Project Report
ATC-320

Operational Benefits of the Integrated Terminal Weather System (ITWS) at Atlanta

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16. Abstract

The delay reduction provided by the initial operational capability production Integrated Terminal Weather System (ITWS) at Atlanta International Airport (ATL) was estimated using interviews with operational ITWS users to provide the inputs for Atlanta-specific models of delay reduction. Improved arrival decision making by terminal (TRACON) users provided the bulk of the benefits identified thus far. The projected delay savings are 7,322 hours per year (including reduced "downstream" delays) with an estimated monetary value in excess of $23M per year.

The "reasonableness" of the model-based delay reduction estimates were assessed by comparing those savings with estimates of the weather-related arrival delays at ATL. A comparison of arrival flight times from 100 nautical miles to touchdown on thunderstorm days pre- and post-ITWS at ATL showed lower flight times after ITWS was installed, but are not statistically significant due to ASPM data quality problems, differences in weather severity and, the possible role of CTAS in reducing flight times. Analysis of ASPM downstream delay data showed that the "downstream" delay model used was very conservative.

We recommend follow-on real time observational and, offline flight track and delay statistics studies of the ITWS delay reduction at Atlanta and other ITWS facilities.

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ABSTRACT

This report summarizes the results of an initial study to estimate the yearly delay reduction provided by the initial operational capability (IOC) Integrated Terminal Weather System (ITWS) at Hartsfield-Jackson Atlanta International Airport (ATL). Specific objectives of this initial study were to:

- analyze convective weather operations at ATL to determine major causes of convective weather delay and how those might be modeled quantitatively.
- provide estimates of the ATL ITWS delay reduction based on the "Decision/Modeling" method using questionnaires and interviews with Atlanta Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC) operational ITWS users.
- assess the "reasonableness" of the model-based delay reduction estimates by comparing those savings with estimates of the actual weather-related arrival delays at ATL. In addition, the reasonableness of model-based delay reduction estimates was assessed by determining the average delay savings per ATL flight during times when adverse convective weather is within the coverage of the ATL ITWS.
- conduct an exploratory study confirming the ATL ITWS delay savings by comparing Aviation System Performance Metrics (ASPM) database delays pre- and post-ITWS at ATL.
- assess the accuracy of the "downstream" delay model employed in this study by analyzing ASPM data from a major US airline, and
- make recommendations for follow-on studies of the ITWS delay reduction at Atlanta and other IOC ITWS facilities.

All of these objectives were achieved and are briefly summarized below.

ATL is the second busiest airport in the country in terms of operations per year and is typically one of the top ten airports with the highest number of annual Air Traffic Operations Network (OPSNET)-reported delays. Therefore, it is not surprising that airborne and ground queues are a fairly common feature of ATL operations in convective weather. This finding is very important for studies of the Atlanta ITWS delay reduction since queue delays are very sensitive to changes in capacity, demand, and weather event duration.

The terminal (TRACON) user provided the bulk of the benefits identified in this study. The projected delay savings are a direct delay reduction of 4,068 hours, with a total delay reduction of 7,322 hours per year (including downstream delay). This results in an estimated monetary value in excess of $23 M per year.

These delay reduction numbers correspond to about 5% of the "after ITWS" arrival delays (relative to schedule) due to weather at Atlanta in 2004 and about 7% of the "after ITWS" arrival delays (relative to schedule) due to weather at Atlanta in 2003. The expected airborne arrival delay savings per aircraft

ranges from 0.67 minutes per flight to 1.5 minutes per flight, depending upon whether or not the storms impact the Atlanta airport. The projected departure delay savings are approximately 0.42 minutes per aircraft on days with convective weather impacts in or near the terminal area.

An exploratory comparison of ASPM delay statistics for arrivals pre- and post- ITWS at Atlanta shows a reduction in flight times from 100 nmi-to-touchdown of about 1 minute per flight on days when there was a thunderstorm impact at the airport. However, we do not regard this as a statistically meaningful result as we were not able to normalize the results to account for differences in many key factors such as weather severity, problems with the ASPM delay statistics, and the use of other systems (especially the Center-TRACON Automation System [CTAS]).

When thunderstorms occur at the Atlanta airport, the effective capacity of the airport is often reduced. A comparison of traffic counts during the time periods when the Atlanta surface report (METARs) indicated a thunderstorm with rain (TSRA) was present supports the user statement that ITWS reduced the frequency of airport closures. Specifically, the fraction of TSRA incidents with 15 minute arrival plus departure counts of less than 15 aircraft was reduced from 12% in 2001 to 6% in 2003. The lower frequency of TRSR incidents that result in abnormally low Atlanta operations rates provides objective operational data supporting the ATC user feedback on ITWS benefits.

Based on our analysis of delay propagation of a major airline's delayed flights for three different days, plus recent literature on delay propagation for a hubbed major airline, we conclude that the downstream delay model used in this (and, an earlier) ITWS benefits study is very conservative.

The report concludes with recommendations for follow-on studies to address two relatively near term ITWS program issues.

- Provide benefits results for an Office of Management and Budget (OMB)-300 submission to demonstrate that the ITWS program has been achieving major performance goals and
- Provide data to substantiate the projected benefits for the ITWS locations that are not a part of the initial ITWS production system deployment (e.g., Dayton, OH; Tulsa, OK; etc.).

To augment the results reported here, we recommend additional operationally oriented training using experienced ITWS users from the ITWS demonstration sites. This should be followed by additional product usage interviews, real-time on-site observations of product usage, and a comparison of flight tracks and weather pre- and post-ITWS.

Queue delays are very sensitive to small changes in demand, weather event duration, and severity. For this reason, the use of ASPM delay statistics pre- and post-ITWS as a basis of benefits assessment is very challenging. We suggest that such comparisons be done for very carefully selected weather events and flights. This minimizes the complexity of the delay normalization models needed to account for the differences in key factors between the time periods used to compare delays.

ACKNOWLEDGEMENTS

We would like to acknowledge several people who made significant contributions to this report. Gary Paull of MCR was consulted extensively on the content in Chapter 4 and made many valuable suggestions that led to improvements in the benefit estimates. Thanks also to Dan Citrenbaum of ATO-P for many insightful questions and comments on benefits analysis. Thad Carpen, from the ITWS Program Office, provided a thorough review of this report and made many helpful comments. Billy Joyce of the Atlanta TRACON, Mike Ogles of the Atlanta Air Route Traffic Control Center, and several other FAA users in Atlanta took the time to answer questions or provide data that was critical for this benefits report.

We owe thanks to several people associated with the Weather Sensing Group at MIT Lincoln Laboratory, who contributed greatly to this report. Diana Klingle-Wilson and Elizabeth Ducot spent many hours editing the document and their contributions were invaluable. Richard Ferris carried out the analysis of the relationship of METARS to weather impact times in Section 5.2, as well as detailed analyses of storm impacts on Atlanta operations. Darin Meyer flew to Atlanta twice to administer the questionnaire and get detailed feedback from all users of the Atlanta ITWS, for which we are grateful. Christopher Gross and Jerry Mellon provided data analysis that contributed to the content of this report.

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1. INTRODUCTION

1.1 OVERVIEW

This report details the results of a study to determine the delay reduction operational benefits of the initial operational capability (IOC) Integrated Terminal Weather System (ITWS) at Atlanta, GA. The Atlanta ITWS was first used operationally on 10 July 2002 and formally commissioned on 30 September 2003.

Figure 1 shows the US airports that have the highest number of operations delayed by weather, according to the Federal Aviation Administration (FAA) Air Traffic Operations Network (OPSNET) database. The Hartsfield-Jackson Atlanta International Airport (ATL) is ranked second for weather delays. Although not shown, it is also the second busiest airport in America and ranks 7^{th} in delay-minutes per delayed operation, according to OPSNET. Since a principal objective of the ITWS is to reduce delays, the high rate of delays made Atlanta a prime candidate for an ITWS.

Specific objectives of this study were to:

- analyze convective weather operations at ATL to determine major causes of convective weather delay and how those delays might be modeled quantitatively.
- provide estimates of the Atlanta ITWS delay reduction based on the "Decision/Modeling" method using questionnaires and interviews with Atlanta Terminal Radar Approach Control (TRACON) and Air Route Traffic Control Center (ARTCC) operational users.
- assess the "reasonableness" of the model-based delay reduction estimates by comparing those savings with estimates of the actual weather-related arrival delays at ATL. In addition, the reasonableness of model-based delay reduction estimates was assessed by determining the average delay savings per ATL flight during times when adverse convective weather is within the coverage of the Atlanta ITWS.
- conduct an exploratory study to confirm the Atlanta ITWS delay savings by comparing the FAA's Aviation System Performance Metrics (ASPM) database delays pre- and post-ITWS at ATL.
- assess the accuracy of the "downstream" delay model employed in this study by analyzing ASPM data from a major US airline, and
- make recommendations for follow-on studies of the ITWS delay reduction at Atlanta and other IOC ITWS facilities.

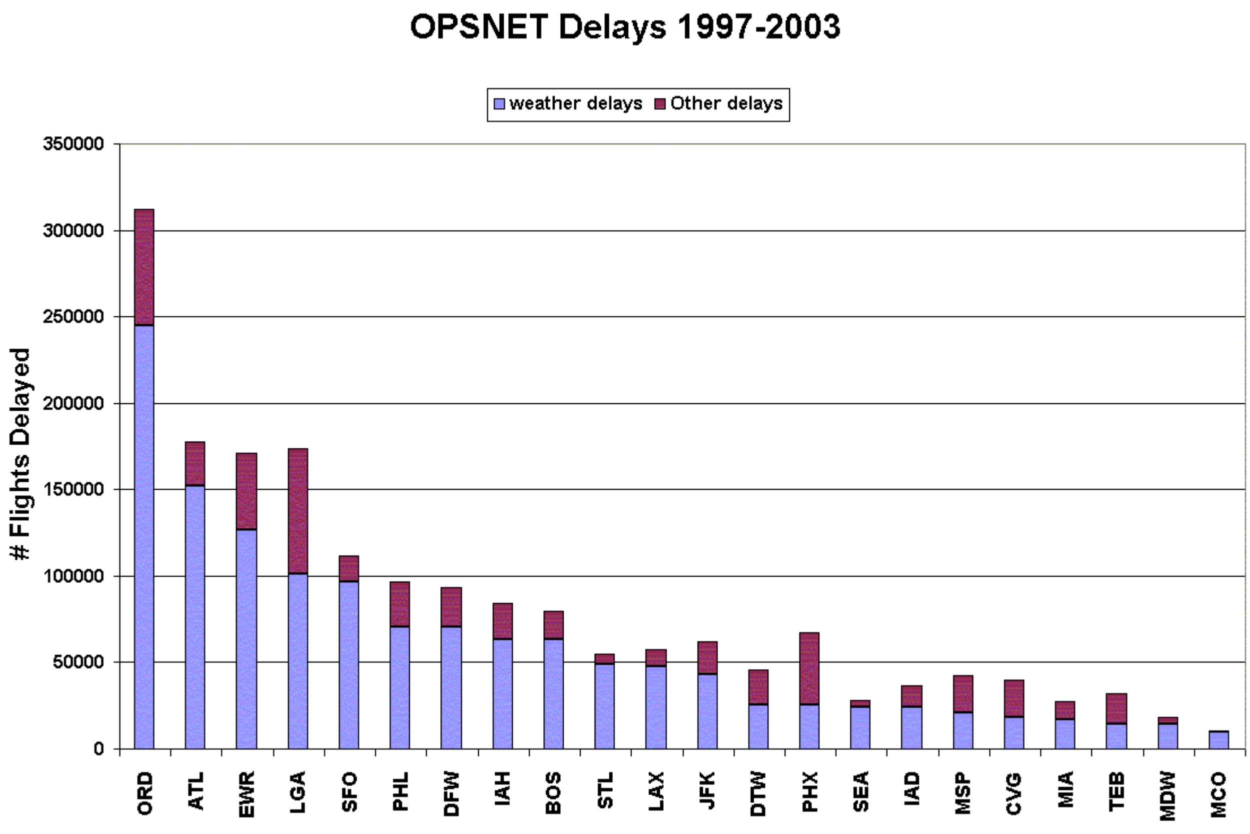

Figure 1. Number of flights delayed at each listed airport between 1997 and 2003. OPSNET defines a delayed flight as a flight that is delayed 15 minutes or more while under FAA control.

1.2 DESCRIPTION OF ITWS CAPABILITY

The ITWS produces fully-automated, integrated terminal weather information. This information is provided to air traffic controllers and traffic managers to improve the safety, efficiency, and capacity of terminal area aviation operations. The ITWS acquires data from FAA and National Weather Service (NWS) sensors, as well as from aircraft in flight in the terminal area. The ITWS produces products for Air Traffic Control (ATC) personnel and aviators that are usable without further meteorological interpretation. These products include current terminal area weather and short-term (0-20 minute) predictions of significant weather phenomena.

The ITWS provides products that enable air traffic and airline users to significantly improve safety and reduce delays at major terminals and in the en route airspace that surrounds these terminals. With some exceptions, product update rates are determined by the input sensors or data. In adverse weather conditions the maximum nominal update rate for any product is five minutes. The nominal update rate of the TRACON precipitation product, which is based on Airport Surveillance Radar Model 9 (ASR-9), and products that are computed from the TRACON precipitation product (e.g., storm motion and extrapolated position) is 30 seconds. The rapid update of the precipitation and storm motion products and the wide availability of the information to traffic planners at Towers, TRACONs, and ARTCCs create a powerful traffic planning and safety tool for traffic managers and controllers using the ITWS. Table 1 provides a list of the ITWS products, their update rates, data sources, and performance requirements. Table 2 summarizes the safety enhancements afforded by the ITWS.

