QUANTIFYING CONVECTIVE DELAY REDUCTION BENEFITS FOR WEATHER/ATM SYSTEMS*

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Abstract

This paper investigates methods for quantifying convective weather delay reduction benefits for weather/ATM systems and recommends approaches for future assessments.

This topic is particularly important at this time because:

1. Convective weather delays continue to be a dominant factor in the overall National Airspace System (NAS) delays, and

2. Benefits quantification and NAS performance assessment have become very important in an era of significant government and airline budget constraints for civil aviation investments.

Quantifying convective weather delay benefits for ATM systems has proven to be quite difficult since the delays arise from complicated, highly variable, poorly understood interactions between convective weather and a very complex aviation system. In this paper, we consider key aspects of convective weather disruptions of the aviation system, how the weather severity can be characterized, and discuss practical experience with benefits quantification by a variety of approaches. The paper concludes with recommendations for a methodology to be used in future convective weather delay reduction quantification studies.

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Introduction

The main contribution of this paper is to discuss how convective delay benefits can be estimated for various ATM systems. This topic is very important given the significant growth in convective season delays in 2004 (figure 1). Strengths and weaknesses of user interviews/modeling and comparisons of measured delays for benefits assessment are discussed based on actual usage for a variety of systems and, user locations.

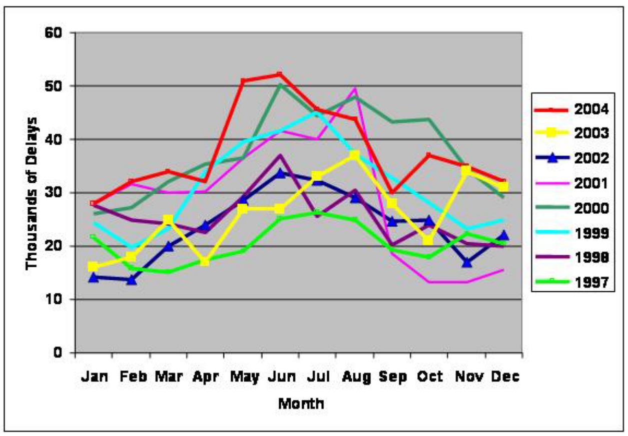

Figure 1. U.S. OPSNET delays by month. Note the dramatic increase in delays in the summer months characterized by convective weather. The delays for much of the summer of 2004 exceeded the delays for any of the seven previous years.

Many different ATM systems can contribute to reducing convective weather delays. Contemporary convective weather information systems (e.g., CCFP, ITWS, CIWS, WARP) provide (to varying degrees) information on the weather impacts. Traffic flow management and automation tools assist in developing and executing the convective weather mitigation plans. These include ETMS (CRCT, FEA/FCA), TFM-M, ERAM, URET, and CTAS TMA.

FAA and Office of Management and Budget (OMB) initiatives stress the importance of quantitative system performance metrics that are related to aviation weather. For example, the new FAA Air Traffic Organization (ATO) and the FAA Flight Plan 2004-08 both have quantitative performance metrics that are closely related to reducing convective weather delays. Additionally, the Office of Management and Budget (OMB) requires quantitative measures for system performance, an estimate of the baseline performance, the planned improvement to the baseline, and actual results including a discussion of the methodology for the results.

Ideally, one would like to quantify benefits by simple comparisons of delays before and after a system was installed. This is quite difficult. Convective weather events are in general not repeatable and change relatively rapidly with time. Additionally, they give rise to highly nonlinear queue driven delays in congested airspace. As a consequence, the delays that occur are very sensitive to changes in the demand.

We frame this benefits assessment problem as a classic physical systems problem:

I. what is the phenomenology we are concerned about?
II. how is it "observable" with our measurement tools?
III. what are the data processing approaches?
IV. how are we doing at achieving the desired analysis results?

