. This occurs when actual throughput (green) falls below the TNFRA throughput estimates (red).

If these regions of underutilized capacity could be accurately predicted using CIWS during operational AFP events, it may be possible to systematically increase capacity usage (and decrease delay) by identifying specific airport flows that can tolerate additional short-term releases (e.g., ground stop releases from near-destination airports) or revised EDCTs for AFP (or even GDP) flights.

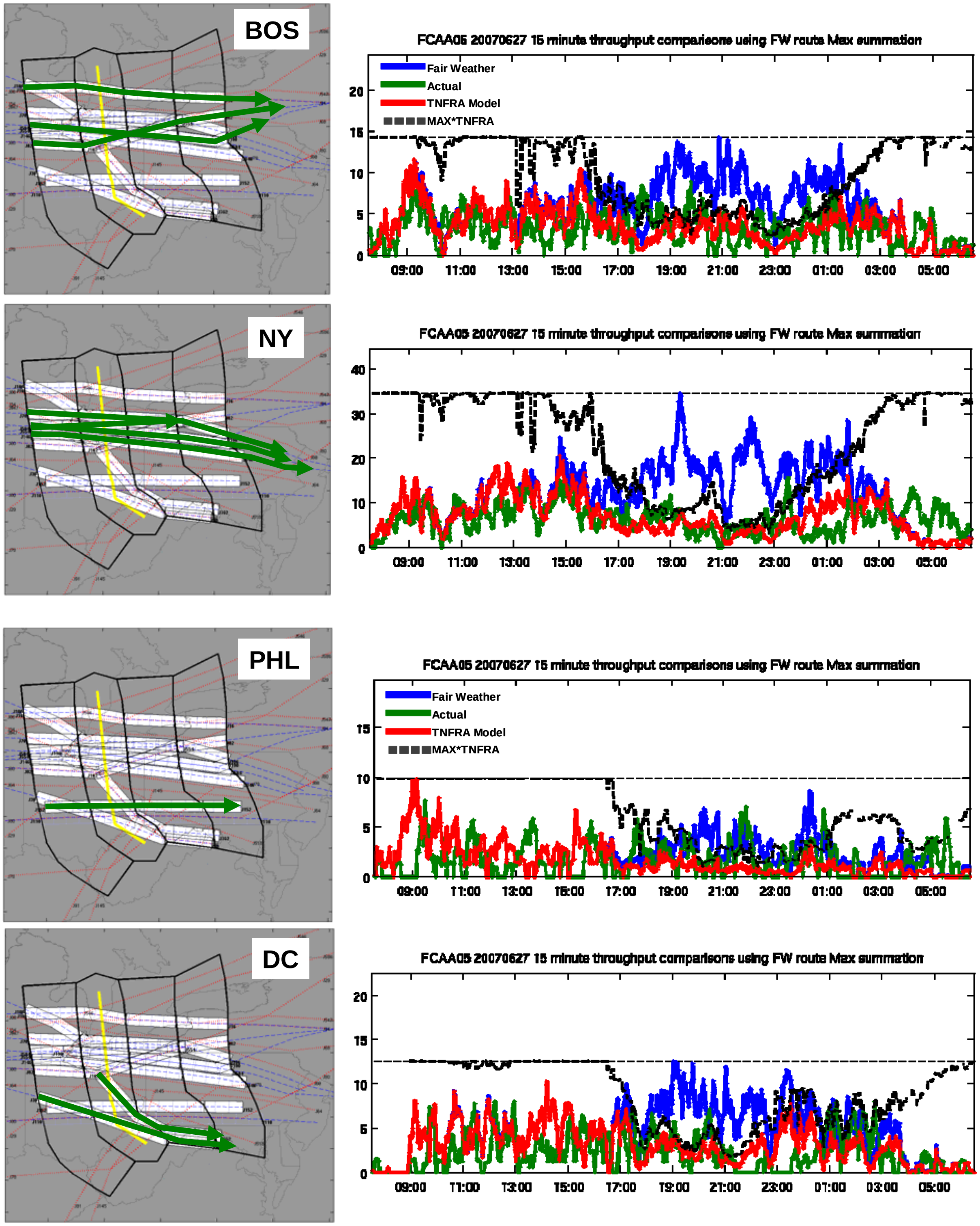


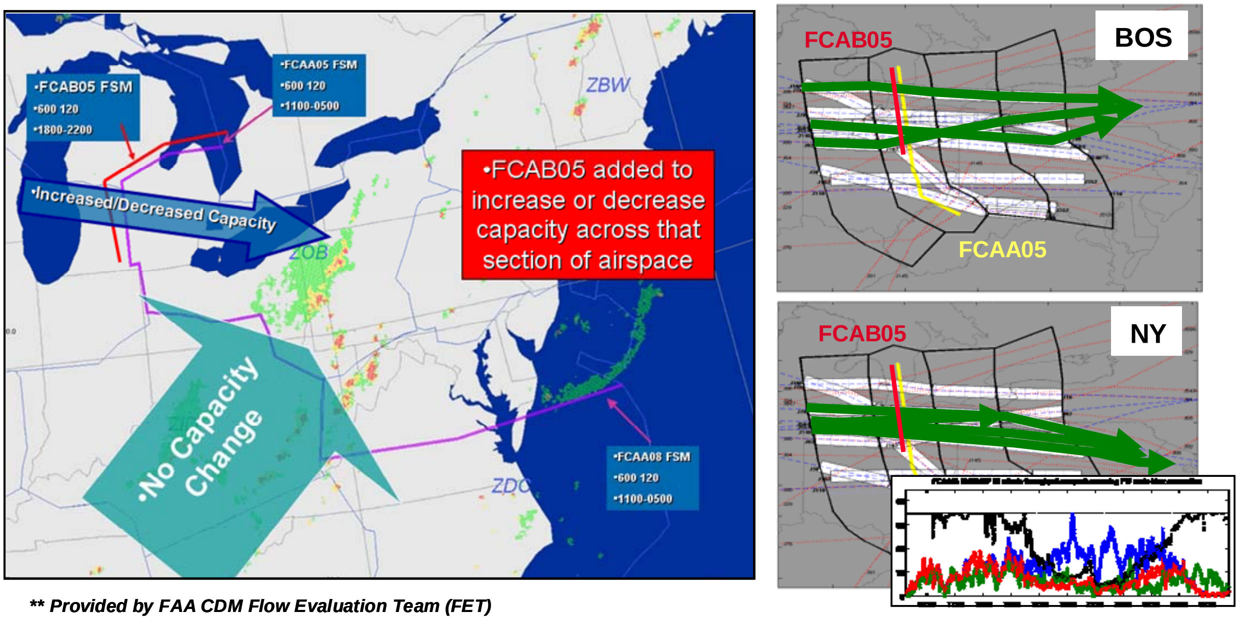
Figure 16. Tactical FCAA05 AFP throughput assessment, with route availability and usage (estimated vs. actual) deconstructed for individual traffic flows to Boston, metro-NY (EWR, LGA, and JFK), Philadelphia, and metro-DC (IAD, DCA, and BWI) airports. Throughput time series results (right-side) are presented as in Figure 14.