TABLE 1
ITWS Product Update Rate[1] and Technical Performance[2]

Product	Data Sources	Product Update Interval (min[3])	Product Spatial Resolution (nmi[3])	Typical Performance
Microburst detection	TDWR[3]	1	1	P_d[3] > 0.95, P_{fa}[3] < 0.05
Microburst prediction	TDWR, MDCRS[3], Soundings, ASOS[3]	2.5	---	$P_d \approx 0.3$ $P_{fa} < 0.1$
Gust Front detection	TDWR	5	1	$P_d \approx 0.7$, $P_{fa} \approx 0.1$
Gust Front current location	TDWR	1[4]	1	----- -----
Gust Front 10- and 20-min. predictions	TDWR	1[4]	1	20 min prediction within ± 1.4 nmi 80% of time for wind shifts > 15 knots
Wind Shift	TDWR, LLWAS[3]	5	---	Wind to within ± 8 knots, ± 30° 60% of time for wind shifts > 15 knots[6]
Airport precipitation	TDWR	1	0.13	----- -----
TRACON precipitation	ASR9 mosaic[5]	0.5	0.5	----- -----
Long Range precipitation (100 and 200 nmi)	NEXRAD[3]	5 - 6	0.5, 2.2	----- -----
Storm Motion	Precip source	1– 5[7]	---	Within 10 knots for 90% of storms moving faster than 10 knots
Storm Extrapolated Position (SEP)	Precip source	1-5[7]	---	Within 1 nmi 85% of time for 10 min SEP and 65% of time for 20 min SEP
Storm Cell information (hail, severe storm, echo tops, lightning)	NLDN[3], NEXRAD	1-5[7]	---	-----
Terminal Winds	TDWR, NEXRAD, MDCRS, RUC[3]	5[4]	Vertical: 50 mb[3] Horizontal: ≤1 nmi within the TRACON and ≤18 kft[3]; ≤5 nmi outside the TRACON or >18 kft	-----
Tornado Vortex Signature	NEXRAD	5	0.5	
Ribbon display alerts and active runways	TDWR, LLWAS	0.15[8]	---	-----
Lightning within 20 nmi of airport	NLDN	0.083	0.25	NLDN detects 80-90% of cloud-to-ground lightning[9]

Table Footnotes:

1 Unless noted otherwise, update rate is nominal because the actual update is triggered by an external sensor.

2. Performance results from Klingle-Wilson (1995) unless otherwise noted.

3.

min	minutes
nmi	nautical mile
TDWR	Terminal Doppler Weather Radar
P_d	Probability of Detection
P_{fa}	Probability of False Alarm
MDCRS	Meteorological Data Collection and Reporting System
ASOS	Automated Surface Observing System
LLWAS	Low Lever Windshear Alert System
NEXRAD	Next Generation Weather Radar
NLDN	National Lightning Detection Network
RUC	Rapid Update Cycle
mb	millibar
kft	thousands of feet

4. Update rate is clock-driven.

5. ASR reflectivity is quality checked against TDWR and Next Generation Radar (NEXRAD) data.

6. Performance requirement for accuracy of predicted wind shift.

7. Update interval is a function of the underlying precipitation product.

8. At Low Level Wind shear Alert System (LLWAS) expanded network (NE) airports, TDWR derived alerts are integrated with LLWAS NE alerts. The Ribbon display alert update at a rate consistent with the fastest update rate associated with the input sensors.

9. Cummins et al., 1998 and Idone et al., 1998.

TABLE 2
Safety Enhancements with ITWS Products

SAFETY CONCERN	ITWS PRODUCT(S)	HOW SAFETY IS ENHANCED BY ITWS (Above and Beyond TDWR and ASR-9)
Rapidly intensifying microburst	Microburst Prediction	Provides two- to five-minute predictive warnings
Extreme microbursts with airspeed losses greater than 60 knots requiring total avoidance	Microburst Prediction	Provides predictive strength estimate
Controller overload and pilot deviations from normal paths yielding "operational errors"	Precipitation, Storm Cell Information, and Storm Motion/Extrapolated Position	Shows location and movement of significant weather so Air Traffic Control can proactively plan a safe, efficient flow of aircraft
Tornadoes (e.g., a tornado narrowly missed Orlando in 1998)	Tornado	Provides point location of tornadoes (TDWR provides no information on tornadoes.)
Hailstorm (e.g., a hailstorm hit Dallas-Ft. Worth in 1995)	Storm Cell Information	Shows location and movement of hailstorms (TDWR provides no information on hail.)
Mesocyclone (frequently causes tornadoes and/or damaging winds)	Storm Cell Information	Shows location and movement of mesocyclones (TDWR provides no information on mesocyclones.)
High reflectivity storm location and movement (identified as a high priority by National Transportation Safety Board) (e.g., American Airlines DC10 accident at Dallas-Ft. Worth International Airport in 1993)	Precipitation, Storm Cell Information, and Storm Motion/Extrapolated Position	TDWR does not provide adequate vertical coverage over two-thirds of the TRACON and is subject to attenuation. ASR-9 at times has false storm depictions due to anomalous propagation and is not always viewed as reliable by controllers.
Lightning	Storm Cell Information, Lightning	Shows location and movement of storms with lightning (TDWR and ASR-9 have no lightning information/) Indicates when lightning is detected within 20 nmi of the airport

In addition to safety enhancements, the ITWS provides products to help reduce delays during adverse weather conditions. The delay reduction/efficiency enhancements identified in operational testing with functional ITWS prototypes in 1993-2001 included:

- Improving traffic merging and sequencing during adverse wind conditions at airports that have inadequate capacity during Instrument Meteorological Conditions
- Recognizing that a runway will remain open as thunderstorms pass
- Anticipating departure transition area (DTA) closure
- Anticipating arrival transition area (ATA) closure
- Anticipating re-opening of an ATA
- Landing, rather than holding, aircraft before airport shutdown
- Minimizing diversions before airport shutdown
- Minimizing unnecessary diversions prior to the airport re-opening
- Anticipating airport re-opening
- Positioning holding aircraft for quicker landings
- Landing more airplanes before arrival rate reductions
- Balancing DTA traffic better
- Reducing the duration of ground stops
- Anticipating runway shifts due to thunderstorms
- Reducing terminal flying distances
- Holding jets at higher altitudes
- Recognizing opportunities for advantageous ground stops
- Improving use of severe weather avoidance programs

Another key ITWS benefit is shared situational awareness. Tower, TRACON, ARTCC, and the Delta Airlines System Operations Center users have access to the same accurate weather information from the Atlanta ITWS, which aids in coordination and planning.[1]

The ITWS situation displays in Atlanta are located at the airport tower, the terminal radar approach control (TRACON) for Atlanta, the Traffic Management Unit (TMU) at the Atlanta ARTCC (ZTL), and the Center Weather Service Unit (CWSU) at ZTL. Airline users can gain access to the ITWS data via a Web browser interface operating over CDMNet. It is important to

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[1] Although Delta Airlines has access to the ITWS production web site through a special arrangement, this is not the case for the other airlines. Limitations on access to the web site will significantly affect the coordination and planning benefit when applied to other locations and, to a certain extent, to ATL.

note that the only weather information available in the Atlanta TRACON prior to the installation of the ITWS was the ASR-9 data on the controllers' scopes. These data exhibited data quality issues, including anomalous propagation, ground clutter contamination, and attenuation.

Figure 2 is a representative image from the Atlanta ITWS Situation Display. There is a product status button for each product. These are located in the upper left corner of the image beneath the gray display configuration buttons. If the button is green, the product is available and displayed in the window. If the button is yellow, the product is available and filtered; that is, the product is not completely displayed. If the button is white, the product is available but not displayed. If the button is red, the product is unavailable.

To the right of the product status buttons is the alert panel. The boxes in this area change color to alert the users when a hazard (tornado, lightning, etc.) has been detected within the parameters of the alerting strategy. For example, if lightning is within 20 nmi of the airport the lightning alert turns yellow. If a tornado is within 10 nmi of the airport, the tornado panel turns black. In this image there are no active alerts.

The lower portion of the display contains graphics and text product windows. The main window in Figure 2, titled "ATL-30nm", offers a rapid update mosaic of precipitation from the two ASR-9s. Black arrows depict the motion of the storms, with associated numbers indicating their speed in knots. The leading edge of the level 3 weather is indicated by solid cyan lines, while storm extrapolated positions at 10 and 20 minutes are shown by dashed cyan lines.

The window titled "ATL-Terminal Winds" gives a table of wind speed and direction at various altitudes over locations of interest to users (typically points along the arrival paths). Traffic managers use this information to determine traffic spacing on days when winds cause compression on final approach.

Finally, the window labeled "ATL-100nm" provides high-resolution precipitation as depicted by the NEXRAD radar located at Peachtree City Airport about 18 nmi southwest of ATL. Although the update rate is slower than the ASR-9 mosaic, this window presents an expanded view of the weather. Storm motion and extrapolated position are also shown in this window.

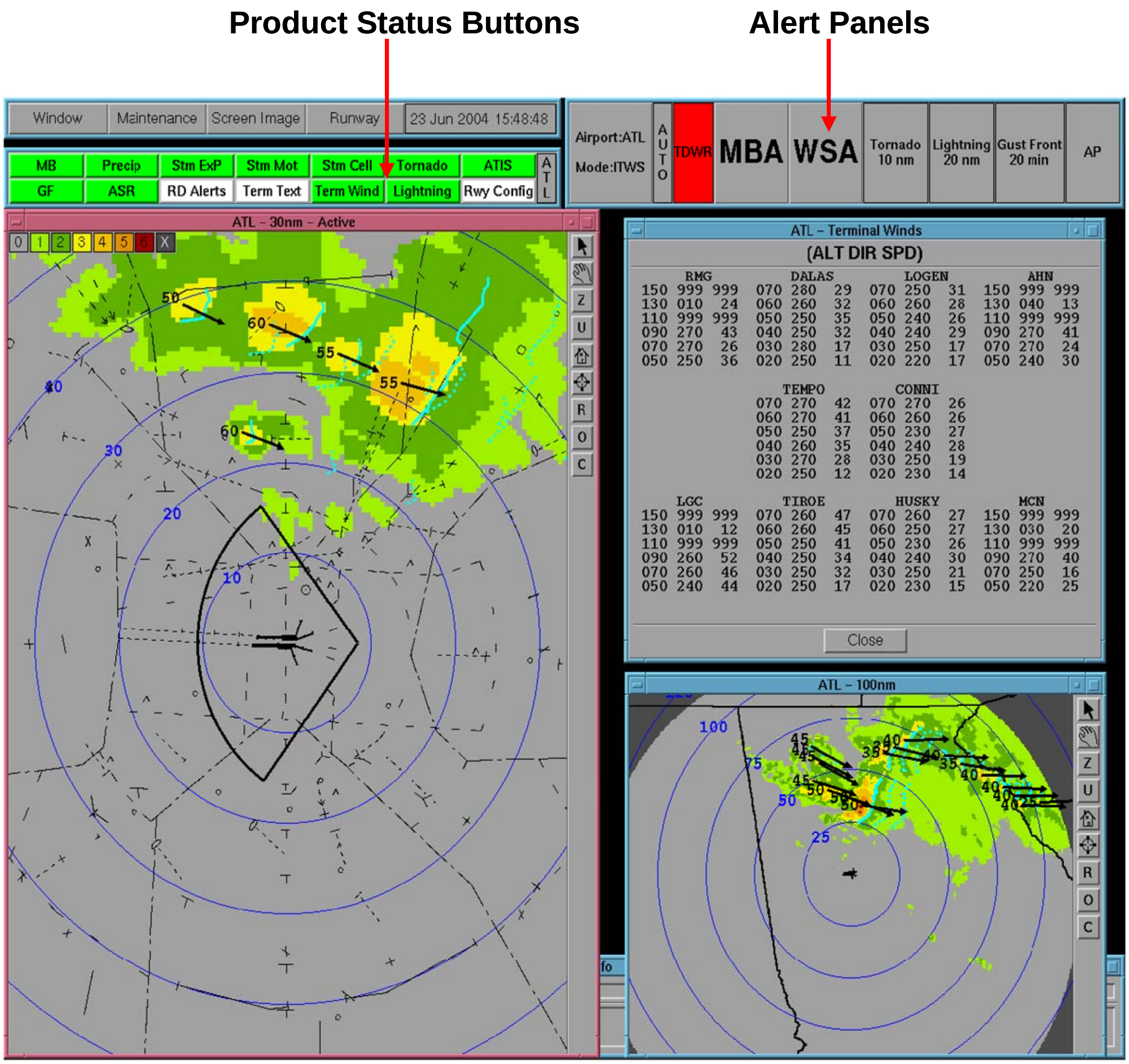

Figure 2. An image of the Atlanta ITWS Situation Display on 23 June 2004.

When present, microbursts, wind shears, and gust fronts are shown in the ASR-9 mosaic window. This is especially helpful to ZTL managers who previously did not have a display of these impacts at the airport. In addition, traffic managers can click on any of the storm cells in these images to display the cell top height in a storm cell information box. This same box indicates if there is lightning, hail, or severe storm circulation in the cell.

For additional information on the ITWS features, the reader is referred to Evans and Ducot, (1994) and the MIT Lincoln Laboratory Aviation Weather web site (http://www.ll.mit.edu/AviationWeather/).

1.3 OUTLINE OF REPORT

Chapter 2 reviews previous methods of measuring delay reduction benefits (including the use of the FAA's OPSNET and ASPM databases) and determining whether the delay estimates are "reasonable".

Chapter 3 describes the airspace in and around Atlanta airport. It also discusses how operations are affected by adverse weather, including thunderstorms and vertical wind shear. Atlanta convective operations are significantly impacted by queues as manifested in airborne holding at long distance (e.g., > 100 nmi) from the airport, ground stops, and ground delay programs.

Chapter 4 presents the methodology and results of the MIT Lincoln Laboratory benefits assessment of the Atlanta ITWS. These results are based on quantitative models of Atlanta convective operations using data derived from:

- feedback from the FAA and Delta Airlines users in the form of questionnaires and interviews, and
- climatological statistics on the relative frequency of convective weather events at Atlanta.

Chapter 5 provides an estimate of the total delay at ATL due to convective weather. We compare the measured benefits (Chapter 4) to the total amount of delay and compute the average number of minutes of delay savings per convective weather-impacted flight at Atlanta.

Chapter 6 describes the results of a preliminary study of using ASPM delay statistics to estimate the Atlanta ITWS benefits. It illustrates many challenges that exist in using ASPM data to estimate the delay savings at complicated, congested airports such as ATL.

A significant fraction of the ITWS delay-reduction benefit is reducing "downstream" delays that arise when a plane is delayed. In Chapter 7, we present the results of our study to validate the downstream delay model (Chapter 4) using ASPM delay statistics from flights of a major, financially successful airline. These results, which are new to the delay analysis area, indicate that the downstream delay model used in Chapter 4 is very conservative.

Chapter 8 summarizes the results of this study and makes recommendations for:

- Follow-on studies to refine the Atlanta ITWS delay reduction benefits estimates, and
- Studies of the benefits at other IOC ITWS airports that may be more representative of the 12 terminals that did not receive an IOC ITWS in the initial ITWS production system deployment.

2. METHODS OF MEASURING BENEFITS – A REVIEW

2.1 INTRODUCTION: APPROACHES TO CONVECTIVE DELAY REDUCTION BENEFITS ASSESSMENT

There are two basic approaches to determining the achieved delay reduction benefits for a system such as the Atlanta ITWS. "Direct" measurement compares the delays in a baseline time period when ITWS was not in use to delays in a subsequent time period during which the system was in use. Alternatively, a "Decision/Modeling" approach employs interviews and/or direct observations of applied traffic management decisions to determine the parameters of models that are then used to estimate the delay reduction benefits. The basic assumption is that the weather products are useful only to the extent that they change user decisions. Thus, one can analyze the various decisions that, according to users, are improved as a result of having access to the Atlanta ITWS. The pros and cons of the two approaches are shown in Table 3.