The mechanisms by which convective weather delay can occur in the NAS, the magnitude of this delay, and how to account for variations in the amount and severity of convective weather are reviewed. Recent experience from ongoing analyses of delay reduction for both terminal and en route systems using user interviews, direct observations of ATM decision making in convective weather, and analysis of delay statistics are discussed. We conclude by recommending a multifaceted approach to quantifying convective weather benefits.

Background

There is a copious literature on aviation delays due to low ceilings and visibility that focuses on the queue delays that arise when the airport capacity is less than the demand. However, there is relatively little published work that addresses the interplay of convective weather characteristics with ATC operations.

Although the topic of quantitative convective weather benefits assessment has become very important recently, there also has been relatively little published work on how this can best be accomplished. Some summary results have been presented at past ATM workshops [8], but there has been very little discussion of key issues in accomplishing such analyses.

I. Phenomenology of the Delays

A. Delay Causality

Understanding of the mechanism by which convective weather delays arise is essential for determining appropriate measurements and the development of effective benefits quantification methodologies.

Convective weather impacts on the airport and on the airspace well away from the airport (especially the boundary between terminal and en route airspace) are a principal cause. Convective weather impacts on the airport (e.g., within 5 nmi of the airport) cause delays because they will often reduce the capacity of the runways. However, convective storms do not close all of the runways very often. A Lincoln Laboratory study of 20 convective weather event days at Orlando (MCO) and Dallas-Ft. Worth (DFW) airports found only one day where arrival and departure traffic stopped for 15 minutes or more when thunderstorms were over the runways or within 5 nmi of an airport. Storms were within 5 nmi of the airport for 886 minutes over 10 days at MCO and 992 minutes over 10 days at DFW. It was convective weather impacts on the ARTCC-terminal fixes and other regions away from the airport that caused most of the delay on the 20 days analyzed.

This surprising small fraction of time that the runways were closed may reflect pilot preferences on storm penetrations versus deviations when the aircraft are near the airport as discussed in Rhoda [9]. It should also be noted that delays due to thunderstorms within the terminal area often occur during VMC conditions at the runways [1]; thus IMC airport capacity is not a key cause of convective delays.

Principal delay generating mechanisms that arise from convective weather impacts to the NAS are (1) aircraft flying longer paths than desired so as to avoid convective weather and (2) the queue delays that arise when demand is greater than effective capacity in regions of airspace.

The "flying longer paths" delay is given by:

Delay ≈ (number of aircraft impacted) x (extra distance per aircraft) x (number of such events) **(1)**

Or

≈ (demand) x (time duration of an event) x (extra distance flown per aircraft per event) x (number of events per year)

Queue delays have a very different, nonlinear dependence on demand capacity, and the time duration of events[1]. In the simplest case, the fair-weather capacity (C_V) of airspace under the control of an Air Traffic Control (ATC) facility (e.g., an airport or an en route sector) is reduced by convective activity to a lower convective weather capacity (C_W) for a time duration, T. Typically, C_V is greater than the demand, D, but $D > C_W$. For this case of constant capacities and constant demand, the accumulated delay for all the aircraft involved in the queue can be shown to be:

$$\Sigma D_k = 0.5\, T^2 (D-C_W)(C_V-C_W)/(C_V - D) \qquad \textbf{(2)}$$

where D_k is the delay for the k^{th} plane in the queue. Here we see that there is a very nonlinear relationship between demand, fair weather capacity, convective weather capacity, and time duration.

Convective weather impacts on highly congested en route airspace lead to very complicated, multiple queues in the "NAS network". Since both terminal and en route impacts contribute to most of these convective weather impacts, the highly nonlinear nature of the resulting delay means that one cannot easily decompose the total delay into additive terminal and en route contributions.

The process for developing and executing mitigation plans to cope with NAS network problems is a major factor in the delays that occur. Since optimal weather impact mitigation requires multi-hour convective weather forecasts of an accuracy that is currently unachievable, the thunderstorm-related delays that occur arise from a very complicated combination of actual weather characteristics, errors in convective weather forecasts, the decision-making process, and the ability to execute mitigation plans in a timely manner.