Similarly, there are several instances after the start of the actual AFP (1730 UTC) where model vs. actual flow comparisons suggest that the actual traffic throughput (green) exceeded the maximum achievable eastbound capacity (black) and the model-estimated throughput capacity (red). These instances may be examples where traffic was over-delivered, perhaps because the AFP rate was set too high or the FCAA05 program began to late.

If these situations could have been accurately forecasted 0-2 hours in advance using CIWS forecasts, the various ARTCCs and the ATCSCC might have implemented TMI's that were more specific in terms of the included airports, the program scope and rate, and the duration. For example, further deconstructing the metro-NY AFP throughput estimates to examine EWR, LGA, and JFK flows individually may more explicitly demonstrate that a GDP or GS at just one of these airports – whose flow will be most heavily impacted by en route weather, as estimated by the AFP throughput model – might have been sufficient to manage the demand/capacity imbalances.

Flow-specific throughput forecasts from the Tactical AFP model may also improve the planning, implementation scheme, and efficiency of partial or "override" AFP initiatives proposed by the CDM community. The concept of the override AFP is to replace a segment of the implemented AFP with a new, partial AFP as capacity impacts in specific portions of the original restricted airspace region are expected to improve or worsen. The benefit of a partial, override AFP is that "surgical" adjustments can be made to evolving capacity impacts within the larger AFP control region. However, as with the predefined AFPs, override AFPs would still require high-quality weather forecasts to be translated into statements of airspace availability. With the support of *flow-specific* airspace throughput forecasts, override AFPs may likely be implemented with greater flexibility and efficiency (Figure 17).

FCABO5 AFP "Override" Concept



*** Provided by FAA CDM Flow Evaluation Team (FET)*

Figure 17. AFP "override" concept for FCAA05 (left), where a new, partial AFP (FCAB05) is implemented, with independent throughput rates and EDCT assignments, to address expected capacity changes within a subregion of the original AFP airspace. Flow-specific throughput forecasts from the tactical AFP model(right) may prove useful in refining partial AFP parameters and increasing airspace usage efficiency.

4. SUMMARY

This report described the results of an exploratory effort to:

a) Achieve an initial understanding of the AFP parameter decision making process by studying the usage of FCAA05 during the 2007 storm season and
b) Develop a model to objectively predict the achievable AFP throughput from CIWS-measured precipitation and echo tops as the convective weather impact varies in time and space during a storm impact event.

Results from this preliminary analysis of FCAA05 usage in 2007 highlighted a number of situations where the operational effectiveness of an AFP could have been improved through the use of objective tactical AFP throughput forecasts. We adapted the RAPT route-blockage model to en route flow structures in order to objectively estimate achievable flow rates through the boundaries established for AFP FCAA05 and FCAA08 (the most frequently used AFPs in 2007). The concept of use would be to tactically reduce demand in situations where the established AFP rate exceeds the achievable throughput so as to avoid congestion on arrival paths into east coast airports, thereby adversely impacting departure operations. During the converse situation where the achievable throughput rate is greater than the established AFP rate, demand could be increased (for example, by lifting departure restrictions on eastbound traffic from airports near the AFP boundary) to take advantage of the available capacity.

Preliminary results from this modeling exercise, where traffic throughput estimates are made using actual weather, have been encouraging and they substantiate the premise that the operational effectiveness of AFP's can be improved through tactical use of AFP throughput forecasts. Additional effort is needed to refine and validate the weather-restricted flow-rate models, to assess the accuracy and operational applicability of model results when using CIWS forecasts (as opposed to actual precipitation and echo tops data), and to further assess concepts of integration into the Traffic Management process.

The Lincoln studies need to consider related work on tactical flow rate adjustments being conducted by the CDM Flow Evaluation Team (FET). A specific mechanism that could be utilized by 2009 is the use of "override AFPs" (wherein an AFP can overlap another AFP). For example, the FET has specifically suggested that one could modulate demand tactically on FEA/FCAs that are smaller than the current canned AFP boundaries. The FET has also suggested suspending Estimated Departure Clearance Times (EDCTs) for some specific airports if near-term demand could be increased higher than the suggested AFP rate. These FET initiatives suggest a need to provide flow-rate forecasts for portions of the existing high-use AFPs. An example of this - throughput forecasts for specific airport flows through the AFP region – was presented in this report.

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