TABLE 3
Pros and Cons of Delay Reduction Determination Methodologies

	"Direct" Method	"Decision/Modeling" Method
Synopsis	Direct comparison of delay before and after a system is introduced	FAA operational user interviews and questionnaires + delay modeling
Good features	Actual delay reflects actual cost incurred Easy to explain to recipients of a report	Factors which account for delay reduction are clearly understood Extrapolation to changed circumstances (e.g., operations increases, schedule changes, weather severity and duration) is relatively straightforward Only feasible way to assess potential improvement in system products
Problems	Requires very sophisticated knowledge of delay causality to compensate for differences between the "baseline" and "system test" time periods. Factors that must be quantitatively considered are: - Weather (severity, time of day, duration) - Weather in other locations - Traffic changes - Airline operations and scheduling - Air traffic procedures - Traffic flow management changes Not clear which elements of the National Airspace System (NAS) account for the delay reduction	May be difficult to validate the approach in some cases Need to make sure that factors considered are independent or that common elements are identified and the impact addressed (e.g., One must make sure one is not counting a factor several times by giving it different names.)

Our experience is that the "Direct" method is very hard to carry out in practice, even though it appears quite straightforward. We review past work on both methods. First, we discuss three examples of the "Decision/Modeling" approach and how one might validate the results of such an approach by comparing user feedback to analysis of traffic management actions during convective weather events. We then discuss issues associated with the "Direct" method in the context of convective weather delay mitigation. The Atlanta ITWS benefits research reported here utilizes both approaches.

Whether one uses the "Direct" method or the "Decision/Modeling" approach, it is important to have a good understanding of the principal mechanisms by which delay occurs. For the "Decision/Modeling" approach, this is clearly necessary. However, the "Direct" approach requires an in depth quantitative understanding of the delay causality mechanism. In particular, one must:

- Consider adjusting the measured delays to take into account the differences in key factors (such as the convective weather and/or demand) between the delay measurement times and/or
- Design the experiment and data analysis to minimize the impact of these confounding factors on the change in measured delays.

Hence, in Section 2.2, we present the principal convective delay reduction models used in the Atlanta ITWS study.

One of the unfortunate aspects of the Atlanta ITWS delay reduction benefits assessment is that other systems (specifically the Center-TRACON Automation System [CTAS]) that could be a factor in convective weather delay reduction were introduced at Atlanta at essentially the same time as ITWS. In Section 2.3, we review past work on experiments where multiple factors that may be germane to the parameter of greatest interest (delays at Atlanta) are present simultaneously.

Section 2.4 reviews past work and important considerations in the use of aviation delay databases for performance assessment. We consider both of the FAA principal databases (OPSNET and ASPM). This section provides a background for the detailed ASPM delay statistics analysis in Chapter 6.

In Section 2.5, we consider past work and important considerations in "reasonableness" tests for the magnitude of the convective weather delay reduction that might be achieved by the ITWS at Atlanta. In particular, we discuss whether a "holy grail" of such tests (a quantitative estimate of the "avoidable" convective weather delay at Atlanta) can be generated. We conclude that accurately estimating the "avoidable delay" at Atlanta is not practically possible at this point[2].

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[2] However, in Chapter 5 we describe two alternative bounds on the reasonableness of Atlanta delay reduction based on analysis of ASPM data and on analysis of the number of flights that are impacted by convective weather within the Atlanta ITWS coverage.

2.2 QUANTITATIVE MODELS USED TO DETERMINE DELAY SAVINGS

The "Decision/Modeling" approach begins with interviews and direct observations. After the interviews, two basic models are used to translate the operational impact results into quantitative estimates of the delay reduction benefits. These are described below.

2.2.1 "Linear" Delay Reduction

The first model corresponds to a transient event (e.g., a group of aircraft must fly a longer route) where there is no reduction in the overall average rate of aircraft movement. Figure 3 illustrates this for the case of a thunderstorm impacting an entry gate into a terminal area. Other examples of this include optimal rerouting around a region of convective weather, through a gap in a squall line as opposed to flying around the end of the squall line, and flying over a squall line as opposed to flying around the end of the squall line. For this type of delay, the benefit for improved performance is typically <u>linear</u> in each of the pertinent variables (e.g., traffic density, likelihood of occurrence, ability to realize the benefit in a given situation with an aviation system feature).

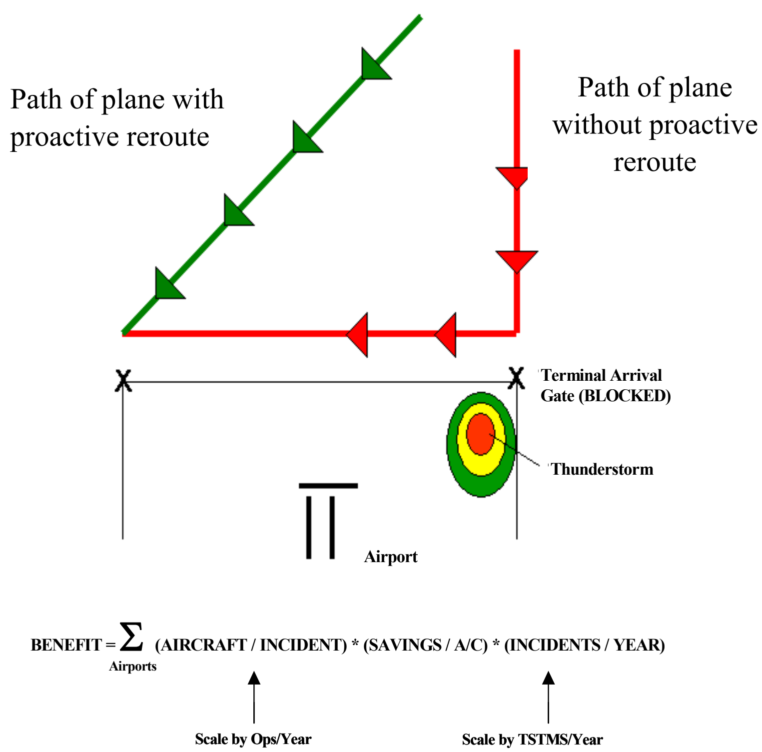

Figure 3. Example of the "fixed" delay linear model as it might be used to analyze a case where a number of aircraft fly a better route due to the use of the Atlanta ITWS products. Proactive reroutes using ITWS storm motion and extrapolated position forecasts enable aircraft to fly the direct route shown in green, as opposed to the longer route shown in red.

2.2.2 "Queue" Delay Reduction

Figure 4 shows a simple example of the classic queuing situation where the weather reduces the effective capacity of an airspace resource (e.g., a terminal or an en route sector) for a finite time during which the demand exceeds the capacity. It should be emphasized that the case shown in Figure 4 is a special case of the more general queue situation discussed in Newell (1982) and Daganzo (1997). In particular, both Figure 4 and Equation 1 assume that the demand is constant, whereas in practice it typically varies considerably over the period of reduced capacity. When the demand (and/or capacity) is time varying over the period of reduced capacity, there is no simple closed-form expression for the resulting delay and one must resort to numerical integration to determine the queue delays.

Queue models can be used to address both air traffic control/airport reductions in effective terminal capacity and traffic flow management actions by interpreting:

- The effective capacity as the minimum of the air traffic control/airspace constraints on the traffic flow and the flow rate imposed by FAA traffic flow management decisions and
- The effective duration as the sum of the actual weather event duration and the time period over which an insufficient number of aircraft are available to utilize the airspace resource due to non-optimal traffic management actions.

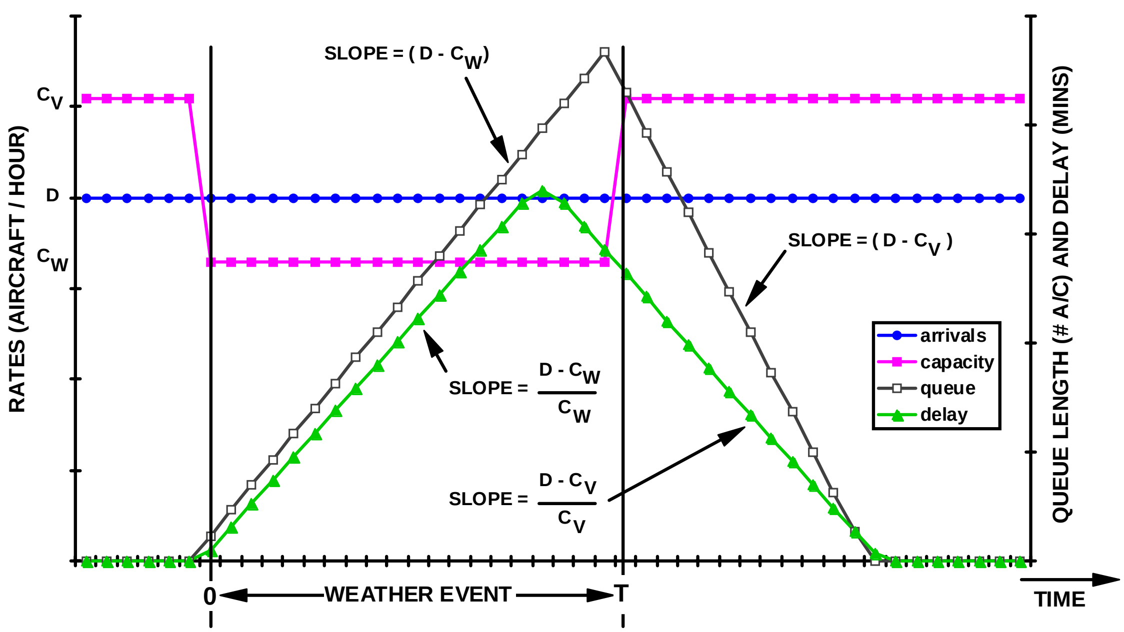

Figure 4. Queuing model for delay when adverse weather reduces the effective capacity of an aviation system resource (e.g., a route, an en route sector, or a terminal).

To illustrate the second bullet above, if an actual weather event at Atlanta lasts for two hours and causes a number of aircraft destined for Atlanta to be held on the ground at their respective departure airports, the delay event may be viewed as continuing until the held aircraft are released and land at the Atlanta. If forecasts are not used to proactively end the ground hold and the minimum flight time for the aircraft being held on the ground is one hour, then the effective duration is at least three hours.[3] It is straightforward to show that the accumulated delay for all the aircraft involved in the incident shown in Figure 4 is given by

$$\Sigma \text{ (delay to various aircraft)} = 0.5\, T^2\, (D-C_W)\, (C_V-C_W)/(C_V-D) \qquad \textbf{(Eqn. 1)}$$

where D = demand, C_W = capacity during adverse weather, C_V = capacity during benign weather, and T = effective event duration.

The dependence of delays on the demand and various capacities here is quite nonlinear. For example, we see that small increases in the effective capacity during a weather event (C_W) can produce larger proportional reductions in the accumulated delay because C_W appears in the product of terms.

Since T is squared, reducing the effective duration of a weather event (e.g., by better weather predictions and traffic flow management decision making) can also produce large delay reductions. For example, if storms block the runways at Atlanta so that no landings are possible, arrivals will be held in holding patterns in the ZTL airspace. This is the physical manifestation of a queue due to reduced airport capacity. Let us suppose the storms blocked an Atlanta runway for 20 minutes. At the end of the storm blockage, there may be few if any landings on the runway because the aircraft that were scheduled to land must fly from the en route center to the end of the runway. Thus, it easily may be 10 minutes after the storm impact ends before a significant number of landings actually occur. If the Atlanta ITWS storm forecast enables the Atlanta TRACON and ZTL to proactively release arrivals holding in the ZTL airspace so that aircraft start landing promptly after the storms move away from the runway, the accumulated delay would be reduced by the ratio of the respective values for T^2= 400/900= 0.44 (i.e., a delay reduction of about 56%).

By contrast, if the delay in this situation were linear in weather event duration (as in the equation shown in Figure 3), the percent of delay reduction from reducing the period of effective weather impact from 30 minutes to 20 minutes would be 33%.

We show in Chapter 3 that queues are quite common at Atlanta when convective weather occurs. Therefore, Equation 1 is quite important for understanding the challenge that exists in comparing ASPM delay statistics for Atlanta between different thunderstorm days. We can see from Equation 1 that the queue delay changes significantly with changes in either the capacity during adverse weather (C_W; which is related to the severity of the weather in terms of blocking

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[3] The use of holding patterns near the airport (as in the FAA's Managed Arrival Reservoir technique) will result in a more complicated relationship than illustrated in Figure 4, but the general principle still remains that ground holds increase the effective duration of a weather event.

fixes and/or runways) or the duration of the weather events (T). Hence, one must carefully estimate the effective capacity (Cw) and the duration of the weather events (T) if one is to compare queue delays for different weather events (e.g., thunderstorm events pre-ITWS to thunderstorm events post-ITWS).

Some of the quantitative queuing results shown in the subsequent sections of this report utilize an enhancement of the very simple queuing model shown in Figure 4, whereby one allows both the airport (or en route sector) capacity and the user demand to vary significantly with time. The model is implemented by use of a spreadsheet program. Part of the elegance of the model is that it requires only two input fields; demand and capacity as a function of time. Despite the limited input, the model is able to capture the actual delay fairly well and is surprisingly accurate in modeling peaks and valleys in the real data. An example of the accuracy of the queue model using operational data from Atlanta is shown in Appendix A.

To obtain accurate, realistic delay results from the model, the demand profile used was derived from an analysis of flight counts contained in the ASPM database. In order to produce a demand that was realistic, the demand profile from non-weather days was assumed to be the actual demand profile on the day in question. The nominal capacities used for the model varied significantly depending on the scenario. These are discussed with the actual scenarios.

2.3 REVIEW OF PREVIOUS CONVECTIVE WEATHER DELAY REDUCTION BENEFITS ASSESSMENTS

2.3.1 ITWS Initial Demonstration System Studies

The first major study of this type that we are aware of was carried out in the context of an assessment of the delay reduction provided by the ITWS. The first of these studies, which formed the basis for the subsequent ITWS benefits studies, was conducted by L. Stevenson of the Volpe Transportation Center and D. Rhoda of MIT Lincoln Laboratory after the ITWS operational demonstrations in 1994. ITWS operational users were interviewed at the end of the demonstration period to determine:

- Operational decisions improved by use of ITWS products, above and beyond the baseline terminal weather information systems at the airports (TDWR and ASR-9),
- The number of aircraft (or time duration) over which the improvement was achieved on a “typical” day with thunderstorm impacts, and
- The benefit (e.g., minutes of reduced delay time) experienced by the individual aircraft.

Based on the interview results, the linear model discussed above was used to quantify the delay savings associated with the various ITWS products above and beyond the baseline weather information systems at the airports.