Another very important factor in convective weather delays is the "downstream delay ripple effect". This arises when aircraft and/or flight crews are delayed on one leg of a flight (e.g., due to adverse weather), resulting in delays on the next leg (and subsequent legs) flown by that aircraft and/or crew on that day. The ensuing downstream delay is often comparable to or several times greater than the initial delay [2].

B. Magnitude and variability of convective weather delays

The magnitude and variability of annual convective weather delays is an important factor in delay benefits assessment since one needs to have a sense for the magnitude of the delay change that one might expect from use of an ATM system relative to the variability in convective delays that can occur year to year due to differences in the weather.

The magnitude of the annual convective weather delay is very difficult to estimate due to the complicated nature of convective weather delay causality and the occurrence of other weather delays (e.g., low ceiling/visibility, wet runways and/or adverse winds) at the same times that convective weather delays occur.

A first order estimate of the weather related arrival delay during the convective weather season can be obtained by comparing the average ASPM arrival delay relative to schedule for the various days in the convective weather season to the average arrival delay on a "fair weather day". It turns out to be very difficult to find such a day. For 2004, we found that 4 May was a minimal weather impact day

[1] The queue model we are discussing here is the classical deterministic model considered standard in traffic analysis [5]. With this model, one can operate quite close to capacity without incurring delays, which is quite different from the random process queue models (e.g., a Poisson process). With random process queues, delay rises rapidly as the demand approaches the capacity.

at the major US airports except ORD and MDW. By removing the contribution of ORD and MDW to the overall NAS delay on 4 May and adding back in the ORD and MDW arrival delays on 5 May 2004, we arrived at an average "fair weather" arrival delay of -3.3 minutes per flight (that is, the average flight arrives early). For the period May through August 2004, the average arrival delay relative to schedule was +8.4 minutes. One then multiplies the difference between these two average delays (11.7 minutes) by the estimated number of NAS air carrier flights to obtain an estimate of 784,000 hours of delay due to adverse weather in May-August 2004.

A similar analysis for 2003 obtained an estimate of 535,000 hours of delay due to adverse weather in May-August 2004. Thus, we see that year-to-year variability in convective weather season NAS delays can easily be in excess of 200,000 hours.

III. Measurement Tools for Assessing the Severity of Convective Weather

Given the high year to year variability in convective season weather characteristics and delays, it generally will be necessary to adjust delay statistics to account for the differences in convective weather severity. The data used to assess the frequency and severity of the convective weather is an important issue. The principal data sources used are station observations (METARs), cloud-to-ground (CG) lightning data, and weather radar data.

The use of METARs is very attractive since the data volume is relatively low and has been incorporated in delay databases such as ASPM. Unfortunately, METARs alone do not appear to be a highly reliable means of determining convective weather impacts. Lincoln Laboratory conducted a study of the relationship between the times METAR reported a thunderstorm at Atlanta and times during which convective weather in or near the terminal area was clearly impacting Atlanta operations (e.g., causing diversions, significant flight deviations around storms, holding patterns, and/or reduced departure rates)[2]. It was found that METARs greatly understate the duration of convective delay events: The day-to-day variation in the ratio of thunderstorm terminal area impact duration to METAR thunderstorm (TS) observation durations was 2.7 to 28.2 with a mean value of 10.

There were a number of days with Atlanta terminal traffic disruptions due to convective weather within the Atlanta terminal area where there was never a METAR thunderstorm observation.

These Atlanta results are consistent with earlier results from Bieringer et al., [3] who found that the number of days per year where there were convective weather disruptions in or near the terminal area was typically twice the number of days a year where there was a METAR report at any time during the day[3].