This model can be written as

Delay savings = (decision factor coefficient) x (TDWR adjustment) x (WARP[4] adjustment) x (airport type factor) x (operations per day) x (days with thunderstorms) x (convective storm type factor) x (decision dependent climatology adjustment) **(Eqn. 2)**

where:

Decision factor coefficient is derived from the typical savings for that decision x number of times that decision might be made on a thunderstorm day,

TDWR and WARP adjustments account for partial sharing of benefits with other programs,

Airport type factor recognizes the difference between double-hub (e.g., Dallas), single-hub (e.g., Washington-Dulles International Airport), and non-hub airports

Convective storm type factor accounts for relative frequency of squall lines versus air mass storms

Decision dependent climatology adjustment is discussed below

These coefficients were derived primarily from interviews of ITWS users at Memphis, Orlando, and Dallas. A typical "raw" user feedback was that a certain decision (e.g., identifying that an arrival fix would close in 20 minutes) might occur several times on a day and that about 20 minutes would be saved for some number of aircraft. In effect, the user identified the savings per aircraft, the number of aircraft involved, and the number of times the benefit might be achieved on a day with thunderstorms present. The estimates by the operational users at a terminal facility were generally fairly consistent.

The resulting benefits decision factors also seemed fairly consistent between different terminal areas (i.e., Memphis, Orlando and Dallas). For example, the "raw" decision factor coefficient for anticipating that an arrival fix would close (the situation illustrated in Figure 3) was 0.00001 at Memphis and 0.000011 at Orlando. The largest "raw" decision factor coefficient was 0.000024, associated with recognizing that one runway would remain open (based on Memphis feedback).

This similarity in model parameters between the different airports is not surprising because many of the operational factors that underlie the benefits (e.g., the distance between arrival fixes, where planes are held in en route airspace, the time to fly from one arrival fix to another arrival fix, and the maximum number of aircraft that can arrive over a fix per hour) were fairly similar across various facilities. For example, most terminal areas are roughly square with the ATA about 40-50 nmi from the airport. Thus, the flight time to an adjacent ATA and the time to fly from an en route holding pattern through an adjacent ATA to the airport would be quite similar across airports.

These results were then extrapolated to the other ITWS locations based on the frequency of thunderstorm impacts, the number of operations at the various airports, and type of airport. It is

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[4] Weather and Radar Processor

interesting that in this initial ITWS study, the greatest delay reduction benefits (in terms of improved ATC decision-making) actually arose from the traffic management units (TMUs) at the ARTCCs containing the TRACONs. Key high benefit decisions for ITWS (in order of delay reduction obtained) were:

- Anticipation of the closing and reopening of arrival and departure fixes,
- Anticipation of convective weather impacts on runways and runway configurations,
- Optimization of traffic patterns within the TRACON,
- Optimization of airline operations, and
- Higher effective arrival capacity during thunderstorms.

Since a significant fraction of the ITWS delay reduction was associated with decision making by the TMU's at the ARTCC, it was important to consider the role of the other weather products available to the ARTCC TMU's. In particular, the role of the WARP system needed to be assessed. Based on the interviews with the ARTCC users, it was concluded that 1/3 of the ITWS benefit was attributable to WARP and adjustments were made in the following categories:

- Anticipation of ATA Reopening
- Recognition that ATA will remain clear
- Anticipation of ATA Closure
- Positioning holding aircraft for quicker landings

Similarly, other ITWS benefits were adjusted to account for the use of the TDWR precipitation product by terminal and tower supervisors.

The number of times a given decision is made per year clearly depends on the climatology of the region in which the decision is being made. For example, the frequency of storm impacts on the airport surface is not a good estimate of the frequency of storm impacts at the arrival and/or departure fixes (Bieringer, 1999). Hence, Equation 2 contains a decision-dependent climatology adjustment factor.

Based on the Stevenson-Rhoda study models and using the Bieringer et al., (1999) climatology corrections for specific ITWS benefits decisions, it was predicted that the IOC ITWS at Atlanta would provide 6,056 hours of direct delay reduction per year and 4,845 hours of "downstream" delay reduction per year.

2.3.2 New York ITWS Benefits: An Example of Terminals Where Queues Dominate Benefits

An assessment of the operational benefits of the New York ITWS was carried out using the same approach as the first ITWS benefits study (Allan et al., 2001). The New York ITWS study relied heavily on the use of queuing models to determine benefits and on the use of case studies to illustrate benefits situations. Although it was recognized in the initial ITWS studies that queues could be a factor in delay causality, queues were not a frequent feature of ATC operations in convective weather at Memphis and Orlando[5]. In New York, situations in which demand exceeded the effective airport/terminal capacity were quite common during adverse weather. Therefore, demand and capacity as a function of time had to be analyzed very carefully to obtain realistic benefits estimates. For example, increasing departure rates during a Severe Weather Avoidance Plan (SWAP) was determined to be the highest convective weather benefit at New York. The benefits of this were estimated from the change in queue delays as a function of departure rate, using the average actual departure rates observed during a SWAP.

Although queue models were very important for quantifying the New York ITWS benefits, there were ITWS benefits situations at New York that could be modeled using Equation 2 including:

- Determining more efficient (shorter distance) departure routings,
- Landing aircraft before a weather event,
- Not rerouting arrivals or departures to an alternative fix if the storm would miss the desired fix, and
- Recognizing that the airport would remain partially open in a storm event.

The New York TRACON and surrounding en route airspace have much less capability for holding aircraft aloft than do Memphis or Orlando. As a result, the operational responses to convective weather and benefits of various decisions are quite different. For example, if New York ATC is concerned that arrival capacity may be lost in the near future they may impose a ground delay program (GDP) or ground stop (GS) for departures to New York because there is very little airspace capacity for holding planes. Such actions invariably lead to significant queue delays. Therefore, the ability to recognize that a fix and/or airport may remain open is very important at New York.

The projected ITWS delay reduction benefits at New York based on the Memphis/Orlando/Dallas “linear” model were approximately $30 M per year. As a result of the high delay reduction achieved in a number of cases involving queues, it was found that the New York ITWS convective weather delay benefits per year were approximately 3 times greater than had been projected based on the model of Equation 2. This major difference in the estimated benefits at New York emphasizes the need to carefully understand the detailed operations at a major terminal when carrying out a quantitative ITWS benefits analysis.

When attempting to compare delay reduction between different time periods, it is important to recognize that system benefits at the New York airports arise largely from changes in queues. Since queue delay is a highly nonlinear function of demand, capacity, and time duration, one must be prepared to carry out detailed analysis of these factors if one is to assess from delay statistics whether delay reduction is, or is not, being achieved in practice.

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[5] Although Dallas provided some benefits estimates for the initial study, there was far more operational usage of the ITWS at Memphis and Orlando when the Rhoda and Stevenson study was carried out.

2.3.3 Corridor Integrated Weather System (CIWS): Decision/Modeling Based on Direct Observations of Product Usage

The CIWS operational benefits studies (Robinson et al., 2004) 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 CIWS data collection design (Figure 5) used MIT 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, 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 that decision at the ATC facility to arrive at an average annual benefit for each ATC facility. Summing the individual facility benefits over all facilities would result in the annual benefit for a given decision.

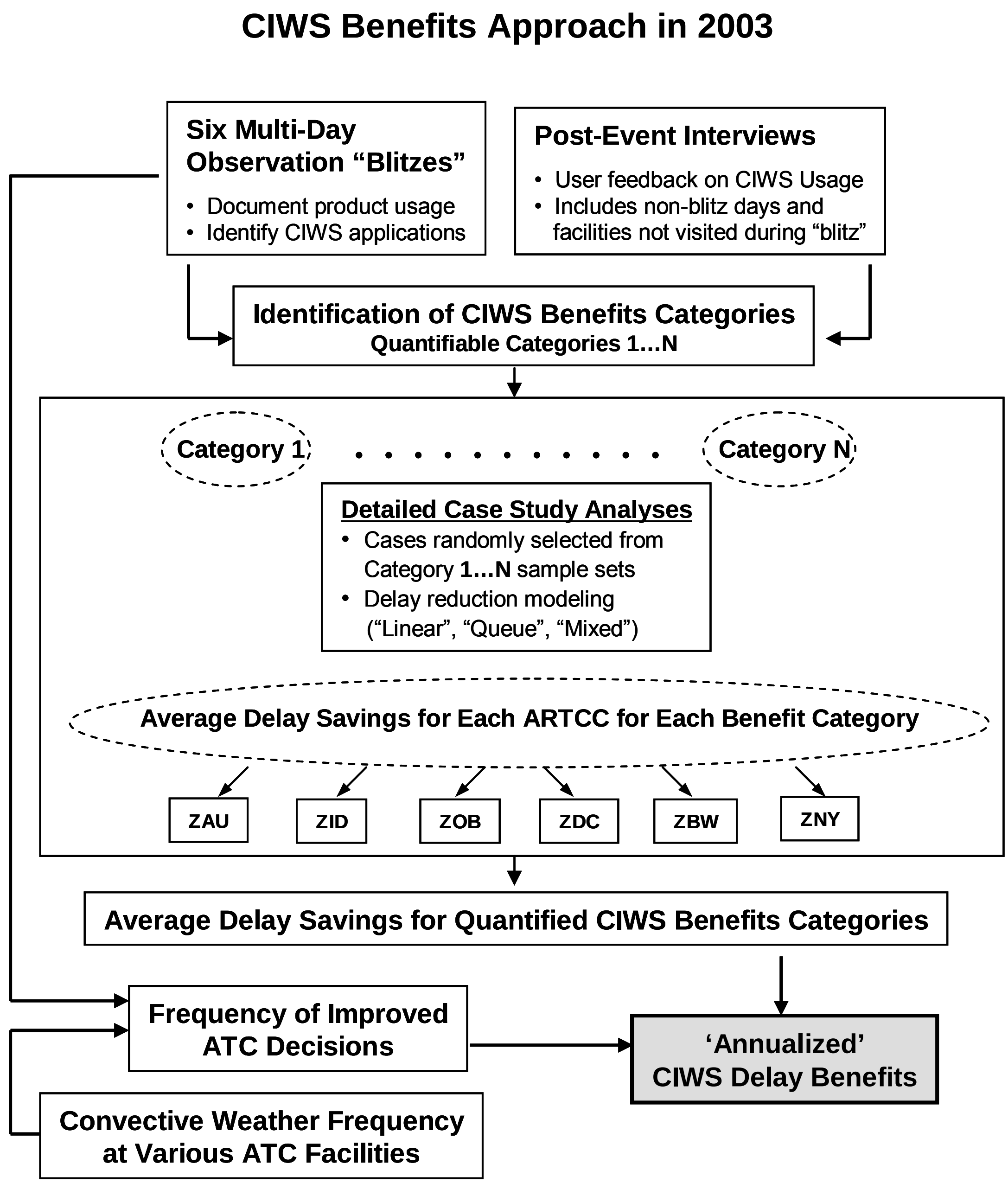

Figure 5. Approach taken in 2003 to estimate the CIWS Annual Delay Reduction Benefits. ZAU is Chicago ARTCC, ZID is the Indianapolis ARTCC, ZOB is the Cleveland ARTCC, ZDC is the Washington DC ARTCC, ZBW is the Boston ARTCC, and ZNY is the New York ARTCC.

The challenge was in determining the average benefit associated with a given decision in each facility. This was accomplished using a random sampling approach. Based on facility operations for 22 days, plus feedback from operational users on product usage on other days, a large number of instances of each type of benefit decision were identified for each ATC facility. A subset of these was selected for detailed analysis using a random number generator. Each instance was then analyzed to determine the benefits for a given situation. In many cases, the benefit consisted of increased capacity (e.g., a route was kept open or reopened earlier). In such cases, it is the measure of the delay that didn't occur (but would have had that additional capacity not been available) that yields the benefit. Estimating this additional delay involves determining an appropriate approach for handling the aircraft that used the route that was kept open. If the route in question were closed, alternative traffic management decisions would include holding aircraft at departure airports and/or using an alternative route from the origin to the destination. In short, one is dealing with a subset of the overall NAS network management problem that is briefly discussed in Appendix B.

2.3.4 Comparing User Feedback with Observed Traffic Management during Convective Weather Events

2.3.4.1 Near-term Validation of the CIWS Benefits Study

One of the concerns raised about the CIWS benefits approach was the reliance on the ATC user judgment regarding improved traffic management decisions during blitz observation periods compared with decisions during similar situations in the past. A study is currently underway to determine if improved ATC decision-making using CIWS can be observed by comparing the management of traffic during similar types of convective weather before and after CIWS was introduced. For example, one of the frequently cited high-benefit situations occurred when

- The storm reflectivity product on the Enhanced Traffic Management System (ETMS) and WARP indicated that routes were blocked by severe weather, but
- The combination of the CIWS precipitation and echo tops products showed that aircraft could easily fly over or around much of the weather.

Work is underway to obtain NEXRAD data and flight track archives for the CIWS test domain for the time period before CIWS was in use. These data will allow comparisons of en route airspace usage (as measured from aircraft flight tracks) before and after CIWS for cases that exemplify the above weather situation.

2.3.4.2 WARP Benefits Study

Such an approach was used in an unpublished study of the WARP delay reduction benefits by MCR, International. Interviews were conducted with air traffic controllers at the Houston and Indianapolis ARTCCs to determine how the availability of NEXRAD mosaics on the controllers' screens aided in the handling of aircraft. The controllers indicated that they used the improved weather depiction to do a better job of directing aircraft to appropriate gaps in storm systems and proactively rerouted aircraft in certain situations.

MIT Lincoln Laboratory personnel, using archives of ETMS data and a 1 nmi NEXRAD base reflectivity mosaic,[6] compared the handling of aircraft in the Houston ARTCC airspace before and after the WARP composite reflectivity mosaic was displayed on the controller screens. Unfortunately, although there were 12 time intervals from 9 different days of recorded data after WARP products were provided to the controllers, there was only a single pre-WARP storm case. In the post-WARP data sets, it was clear that controllers were directing aircraft through holes in storm systems and rerouting them to an appropriate path well in advance of storm encounters (i.e., as suggested by the green line in Figure 3). However, the single pre-WARP data case did not possess storm geometries required to allow assessment of how effectively controllers could direct planes around weather without WARP. Hence, the comparison of traffic handling before and after WARP was deployed was inconclusive, albeit the basic approach seems sound.

2.4 IMPACT OF OTHER SYSTEMS ON ASSESSING ITWS BENEFITS AT ATLANTA

The Atlanta ITWS was introduced at the same time as the CTAS in Atlanta. Additionally, there have been a number of traffic flow management initiatives (e.g., changes to the Collaborative Decision Making [CDM] convective weather strategic planning approach and forecasts, the use of the Flow Constrained Areas, Flow Evaluation Areas, and the Collaborative Routing Coordination Tool) that were also introduced either as ITWS was being installed at Atlanta or shortly after ITWS became operational. This causes major problems in performance evaluation using delay statistics. In this case, many different "treatments" for addressing the Atlanta convective delay "problem" were being tested at the same time, whereas in classical experimental design one would be very careful to test different combinations of the systems in various experimental units (Cox, 1958).

Chapter 1 in the book by Cox has several statements that are particularly appropriate for the convective weather benefits situation at Atlanta. Cox (1958) focuses on "experiments in which the effects under investigation tend to be masked by fluctuations outside the experimenter's control."[7] His recommendations for addressing such cases are:

1. "One seeks in experimental design to apply the alternative treatments to each experimental unit with an observation (or several observations) then being made on each unit."
2. "The main requirements for experimental design are:
   a. experimental units receiving different treatments should differ in no systematic way from one another,

[6] The data were provided by a commercial firm, Flight Explorer. The WARP reflectivity product on the controller displays is a NEXRAD layered composite reflectivity.