Use of cloud-to-ground (CG) lightning data is also appealing as a measure of convective weather severity since it clearly corresponds to thunder and, the associated database is relatively small. However, CG lightning appears in the mature and dissipating phases of a thunderstorm, whereas it is vigorously growing cells that are often the greatest concern. Additionally, CG lightning can appear in storms with low storm top heights, such that en route aircraft easily can fly over the storms.

Therefore, we recommend the use of weather radar data for identifying convective weather impacts even though the volume of data that must be considered is much greater than either METAR or CG lightning. An important factor here is that flight crews rely heavily on the airborne weather radar observations. Additionally, much of our current understanding about pilot preferences in flying in and near convective weather is based on weather radar data [11 and 12].

There are two complexities of weather radar data that must be considered. The reflectivity product used can be very important. Reflectivity measured on a single elevation scan of the radar (e.g., as is currently displayed on ETMS) and maximum composite reflectivity (used on WARP) are very susceptible to anomalous propagation contamination, ground clutter, and spurious high reflectivity returns from melting snow or ice particles.

Vertical integrated liquid (VIL) water is the preferred reflectivity product [14]. Unfortunately, not all VIL products are equivalent in data quality. In particular, it should be noted that the National Convective Weather Detection (NCWD) VIL product

[2] The determination of convective weather impacts was made by analysis of weather radar data overlaid with plane flight tracks plus ASPM delay statistics.

[3] We have extended Bieringer's results to look at the thunderstorm day climatology for ARTCCs compared to locations within the ARTCC: for the ARTCCs in the northeast, the ratio ranged from 2.2 to 3.0 with a median of 2.8

seriously underestimates the spatial extent of Level 3 reflectivity storms[4] owing to overly coarse quantization of the NEXRAD VIL product used to create the NCWD. The preferred precipitation product is high resolution VIL as used by the CIWS system and now being produced operationally by NEXRAD systems [15].

Another key issue for en route convective weather severity assessments is the altitude extent of the convective weather. Rhoda et al., [11] found that aircraft will generally fly over storms if the aircraft altitude is at least 5 kft above the storm echo tops. Here again, one must be careful about the accuracy and spatial resolution of the echo tops information. For our studies, we have exclusively used the CIWS echo tops product which takes advantage of much more accurate NEXRAD echo tops computations [15] than was the case in the past.

III. Approaches to Convective Delay Reduction Benefits Assessment

There are two basic approaches to determining the achieved delay reduction benefits:

1. "Direct" measurement: the delays in a baseline time period when a convective weather ATM decision support system was not in use are compared to delays in a subsequent time period during which the system was in use. This approach would be preferred <u>if</u> it could be readily accomplished and gave reasonable results. However, there are many key factors that will be different between the two time periods. Since the number of events that one is typically talking about for an ATC facility is relatively small, normalizing the results to account for all of these differences is very difficult.

2. "Decision/Modeling": interviews and/or direct observations of ATM decisions `are used to determine the parameters of ATC models that are then used to estimate the delay reduction benefits. The basic assumption is that the weather product or ATM tool is useful only to the extent that it changes user decisions. Thus, one can analyze the various decisions that the users indicated were improved as a result of having access to the ATM decision support system under study. The problems that arise here are possible influence of the interviewer on the responses, poor choice of interview questions, and user difficulty in estimating key parameters.

In the next section, we discuss several contemporary uses of the "decision/modeling" approach and describe the results of an initial effort at executing the "direct" approach.

IV. Results of Applying these Approaches

A. Decision/Modeling

1. Integrated Terminal Weather System (ITWS)

Detailed studies of delay reduction by an ITWS at five major terminal complexes (Atlanta, Dallas, Memphis, New York, and Orlando) have been conducted over the past decade. Users were typically interviewed at the end of the convective weather season to generate terminal specific benefits models.

Memphis (MEM) and Orlando (MCO) are terminals that have excess runway and terminal area capacity during times of major air carrier operations. Even though convective weather reduced the capacities, significant queues rarely arose. Thus, the benefits could be characterized by a linear model analogous to equation (1):

Delay savings = (operations per day) x (days with convective weather) x (times per day a beneficial decision occurs) x (average delay savings per aircraft) **(3)**

The values for the number of times per day a beneficial decision occurs and average delay savings per aircraft were generally consistent for the users at a given facility, and between the two facilities. This provided some confidence that the user estimates were realistic.

The New York terminal complex is quite different. The runways, terminal area, and surrounding en route airspace have very little excess capacity for many hours a day in fair weather. Hence, the capacity reductions that occur with convective weather quickly result in major queue delays. For example, increasing departure rates during a Severe Weather Avoidance Plan (SWAP) was determined to be the highest convective weather benefit of the ITWS prototype at New York. By

[4] VIL level 3 equivalent reflectivity is operationally quite significant since pilots will typically avoid storms with this reflectivity while penetrating storms with VIP level two reflectivity [11 and 12].

contrast, at MEM and MCO, the rerouting of arrival aircraft when there were storm impacts on the terminal arrival and departure fixes was a principal benefit.

The projected ITWS delay reduction benefits at NY based on the Memphis/Orlando/Dallas "linear" model was about 1/3 of what was being achieved at New York. This very major difference in the estimated benefits at New York emphasizes the need to carefully understand the detailed operations of the facilities under consideration in the benefits assessment when carrying out a quantitative benefits analysis.

We have carried out an analysis of the ITWS benefits at Atlanta using the approach used for New York. Atlanta has very little excess runway and terminal capacity at some peak periods, but there is generally excess capacity in the en route airspace and, there are many time periods with excess runway and terminal capacity. It was found that the Atlanta benefits models were a mixture of New York and Memphis/Orlando models. For example, the benefit of recognizing that an arrival fix would remain open needed to be modeled by a combination of a linear "lesser distance flown" model plus a reduction in queue delays at the alternative arrival fixes.

2. Corridor Integrated Weather System (CIWS)

The CIWS operational benefits studies [13] have broken new ground in the methodology for assessing convective weather delay reduction benefits. The CIWS benefits of greatest interest were associated with en route decision making in the most highly congested airspace in the NAS. To assess CIWS benefits, one must come to grips with the NAS as a network in its full complexity.

The 2003 data collection design (Figure 2) used Lincoln Laboratory observers at a number of ATC facilities during "benefits blitz" time periods when significant convective weather was expected. These intensive observation periods were treated as a sampling of the population of significant convective weather events at a given facility. Based on both the observations of users utilizing CIWS displays and user statements of ATC decisions made using the CIWS products, very detailed statistics were generated on the number of times per significant convective-weather day a given beneficial ATC decision was made using CIWS products. Given this information, straightforward computations (similar to those discussed above) could be used to estimate an annual frequency of those decisions, if one had statistics for the frequency of significant convective weather in a given facility. Once one derived an estimate of the average benefit per beneficial decision per ATC facility, one could then multiply it by the annual frequency of the decision to get the total benefit.

This approach was quite successful in generating detailed estimates of the delay reduction benefits for two key air traffic management decisions: "keeping routes open longer/reopening closed routes sooner" and "proactive reroutes of aircraft" by FAA facility. The approach also provided quantitative information on many other benefits whose delay savings estimates were not calculated [11].