[7] Cox mentions an agriculture example where yields on adjacent plots in a field may vary by as much as ± 30% from their mean and a systematic difference of 5% between varieties of a given crop might be important.

b. random errors of estimation should be suitably small and this should be achieved with as few experimental units as possible,

c. the conclusions should have a wide range of validity,

d. the experiment should be simple in design and analysis, and

e. a proper statistical analysis of the results should be possible without making artificial assumptions."

The Atlanta ITWS experimental situation clearly differs from the conceptual approach outlined by Cox in that the other "experimental units" (i.e., sites that currently have ITWS) are clearly quite different from Atlanta, which is one of the busiest terminal complexes in the country.

It is highly unlikely that one could reasonably extrapolate from other similar extremely high-volume terminal complexes (e.g., Chicago or New York) to Atlanta, given the very major differences in the en route environment. Dallas is not a suitable alternative to ATL, since both CTAS and ITWS have been in operation jointly in Dallas for many years. In addition, Dallas has an enhanced ITWS forecast capability not yet available at Atlanta. The remaining extreme volume terminal areas (e.g., Los Angeles or San Francisco) have virtually no convective weather.

Therefore, there is no "experimental unit" to serve as an alternative to Atlanta that would not differ in major systematic ways in terms of convective weather delay sensitivity. Simply stated, there are no other airports in the NAS that are similar to Atlanta in terms of how convective weather impacts the airport and the exact tools that are available. In addition, there are very significant random errors of estimation which occur in ASPM delay statistics (Chapter 6). We know of no previous work that has addressed the issue of air traffic experimental data analysis for a situation where there is only a single unique "experimental" unit to which all of the treatments have been applied simultaneously and in which there are major variations in the desired performance metric (delays) due to factors not within the investigator's control.

2.5 CHALLENGES IN ASSESSING ATLANTA ITWS BENEFITS BY COMPARISON OF DELAY STATISTICS

Major FAA performance metrics are couched in terms of reduction in delays. Hence, there is a very strong emphasis within the FAA to demonstrate that convective weather delay reduction is being achieved by analysis of actual delay data. Simply comparing ATC delays before and after introducing a convective weather delay reducing system is equivalent to asserting that *correlation* (if it existed) between the introduction of a system and a change in the overall delays *is evidence of causality* that could be associated with the system under test.

As was discussed in section 2, the measured delays for flights arriving or departing from Atlanta are impacted by many factors, including:

- Weather differences (both convective and non convective) in the test region,

- Demand (e.g., as exemplified by the Department of Transportation high level discussions with airlines regarding scheduling at Chicago O'Hare airport in 2003-04),
- Fleet mix (which impacts use of runways at airports and en route sectors[8]),
- Policies on management of en route congestion caused by convective weather (e.g., Spring 2000, "growth without gridlock"),
- Airline scheduling and operations procedure changes (e.g., changing the scheduled block time for a flights to Atlanta and/or deciding when a flight would be cancelled),
- Introduction of other systems (e.g., Collaborative Convective Forecast Product [CCFP], traffic flow management), and
- Weather outside the ITWS coverage region (e.g., en route convection, low ceiling/visibility [C/V] and/or winds and/or convective weather at the airports that are origins for Atlanta arrivals or destinations for Atlanta departures).

Thus, one of the major challenges in using a comparison of delay statistics before and after ITWS was introduced at Atlanta, as a way to assess the delay reduction provided by the Atlanta ITWS, is accounting for, or minimizing the impact of, the factors noted above.

2.5.1 Choice of delay statistics - OPSNET delays

Another important issue in delay analysis is the choice of delay statistics. Historically, the principal source of information was the OPSNET database. A reportable delay recorded in OPSNET is defined in FAA Order 7210.55B as, "Delays to Instrument Flight Rules (IFR) traffic of 15 minutes or more, experienced by individual flights, which result from the ATC system detaining an aircraft at the gate, short of the runway, on the runway, on a taxiway, and/or in a holding configuration anywhere en route shall be reported." Such statistics include delays due to weather conditions at airports and en route, FAA and non-FAA equipment malfunctions, the volume of traffic at an airport, reduction of runway capacity, and other factors. Flight delays of less than 15 minutes are not reported in OPSNET, but may be recorded by Air Traffic facilities. Non-reportable delays are delays caused by pilot-initiated en route deviations around adverse weather (as opposed to reportable delay for weather conditions at an airport), delay caused by mechanical or other aircraft operator/company problems, and delay for taxi time controlled by non-FAA entities (e.g., company/airport ramp towers). International delays are caused by initiatives imposed by facilities outside the United States. International delays are recorded in the OPSNET database, but are not separately distinguished from delays incurred in the United States.

[8] One of the very significant changes in the past few years has been the replacement of turbo prop aircraft by regional jets. The regional jets fly at much the same altitudes as larger jet aircraft and require similar runway lengths. As a result, even though there was no change in the total number of aircraft, there was a significant increase in demand in en route airspace, leading to additional delay in congested en route sectors. The airports experienced an increase in demand for the longer runways, leading to longer queuing delays on the main runways such as runway 22/4 at EWR.

Delays are broadly categorized as terminal or en route delays. Terminal delays are the result of conditions at the departure or arrival airport and are charged to the appropriate airport. En route delays occur when aircraft incur airborne delays of 15 minutes or more as a result of an initiative imposed by a facility to manage traffic. En route delays are recorded by the facility where the delay occurred and charged to the facility that imposed the restriction.

OPSNET data has some good features. The database extends back many years and contains causality information associated with the delays (in particular, which delays are attributed to weather), as well as the category of the delay (e.g., arrival and en route, departure, traffic management system).

However, there are also major deficiencies with OPSNET (Lamon, 2004):

- Delays are only reported if they are at least 15 minutes in a facility. Total delay to a flight that is delayed 10 minutes in each of a number of facilities is not reported.
- Gate delays are not recorded.
- Reporting methods are subjective and differ widely by facility (e.g., major airports such as Newark Liberty International Airport [EWR] and Chicago O'Hare International Airport [ORD] report a much higher fraction of delays than do many less busy airports).
- Delays can be inaccurate due to human error in data entry, and
- Delays due to pilot/airline initiated routing around convective weather are excluded. (This would include reroutes developed under collaborative decision making.)

Given these problems, the OPSNET database is not currently regarded as useful for highly detailed quantitative benefits assessments and was not used for any of the Atlanta ITWS benefits studies reported here.

2.5.2 ASPM Delay Statistics

The recent trend in delay analyses has been to use the ASPM database. The ASPM database combines data from the FAA en route system (Host) on aircraft positions, flight plans, Official Airline Guide (OAG) schedules, air carrier Airline System Quality Performance (ASQP), and (for some of the major carriers[9]) Out/Off/On/In (OOOI) data consisting of:

- Actual gate departure time ("Out")
- Actual flight takeoff time ("Off")
- Actual flight landing time ("On"), and
- The actual gate arrival time ("In)

[9] Two major carriers report OOOI data in near real time via the ARINC data link. OOOI times for four other carriers are reported once per month as a part of the reports to the Department of Transportation/Bureau of Traffic Statistics.

Thus, it is possible to make more detailed, objective, quantitative studies of where a flight delay occurred than is the case with OPSNET. On the other hand, there is limited causality information associated with delays. Additionally, for flights that do not have OOOI data, the estimated takeoff and landing times are based on the Host computer estimates. The accuracy of the Host computer estimates of “Off” and “On” times varies widely due to differences in coverage of the airports by the en route surveillance radars.

The ASPM web site (www.apo.data.faa.gov) provides summary statistics for user selectable filter parameters that include arrival and destination airport, time of day, phase of flight, and type of delay. For example, one can obtain the fraction of arrival or departure flights delayed 15 minutes or more and various statistics regarding the delay (e.g., mean, median, 90th percentile) associated with delayed flights. In addition, one can access the individual flight records and compute delays with a different set of criteria than are used in the summary statistics. Given the various OPSNET problems discussed above, plus the objective, much richer set of options for delay analysis offered by ASPM statistics, the delay statistics analysis studies reported here have focused on the use of ASPM.

Nevertheless, it is important to note that one must be quite careful in the choice of ASPM statistics for convective weather delay analysis, given that where a delay is taken is not necessarily the location of the weather that caused the delay. Table 4 summarizes the relationship of the type of delay as characterized by ASPM to the location of convective weather and the location where air traffic management control is exercised.

TABLE 4
Relationship of ASPM Statistics to Locations of Convective Weather

	Convective Weather Location			
Where Delay Due to Convective Weather is Taken	**Origin Airport**	**En Route**	**Destination Terminal**	**ASPM statistic?**
Departure Gate	Rare	Yes	Yes	Yes
Taxi Out	Yes	Yes	Yes	Yes
Excess Distance of Filed Flight Plan	No	Yes	Rare	No
Excess Flight Time Relative to Filed Flight Path Time	No	Yes	Yes	Yes
Taxi In	No	Possible (gridlock)	Possible (gridlock)	Yes

Note that departure delays can arise from convective weather at many locations. The excess flight distance associated with the filed flight plan is discussed below.

ASPM arrival delay relative to schedule = sum of above five delays

"Downstream" delay = late arrival of aircraft and/or crew → late gate departure on next leg

"Block Delay" = gate-to-gate delay (Note: this does not include gate departure delay)

The issue of delays associated with the filed flight plan warrants discussion. Most of the published analyses of ASPM statistics (e.g., to identify benefits of traffic flow automation or User Request Evaluation Tool) have focused on the use of ASPM delay relative to flight plan. The delay relative to flight plan is quite reasonable in non-convective weather, since it significantly reduces the role of winds aloft as a source of delays (both positive and negative).

However, traffic flow management strategies used to deal with convective weather often involve filing flight plans that are significantly longer than usual to avoid regions of convective weather. This generally creates a significantly longer distance flown than would have been the case without convective weather. Even though there is significant extra airborne flight time incurred by filing and flying these longer routes, no airborne delay will show up in ASPM for these cases if one uses delay relative to filed flight plan (provided winds are not a factor). Figures 6 and 7 both illustrate how the filed flight plan may represent a significant factor in the arrival delay relative to schedule for a flight. Note also in Figure 7 that flights from Atlanta may be delayed due to adjustments made to traffic flows to avoid convective weather that is located at great distances from Atlanta.

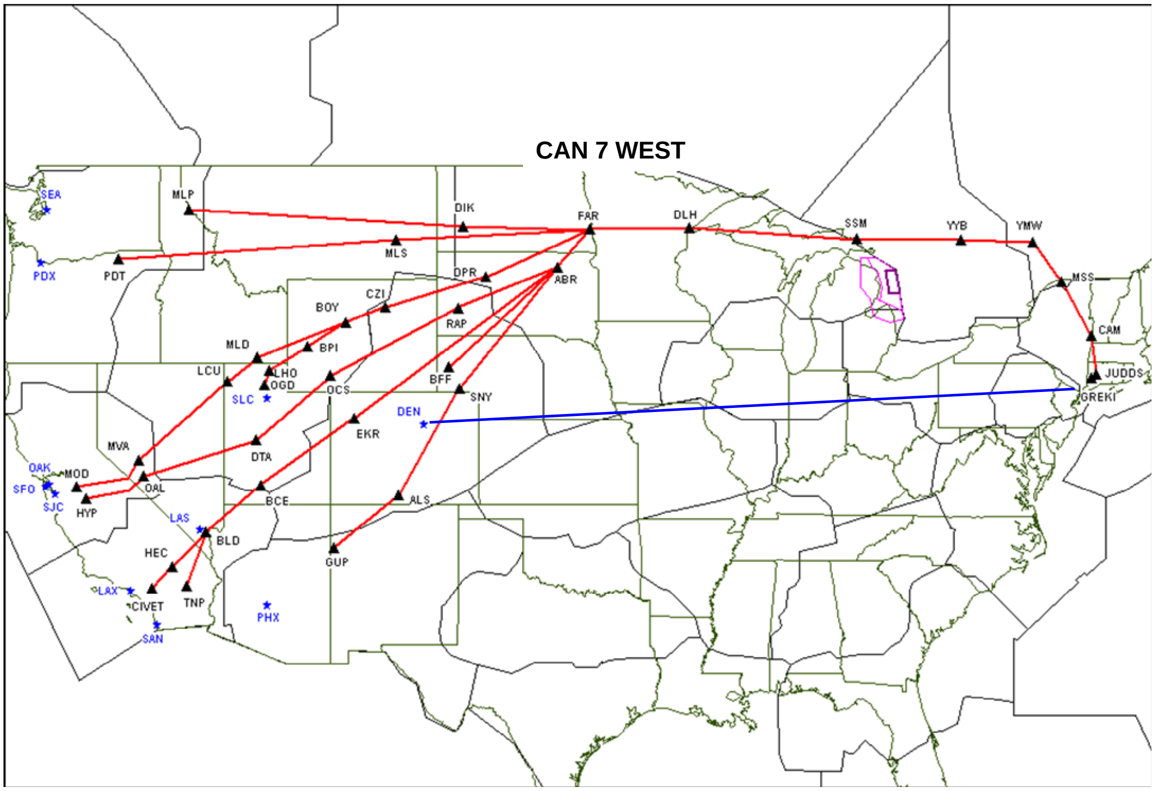

Figure 6. Illustration of how convective weather and forecasts of convective weather can result in a significantly greater flight time on the filed route than would have occurred otherwise. Due to forecast convective weather in the Great Lakes Corridor, a flight from Denver to New York is instructed to use the CAN 7 playbook route (red line) as opposed to the normal route (blue line). If the actual weather is less severe than forecast, this reroute causes unnecessary airborne time which results in a late arrival relative to schedule. If one uses only the ASPM statistics of flight time relative to the filed flight plan, this additional source of delay may be difficult to ascertain from the ASPM statistics alone.

We believe that ASPM is an excellent source of information for aviation data and delay metrics. But considerable care must be taken that ASPM users understand and account for its limitations. We also believe that ASPM has very limited convective delay causality information. Hence, other data sources must be used in conjunction with ASPM in analyzing convective delays. In Section 8.2, we outline an approach to validating ITWS benefits by joint use of ASPM, weather radar, and flight track data.

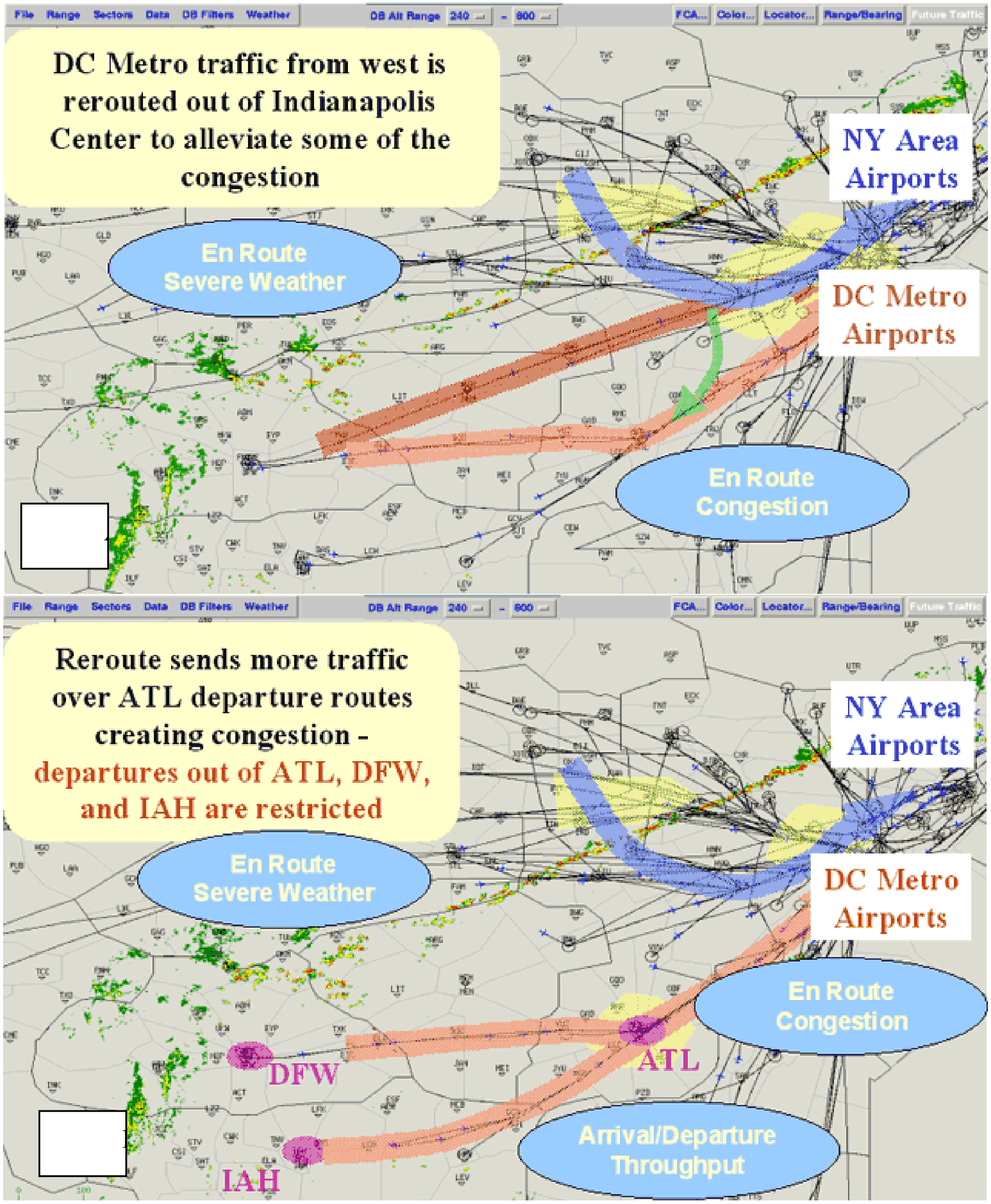

Figure 7. Another example of rerouting to avoid en route congestion due to convective weather, causing the filed flight path to be much greater than the normal flight distance. Note also that in this case there would be departure delays at Atlanta arising from reroutes due to severe weather in the Great Lakes Corridor (MITRE analysis from OEP Web site).

2.6 THE "AVAILABLE POOL" OF BENEFITS FOR ITWS AT ATLANTA

One of tenets of the Office of Management and Budget (OMB) guidelines to federal agencies is that a program such as ITWS must describe the business case for the investment, including performance goals that are linked to the agency's annual performance plan, a discussion of the agency's mission and strategic goals as they relate to the specific performance goals of the investment, and the performance measures that will be used.

The performance goals for the system need to map to the gap in the Agency's strategic goals and objectives that this project is designed to fill. These are the internal and external performance benefits this project is expected to deliver to the agency. The goals must be clearly measurable project outcomes and, if applicable, project outputs[10]. One of the important elements of the performance metric is a description of the "baseline" related to the performance goal.

Since a principal motivation for the Atlanta ITWS is to reduce weather related delays at Atlanta, one of the important issues for the analysis of ITWS benefits vis-à-vis the OMB guidelines is an estimate of the possible delay benefits pool that might be addressed by the ITWS.

Past attempts at estimating the possible weather-related benefits pool (ATO-P unpublished slides in 2004) have argued that one could estimate the possible ITWS delay benefits pool using the following approach.

1. Estimate the weather related delays in the NAS.
2. Make an allocation of the weather related delays to en route and terminal areas.
3. For terminal areas, estimate the fraction of delays due to low ceiling and visibility conditions versus the fraction that are due to thunderstorms (convective weather).
4. Estimate the fraction of thunderstorm delays that are potentially avoidable for thunderstorms in terminal and en route airspace.

This issue of how much delay is potentially avoidable through investments in terminal and en route weather decision support systems is exceptionally important. Unfortunately, the methodology and data to support such calculations are far from mature at this point. Estimating the weather related delay in the NAS from analysis of ASPM statistics, FAA traffic flow management logs, and weather data may be possible. One can seek to find a set of days where the NAS had very low weather delays. For those days, one can determine an average "two-sided" arrival delay[11] per flight for all scheduled flights in the ASPM database. That day hopefully reflects the delay due to congestion and other non related-weather causes.

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[10] The OMB does not allow the performance goals to include completion date of the module or project, or general goals such as "significant, better, improved" that do not have a quantitative or qualitative measure.

[11] "Two-sided" arrival delay considers all arrival times relative to schedule, whether positive or negative. On a weather free day, aircraft often arrive early relative to schedule. Classically only "one-sided" delay is considered; if planes arrive early they are considered to have zero delay.

The difference between that “minimum” average “two-sided” arrival delay per flight for all scheduled flights in the ASPM database and the average “two-sided” arrival delay per flight for all scheduled flights in the ASPM database on other days presumably is an estimate of the average weather-related delay per flight. One can then scale this estimate up by the number of scheduled flights in the NAS over a year. Since a significant amount of the “minimal” arrival delay may reflect congestion at major airports, it may be important to consider the differences associated with changes in demand on weekends and different seasons of the year. A first order analysis of summer NAS weather related delays by the approach outlined above is provided in Chapter 5 of this report.

Unfortunately, when attempting to complete the three remaining steps in the suggested approach to estimating “avoidable delay”, one encounters major difficulties.

(1) Allocation of delays to terminal versus en route domains

For days where there is no convective weather in the NAS (perhaps many days in the winter), there would be two main causes of weather-related delay: strong winds aloft or at the surface and low/ceiling visibility conditions (this would include snowstorms). In Figure 8, we show the results of allocating terminal delays at the New York airports based on the New York ITWS demonstration site observations (Allan et al., 2001). Note that strong surface winds in fair conditions are a significant source of delays. In principle, one could separate the delays from strong winds aloft on en route flight from those due to terminal-related winds. However, it would be difficult to separate the terminal delays due to strong surface winds from low ceiling/visibility delays if the two occurred simultaneously since:

- they both contribute to reducing the effective arrival capacity, and
- the queue delay for arrivals is a strongly nonlinear function of the arrival capacity as we showed in Equation 1.

The case where there is convective weather in the NAS is even more difficult, since the NAS is a network which typically has multiple queue delays due to capacity losses in both terminal and en route airspace. Additionally, the convective weather and low ceiling/visibility conditions can occur during the same months (Figure 9) and even the same time (as documented in Appendix A of Allan et al., 2001).

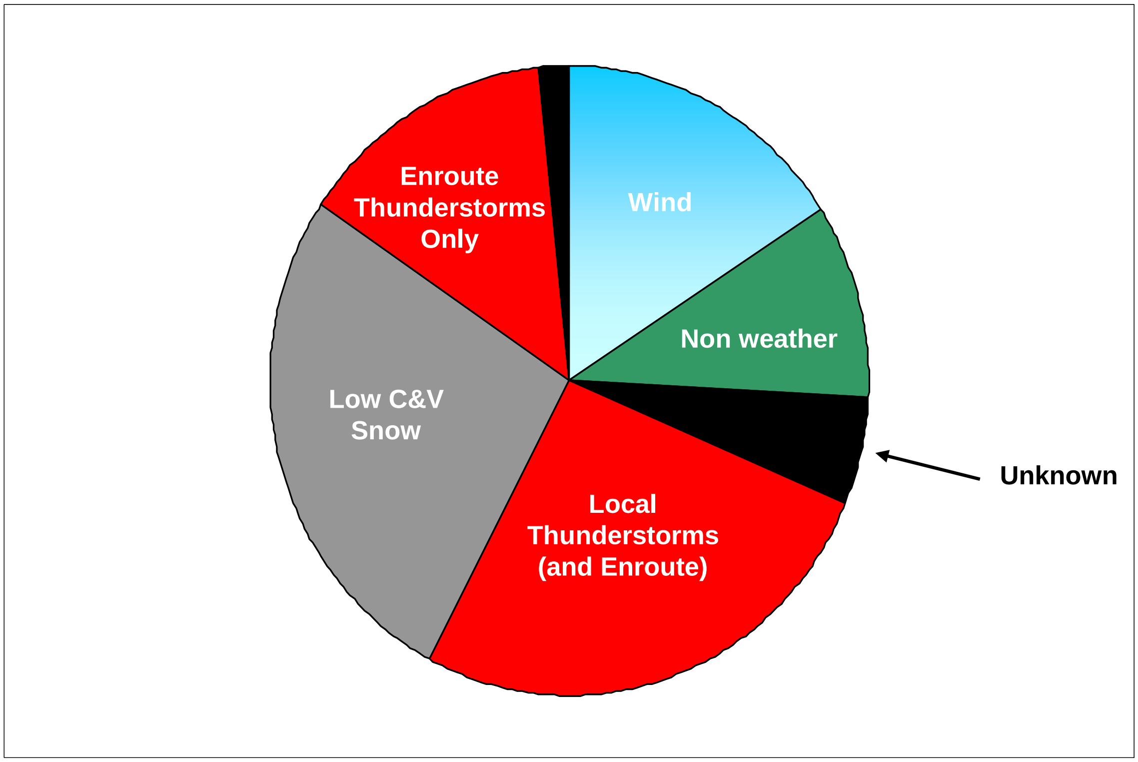

Figure 8. Key factors in delays at the New York airports (from Allan et al., 2001). In many of the cases when thunderstorms are within the New York terminal area, there were also thunderstorms in the surrounding en route airspace.

As a result of the CIWS benefits studies (Robinson et al., 2004) and the operational experience with the Route Availability Planning Tool (DeLaura and Allan, 2003), we have learned that it is rare that there is only convective weather within a terminal area and no convective weather outside that region. Rather, the far more likely prospect is that convective weather exists both inside and outside the terminal area at the same time, such that there are operationally significant losses of capacity both in terminal and en route airspace. In many of the earlier studies on delay causality (e.g., Weber et al., 1991), the researchers focused primarily on occurrences of terminal weather because the only readily available data on weather conditions was Meteorological Actual Reports (METARs), which is typically only available at the airports. Hence, there was an implicit assumption in those studies that convective weather at or near the airport was the principal cause of delays. As a result of the insights gained since 1991 in the CIWS domain, plus the major changes in the NAS in the past 13 years, we now conclude that the estimates in Weber, et al., (1991) are not applicable to the current NAS.

(2) Allocation of delays to various types of weather

To the extent that the earlier analyses assumed that no convective weather was present in cases of high surface winds and/or low ceiling and visibility, the delays that were observed could be fairly attributed to these non-convective causes. However, there are cases at New York where convective weather is in or near the terminal area while the airport is in an IFR condition. (Figure

9 shows that in some months both convective and non-convective weather cause delays.) In such cases, there clearly are multiple constraints on the flow of traffic such that very detailed analyses are needed to determine the principal cause of delay. For example, during periods when the arrival and/or departure operations rates are less than the published IFR capacities for the runway configuration in use, one might assume that convective weather is the principal cause of the delay.

Once the convective weather ends in both en route and terminal airspace, one might then assume that the IFR conditions (if they persist) are the principal cause of constraints. However, generally a large number of aircraft are waiting to land or take off due to the earlier convective weather. The delays to the planes that land or take off after the convective weather ends represent a complicated combination of both convective and non-convective weather causes. (That is, the IFR conditions at the end of the convective weather event may cause the convection-induced delays to be much larger than they would be if the weather is fair when the convection ends.)

(3) Estimation of the fraction of delay which is potentially avoidable

We know of no credible quantitative analysis of the extent to which convective weather delay is "avoidable". There have been studies of the degree to which delays due to low ceilings and visibility might be reduced if there were highly accurate ceiling/visibility forecasts. Under these conditions, GDPs could be ended proactively so that there was no unused capacity at the end of the GDPs (Allan et al., 2001, Wilson and Clark, 1997).

Research to estimate avoidable delay for convective weather is just beginning (Chandra et al., 2004) and no <u>reliable</u> quantitative estimates are available at this time.

2.7 SUMMARY OF PAST WORK ON ESTIMATING THE "AVOIDABLE DELAY" FOR SYSTEMS SUCH AS THE ATLANTA ITWS

In summary, the literature suggests that it is possible to estimate the overall delay due to adverse weather within the NAS. Explicit estimates of this are provided in Chapter 5. In many (but not all) cases, it may be possible to estimate the delay due to a specific cause (especially low ceiling/visibility or high surface winds or convective weather) if there are highly localized weather problems. Assigning the overall NAS convective weather delays to terminal versus en route domains is neither possible nor technically appropriate since

- There is often a simultaneous loss of capacity in both domains and
- The NAS is increasingly subject to network queue delays that are a highly <u>nonlinear</u> function of the various terminal and en route capacities, as well as of the demand.