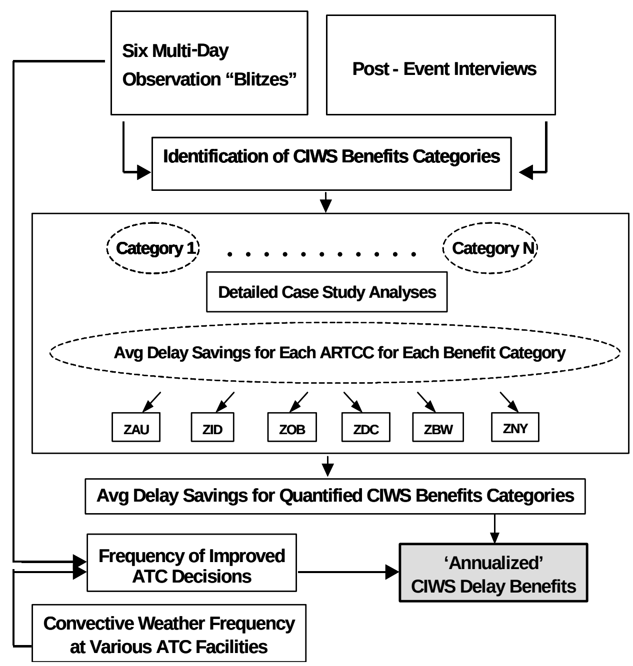

Figure 2. CIWS annual delay reduction benefits estimation.

It was found that 11 of the 15 randomly chosen specific instances of "keeping routes open longer" involved reduction of queue delays. This shows the pervasiveness of queues in the northeast quadrant of the US air system during convective weather.

Subsequent to the completion of the study reported in Robinson et al. [13], it has been necessary to generate estimates of the CIWS convective weather delay reduction benefits for the period 2004-2023 where a number of changes are projected to occur in demand and en route capacity (due to DRVSM). The approach shown in Figure 2 has proved very helpful for such studies since there were a number of concrete cases that could be reanalyzed to determine the impact of additional demand and/or capacity on delay reduction. Additionally, the case study results (e.g., the Lincoln assessment of the number of aircraft utilizing a route when it was reopened sooner) could be independently verified by other organizations.

Work is underway to verify that key operational decisions identified in the in-situ facility observations are in fact being improved with CIWS in operation. Flight tracks with weather radar data for convective events that are similar (e.g., in the 3-D structure of the convective weather and impacted regions) before and after CIWS implementation are being analyzed and the results will be reported in a subsequent paper.

B. Comparison of Delay Statistics Before and After a System is Deployed

1. Atlanta ITWS Study

An exploratory study of the feasibility of using the changes in ASPM delays to assess ITWS benefits was conducted at Atlanta The changes in delays at Atlanta might impacted by many factors including (a) weather differences (both convective and non convective) inside and outside the test region, (b) demand, (c) fleet mix, (d) FAA/airline procedures on management of congestion caused by convective weather (e.g., Spring 2000, "growth without gridlock"), (e) airline scheduling, and (f) other systems[5].

To reduce the complexity of the analysis, we focused on Atlanta arrival handling in convective weather near the ITWS domain. It was assumed that the majority of the reduction in airborne arrival delays attributable to the use of ITWS would occur in close proximity to the airport (within a 50-60 nmi radius). In particular, it was postulated that the change in average ASPM flight times from 100 nmi to touchdown on days with terminal convective activity between 2001 and 2003 could be equated to delay reduction.

It was hoped that using many days from the time periods before and after ITWS was introduced would reduce possible differences in the severity of the convective weather events. To maintain compatibility with FAA internal studies (FAA ATO-P, personal communication) average flight times as deduced from the ASPM summary statistics were compared for 22 METAR-identified thunderstorm days from 2003 and 22 METAR thunderstorm days from 2001.

Our study of Atlanta ITWS benefits using the interview/detailed-modeling approach had found that the expected airborne arrival delay savings per aircraft due to better handling of airport storm impacts was 0.67 minutes for all aircraft on a day where there was a thunderstorm impact on the airport. The expected airborne arrival delay savings for non-airport related delay reductions within the ITWS coverage was 0.47 minutes per aircraft on days with convective weather impacts in or near the terminal area. Taken together, the expected airborne arrival delay savings for all aircraft on days with convective weather either at the airport or near the terminal area was approximately 1.1 minutes.