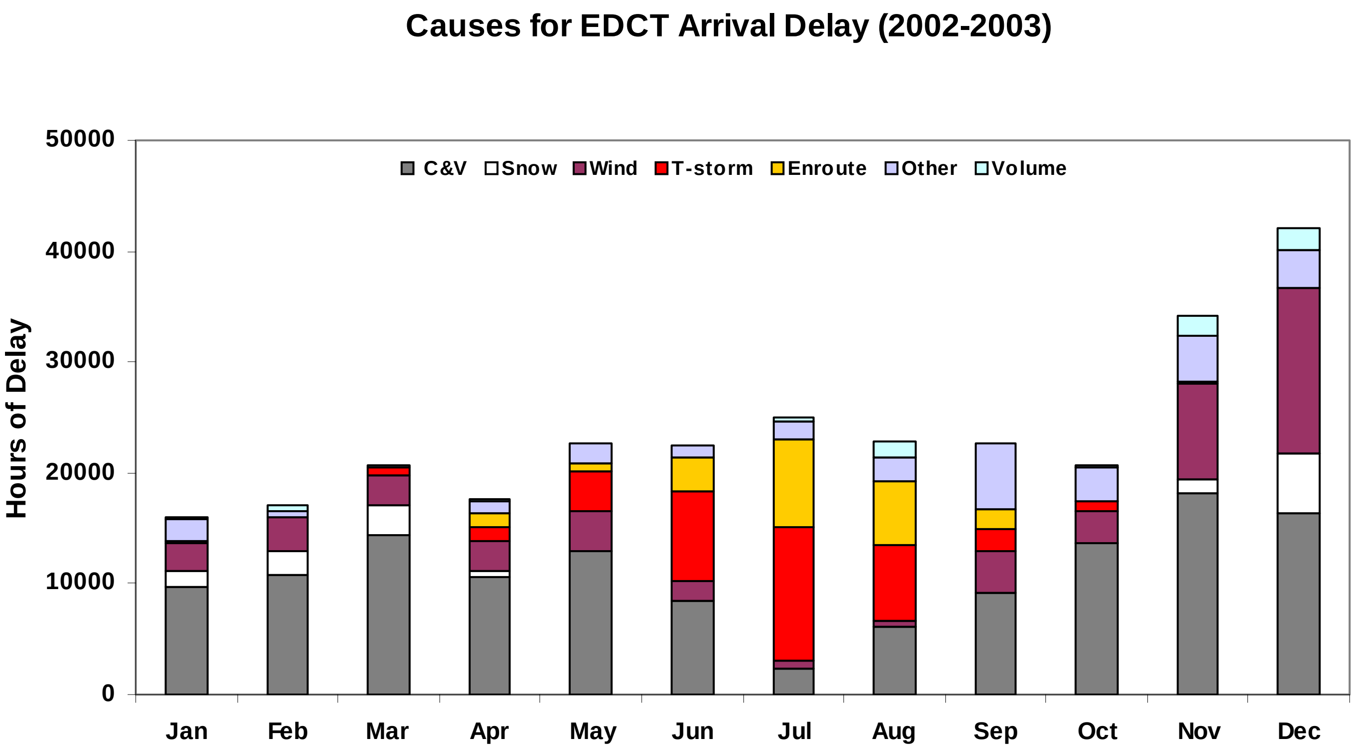

Figure 9. Causes of Estimated Departure Clearance Time (EDCT) arrival delays at New York (2002-03) from the ASPM database. EDCT is only one component of delay and an EDCT program may have been invoked to address multiple simultaneous weather impacts.

3. ATLANTA AIRPORT OPERATIONS

3.1 ATL FAIR-WEATHER OPERATIONS

ATL airport was the second busiest airport in the United States in terms of total operations for 2003. It has four main runways; two on the north side of the airport and two on the south side of the airport. The two outer runways are used for arriving traffic, while the two inner runways are used for departing aircraft. With this configuration, ATL can essentially operate as two separate airports. Traffic destined to/from the north and west uses the north side of the airport. Traffic destined to/from the south and east uses the south side of the airport (Figure 10).

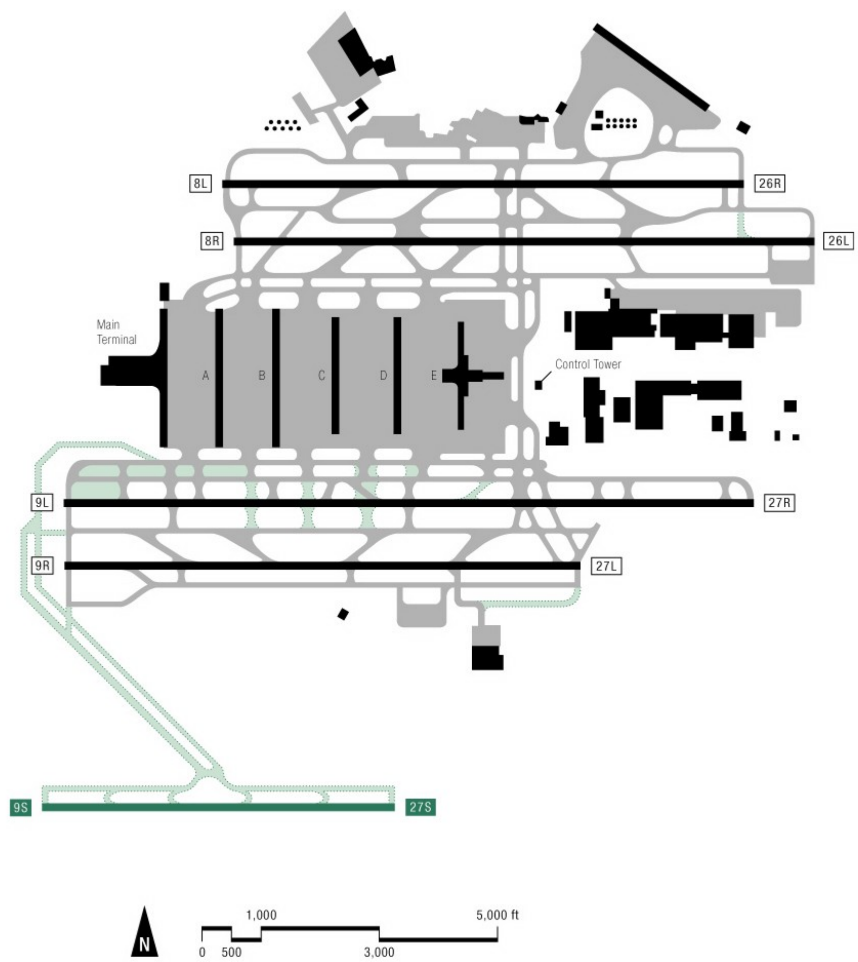

Figure 10. Atlanta airport runway configuration. Runway 9S-27S (at the bottom of the picture) will not be in operation until the end of 2005 or early 2006.

ATL is a hub airport for Delta Airlines. There are over eight concentrated arrival/departure pushes during the day. Even on days when the airport is operating with no weather constraints, these concentrated peaks in traffic push demand well beyond the airport capacity. According to the 2004 FAA Benchmark Capacity Report[12], the current fair weather capacity benchmark at ATL is 180-188 flights per hour in good weather. Figure 11 shows that this benchmark is approached or exceeded three times per day on average. Therefore, it is not surprising that airborne holding occurs several times a day in fair weather.

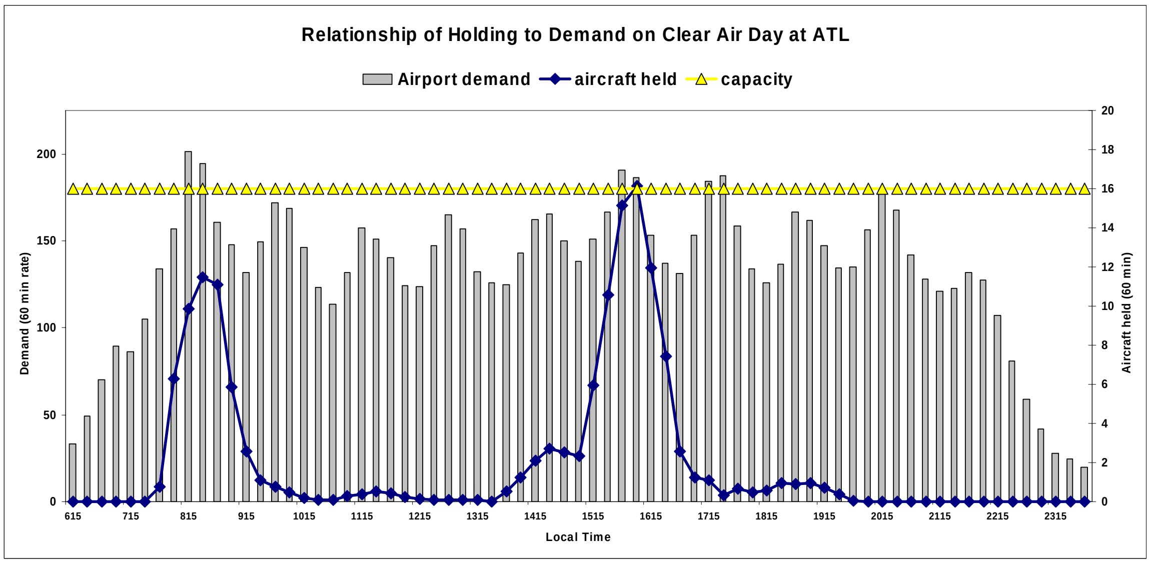

Figure 11. Scheduled airport operations (arrivals + departures) at Atlanta. Holding (solid blue line) information is taken from FAA database of ZTL holding information. A capacity of 185 aircraft per hour is shown as the yellow line.

As part of our studies of delay statistics-based benefits analysis (Chapter 5) it was necessary to determine typical delay at ATL on days with fair weather. ZTL provided a database of holding delays for 2003. To determine the relationship of holding delay to demand on days with good weather, we examined a total of 37 days in October-November of 2003 when there were no known weather impacts at ATL. The median number of aircraft held as a function of local time and total airport demand is shown in Figure 11. There are two well-defined peaks in holding during the day, the first between 8:00 AM and 9:00 AM and the second between 3:30 PM and 4:30 PM. These two periods correspond to peaks in arrival demand that overlap concentrated peaks in departure demand.

There is a period around 5:30 PM when total airport demand exceeds capacity but holding rarely occurs. This is because the airport demand during that time is heavily weighted towards departures. Conversely, around 7:00 PM, a small number of arrivals hold due to a heavy arrival push that occurs without a corresponding heavy departure push. This ability to tradeoff between

[12] www.faa.gov/events/benchmarks/

arrival and departure capacity is fairly typical of congested airports. The tradeoff is commonly referred to in the literature as a Gilbo curve (Gilbo, 1993 and Gilbo, 2000). This relationship has important implications for modeling delay impacts due to convective weather and is discussed in Chapter 4.

Figure 12 shows arrivals being metered into the Atlanta TRACON over four corner posts (i.e., ATAs: DALAS, LOGEN, HUSKY, TIROE) fed from their respective Standard Terminal Arrival Routes (STARs): RMG, MACEY, SINCA, LGC. In our analysis of fair weather days at ATL, we found that the south side STARS of SINCA and LGC had the highest number of holding aircraft. The radius of Atlanta TRACON is roughly 40 nmi and aircraft rarely are held in this airspace. Departures leave Atlanta TRACON via eight departure fixes. These are frequently merged or given Miles in Trail (MIT) restrictions depending on how heavy the traffic volume is.

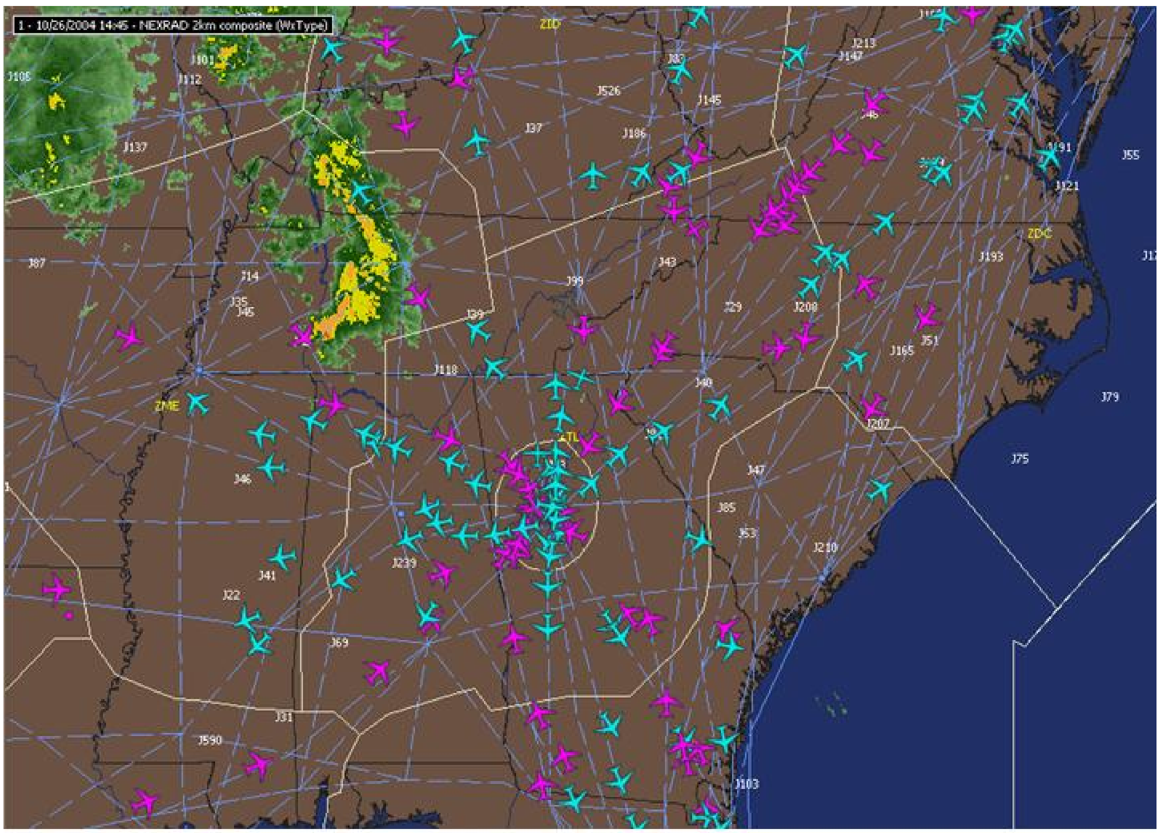

Figure 12. Flight Explorer image of ATL traffic flows on a typical day with minor convective weather. Departures are indicated in blue and arrivals are indicated in pink.

Interaction between ATL traffic and "over flight" en route traffic is also an important factor in the Atlanta ITWS benefits assessments. Figures 13 and 14 show the overall traffic within ZTL (at roughly the same time as Figure 12) and major over-flight tracks. There are a number of major tracks that pass within 100 nmi of Atlanta. The density of traffic on these routes can be an important factor in determining ATL convective weather delays due to competition for the available capacity.