The change in average ASPM 100 nmi to touchdown flight times on 22 thunderstorm days in 2003 was about one minute less than the average flight time for 22 thunderstorm days in 2001. Although this change in ASPM flight times was similar to what was predicted, we do not view this as confirming the interview/decision modeling estimate due to many factors that were different between the two years (e.g., severity and duration of the convective weather in the two years, introduction of CTAS at Atlanta at the same time as ITWS) as well as the very significant data quality problems with the ASPM 100 nmi to touchdown flight time metric.

The data quality problems associated with the ASPM flight times from 100 nmi to touchdown include inability to capture a significant fraction of the airborne holding delays due to convective weather in the Atlanta terminal area, the metric used to compute a distance of 100 nmi from the airport, and the accuracy of the touchdown times for aircraft that do not automatically provide touchdown data.

One might assume that the use of 22 thunderstorm days per year would roughly normalize for the differences in Atlanta convective weather between 2001 and 2003. However, this appears to be an erroneous assumption. Although 2001 and 2003

[5] The Center-TRACON Automation System (CTAS) went into operation at about the same time as ITWS.

had a similar number of thunderstorm days between April and August (31 in 2001 and 34 in 2003), the amount of precipitation that occurred (which might be viewed as a surrogate for the severity and duration of convective events) was quite different. For example, during the period June through August, Atlanta airport recorded 16.2 inches of precipitation in 2003 but only 10.5 inches in 2001.

A far more germane metric for normalizing weather differences is the amount of time that various key points inside and immediately outside the Atlanta terminal area were impacted by convective weather and the extent to which one or more of the arrival fixes into the Atlanta terminal area were impacted.

We conducted a study of the duration of weather impacts in the Atlanta terminal area using the RTVS NEXRAD-based validation data [9]. We found that the number of time periods with continuous convective weather at the Atlanta terminal area was significantly higher in 2003. It follows from equation (2) that one might compare severity of the convective weather delay by considering the respective sum of the squared durations of terminal weather events. That metric suggests that the 22 thunderstorm days in 2003 were **47% more severe** in terms of delays than the 22 thunderstorm days in 2001. We concluded that the convective weather in 2003 was approximately 50% more severe than the convective weather in 2001.

Another unresolved problem in the Atlanta ASPM delay analysis comparison was how to account for the possible contribution of CTAS to the change in flight times. CTAS was clearly helpful at Atlanta in reducing the arrival queues that occur at peak demand periods in fair weather. The issue is whether a similar benefit occurs in convective weather given that the CTAS software does not consider convective weather constraints on usage of the enroute and terminal airspace.

2. What can one do to make delay statistics comparisons a viable measurement option?

Our exploratory study of using a comparison of ASPM statistics before and after the ITWS was introduced at Atlanta has shown that there are many formidable challenges to making this a reliable analysis tool. Thus, we need to consider what can be done to make such comparisons feasible.

(a) Focus attention on specific situations in which one believes that there should be measurable delays

For systems such as ITWS that provide products over a limited domain, it should be possible to systematically define "similar" weather situations before and after system introduction. The word "similar" is quite significant here since a common misconception is that it is easy to find identical convective storm events. It can be shown by combinatorial arguments that the likelihood of identical convective weather events is very unlikely[6]. However, one can seek to find similarities in *degree* of convective impact as characterized by event duration, *specific* event location, comparable demand/capacity profiles (i.e., time of day, day of week, specific routes/airports involved), and unique city pairs involved.

We would emphasize, however, that such simplifications should be developed as an outgrowth of in depth understanding of the ATC/convective weather dynamics for the region under consideration. Such understanding should be developed by discussions with knowledgeable ATC personnel from the facilities of interest (e.g., such as are accomplished in the interview/modeling approach), real time observations and confirmation of the utility of simplified capacity models by examination of movie loops of traffic plus convective weather.

(*b) Is adjusting measured delays by a convective weather severity index feasible?*

It has become clear that a need exists for a quantitative model for the NAS that would permit adjustment of measured delay data to account at least for the differences in convective weather and the demand between different time periods. Metrics that might be applicable have been presented at past ATM workshops and in other forums [4 and 10]. The common denominator in these indices is that the index is the space/time linear sum of the product of a weather severity factor (radar reflectivity or

[6] A detailed discussion of this possibility will be published elsewhere. However, the general assertion is that one can compactly characterize the ATC impact of a convective weather event by assessing which jet routes and fixes have been impacted. Terminals alone would typically have at least 14 such regions which corresponds to 2**14 possible combinations for convective weather impacts for a given time. Each of these over 16,000 combinations typically would evolve into one of a comparable number of other possibilities roughly every half hour. When one looks at assigning about 100-200 storm events per year to such a large number of combinations, it is clear that the likelihood of two assignments agreeing perfectly is exceedingly small.

lightning) at a location and, the fair weather traffic density at that location. These indices are appealing in that they consider weather and demand simultaneously.

However, on close inspection, we have concerns with these indices as a tool for detailed quantitative delay analysis. One problem is that the indices are not sensitive to the manner in which a route is closed. For example, a squall line aligned with a single route is considered to have as severe an impact as a squall line that cuts across many major routes. Also, we noted in section III that the lightning data or the radar reflectivity data alone are not reliable indicators of convective storm severity.

A major factor in the New York and Atlanta terminal convective weather delays, as well as delays in the CIWS domain, is that queues are a key issue in significant delay situations (e.g., delays > 40 minutes). The approximate linear dependency of the weather coverage and duration in the current indices is clearly at variance with equation (2)[7].

(c) Use real time observations of ATM decision support systems to help quantify the relative contributions to delay reduction

We noted that Atlanta, it was not possible from an analysis of the delay statistics alone to determine the relative contributions of CTAS and ITWS to reducing convective weather delays. Real time observations of how the two systems were used during convective weather followed by modeling would have been a great help in assigning benefits.

V. Summary

Convective weather delays are now a principal cause of aviation delays that can be reduced by a number of weather/ATM decision support systems. In today's aviation system investment environment, it is essential that effective methodologies be developed to quantify the convective weather delay reduction benefits provided by weather/ATM systems.

We began by discussing the interaction of storms with ATC operations. Mechanisms whereby delay is generated when convective weather impacts those operations were identified, and we discussed how one might assess the magnitude and severity of convective weather. Results from practical experience at quantifying convective weather delay reduction using a variety of techniques at many different locations were presented. We noted the need to understand facility operations during convective weather including the significant differences that exist from facility to facility in dealing with convective weather impacts. We then discussed an example where an attempt was made to determine benefits from the change in ASPM delays and highlighted the problems that were encountered with this approach.

Based on these various studies, we recommend that a combination of:

1. operational user interviews including direct usage observations followed by detailed case analyses,
2. analysis of flight track data before and after a system was installed, and
3. operational delay statistics (e.g., ASPM) comparisons

be used in concert to quantitatively estimate the delay reduction. The operational delay statistics analyses should minimize the spatial extent for analysis whenever possible by appropriate choice of delay metrics and cases analyzed. Additionally, it may be necessary to process individual flight ASPM delay records as opposed to using the summary ASPM statistics used to date. If one is concerned about TFM decisions, then it will be necessary to normalize for differences in the convective forecasts between different time periods as well as the differences in the actual convective weather in comparing delay statistics

Key Words

Convective weather delays; benefits analysis; metrics; weather radar; lightning; ITWS; CIWS.

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[7] For example, the indices would view a situation in which convective weather shut down all of the arrival fixes into an airport as being roughly twice as severe as a convective weather situation in which half the arrival fixes were shut down. Clearly, the delays that result from a total shutdown is much worse than twice the delays associated with a loss of 50% of the capacity. Similarly, the various indices suggest a convective weather impact of a two hour event is twice that of a one hour event whereas equation (2) would suggest that a 2-hour event causes a delay impact that is four times the delay due to a one-hour storm event.

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