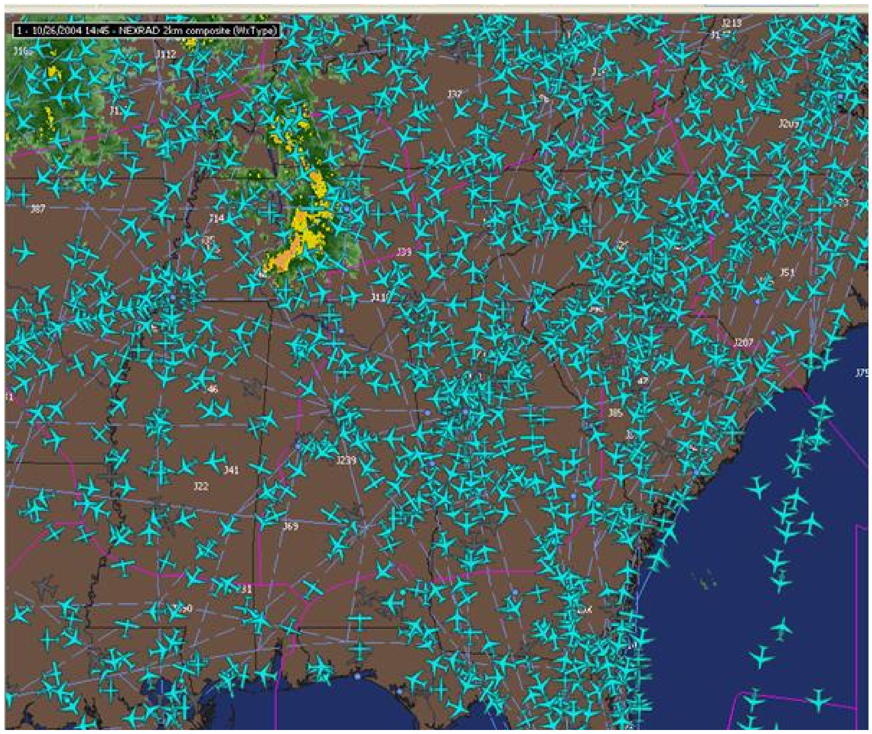

Figure 13. Traffic flows in and near ZTL.

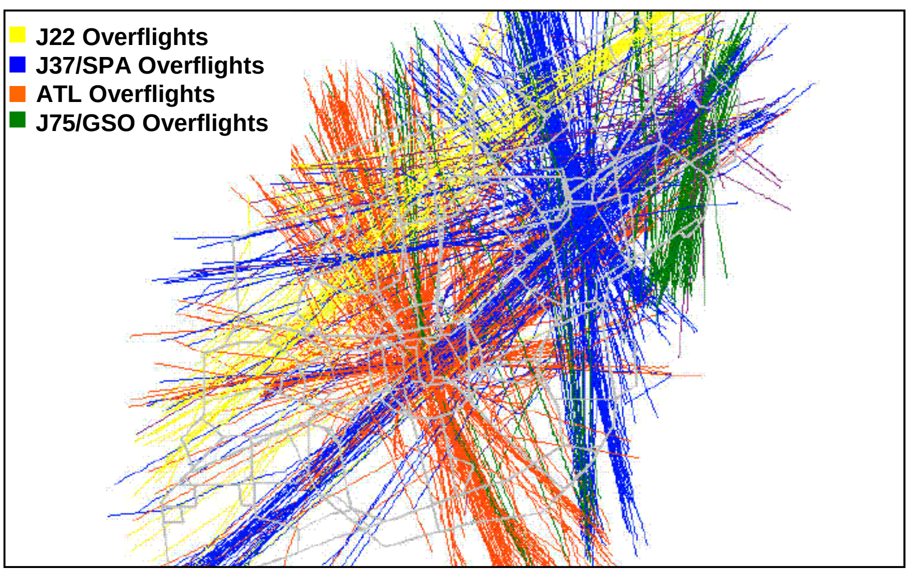

Figure 14. Over-flight tracks for ZTL.

Figure 15 shows that there is insufficient capacity at the Atlanta arrival fixes and runways to handle all of the arrival demand in fair weather during peak periods. Hence, the normal arrival demand can significantly exceed the available capacity when convective weather causes a loss of airport and/or TRACON and/or transitional en route airspace[13] capacity at Atlanta. This is a very significant factor because queue delays are almost certain to occur when convective weather arises during the peak arrival periods. As a consequence, the resulting delays will be very sensitive to the exact details of effective capacity, demand, and duration of the capacity loss (Chapter 2).

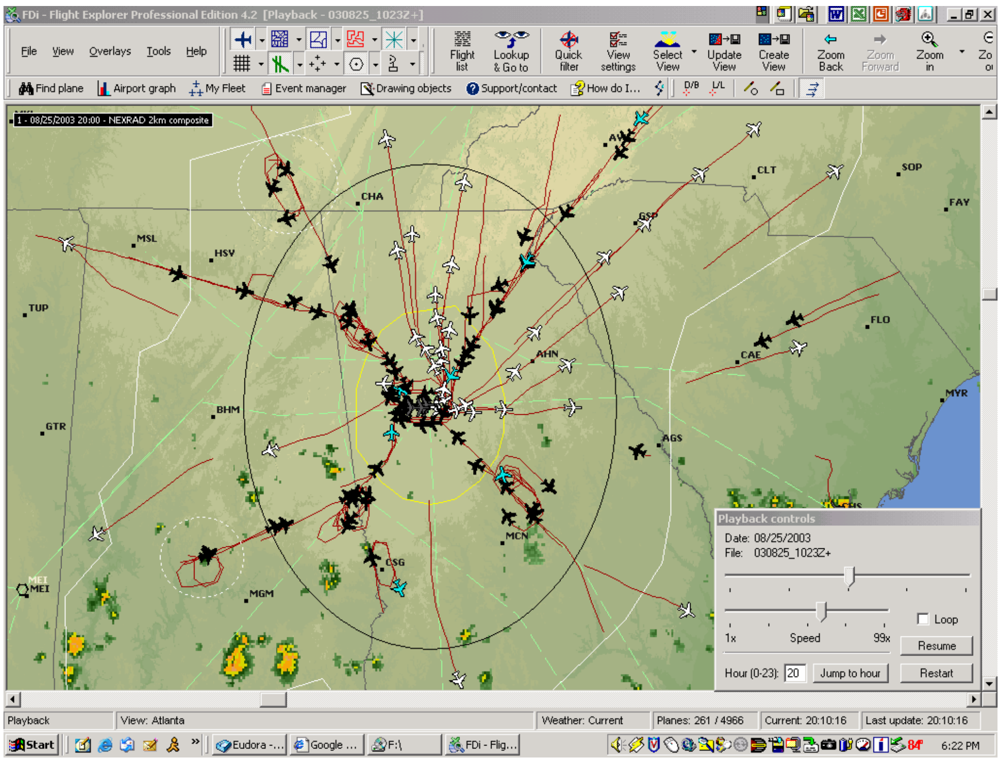

Figure 15. Aircraft tracks at Atlanta on a fair weather day (25 August 2003). Note holding patterns outside the TRACON (yellow ellipse) and even outside 100 nmi from airport (black ellipse) due to high arrival volume.

[13] Transitional en route airspace is the airspace in which the aircraft transition from en route flight levels to the altitude at which they enter the terminal area. This area is typically between 100 nmi from the airport and the boundaries of the terminal area (e.g., about 40 nmi from the airport).

3.2 ATL OPERATIONS WHEN THUNDERSTORMS ARE PRESENT

Thunderstorms have a considerable impact on operations at ATL. From interviews with traffic managers, we learned that a flexible operating policy is employed whenever possible when thunderstorms impact operations. Traffic flows are dynamically adjusted as needed. Arrival holding is used to keep pressure on the airport, as opposed to more disruptive ground stops. Fix balancing with MIT restrictions is used to allow for greater flexibility in managing arrival/departure airspace.

Figure 16 shows a line of storms crossing through Atlanta TRACON and passing over ATL. Holding stacks can be observed at all four corner posts, while departures are flushed from the airport to the weather-free west and to the east through gaps in the line of storms. Figure 17 shows another situation where aircraft are held in a first-tier ARTCCs (i.e., the Memphis ARTCC [ZME]) adjacent to ZTL. From our analysis of 2003 data, holding delays are five times greater on days with thunderstorms than on days when there are no weather impacts (Table 5). Since the database we obtained from ZTL does not include first-tier holding for ATL, total holding delay due to thunderstorms is significantly underestimated.

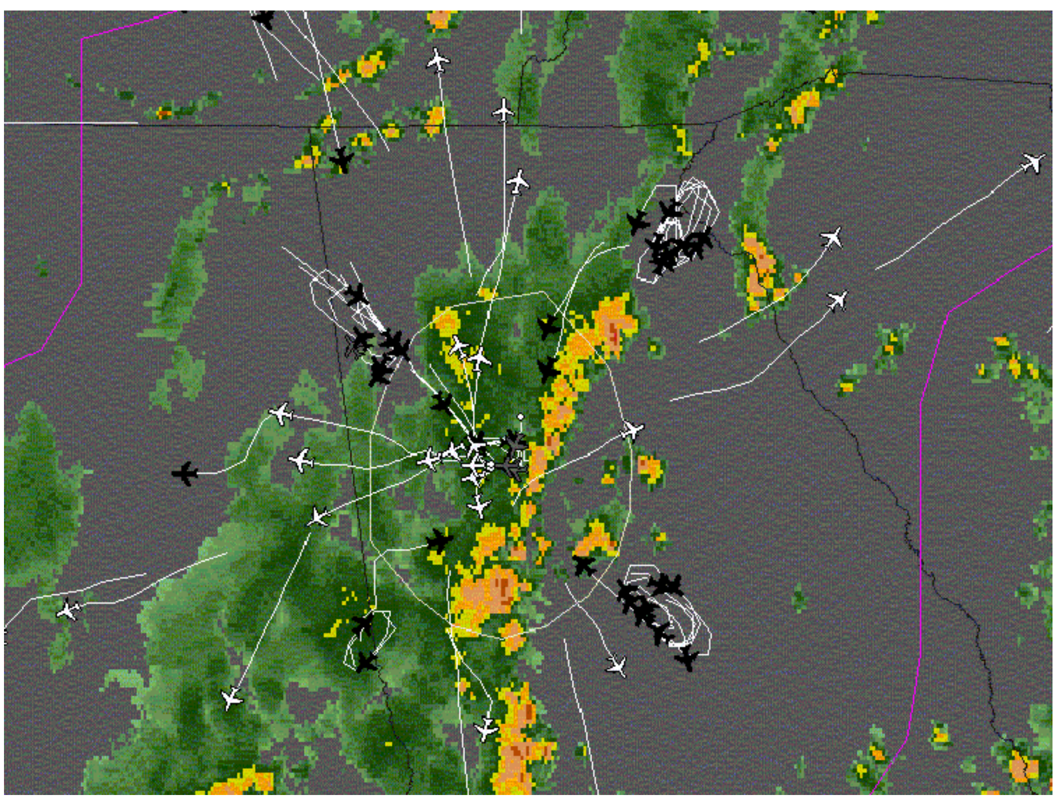

Figure 16. Flight Explorer image of holding patterns near arrival fixes as line of weather moves through the Atlanta TRACON.

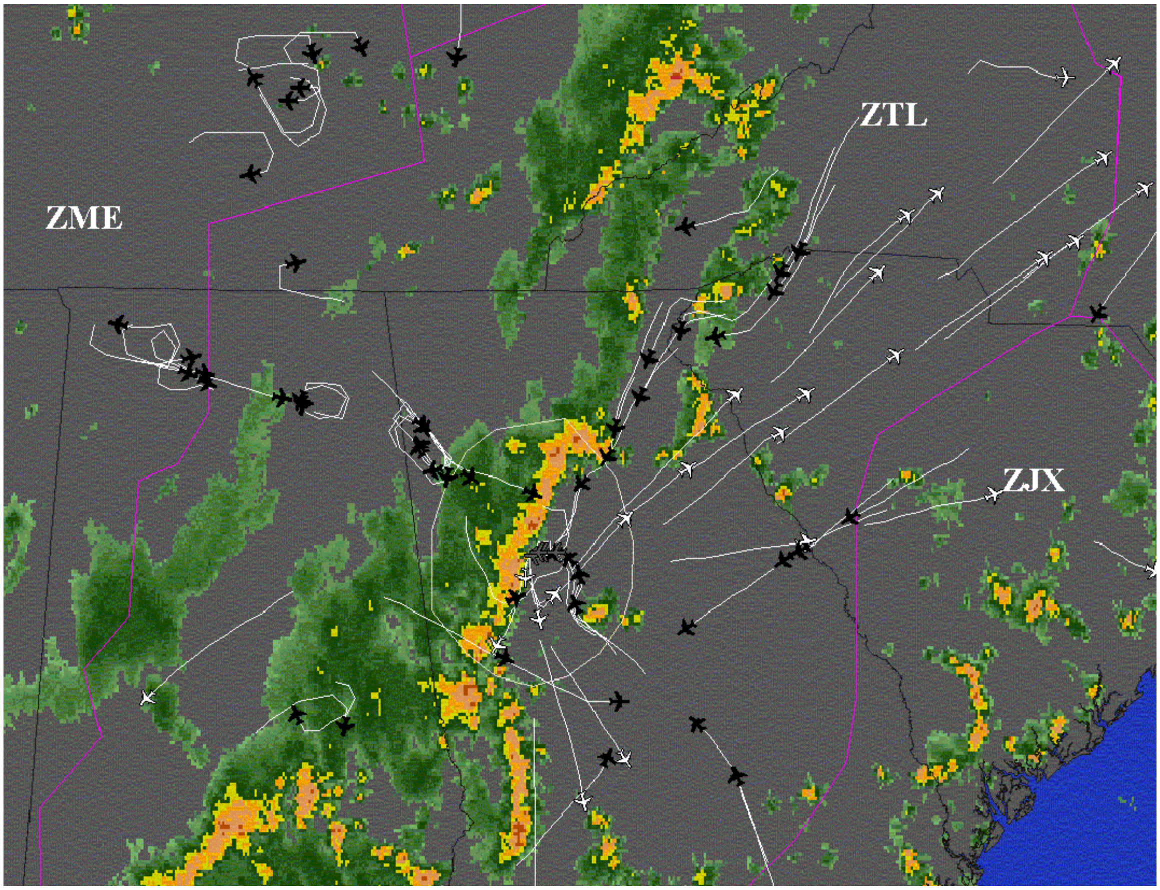

Figure 17. Flight Explorer image of holding patterns for ATL traffic in ZME airspace.

TABLE 5
Holding Statistics Using Median Value for Days with Thunderstorms (TS) and Days with Fair Weather (Clear Air)

	Number Held	Min/Day	Delay/Plane	Max Delay	Std Dev
TS	100	1603	16	39	7.6
Clear Air	36	393	12	21	4.2

Ground stops are frequently implemented for ATL when thunderstorm impacts are particularly severe, such as when a strong thunderstorm is expected to move directly over the airport. An analysis of ZTL traffic management logs for 2003 shows that ground stops were implemented on many of the thunderstorm days between April and September (Appendix C). Ground stops have a significant impact on airlines because they are not pre-planned and typically do not have known end times. Consequently, ground stops can create havoc with hub-and-spoke-based schedules like Delta at ATL.

Figure 18 shows the total number of delay hours by month during 2003 due to Estimated Departure Clearance Times (EDCT) delay programs at ATL for three main weather categories: thunderstorms, low C/V, and wind. The EDCT program causes and dates were supplied by the Air Traffic Control Systems Command Center (ATCSCC). The number of delay minutes was taken from ASPM. A total of 4665 hours of EDCT delay due to either thunderstorms at ATL or en route thunderstorms affecting ATL arrivals occurred during 2003.

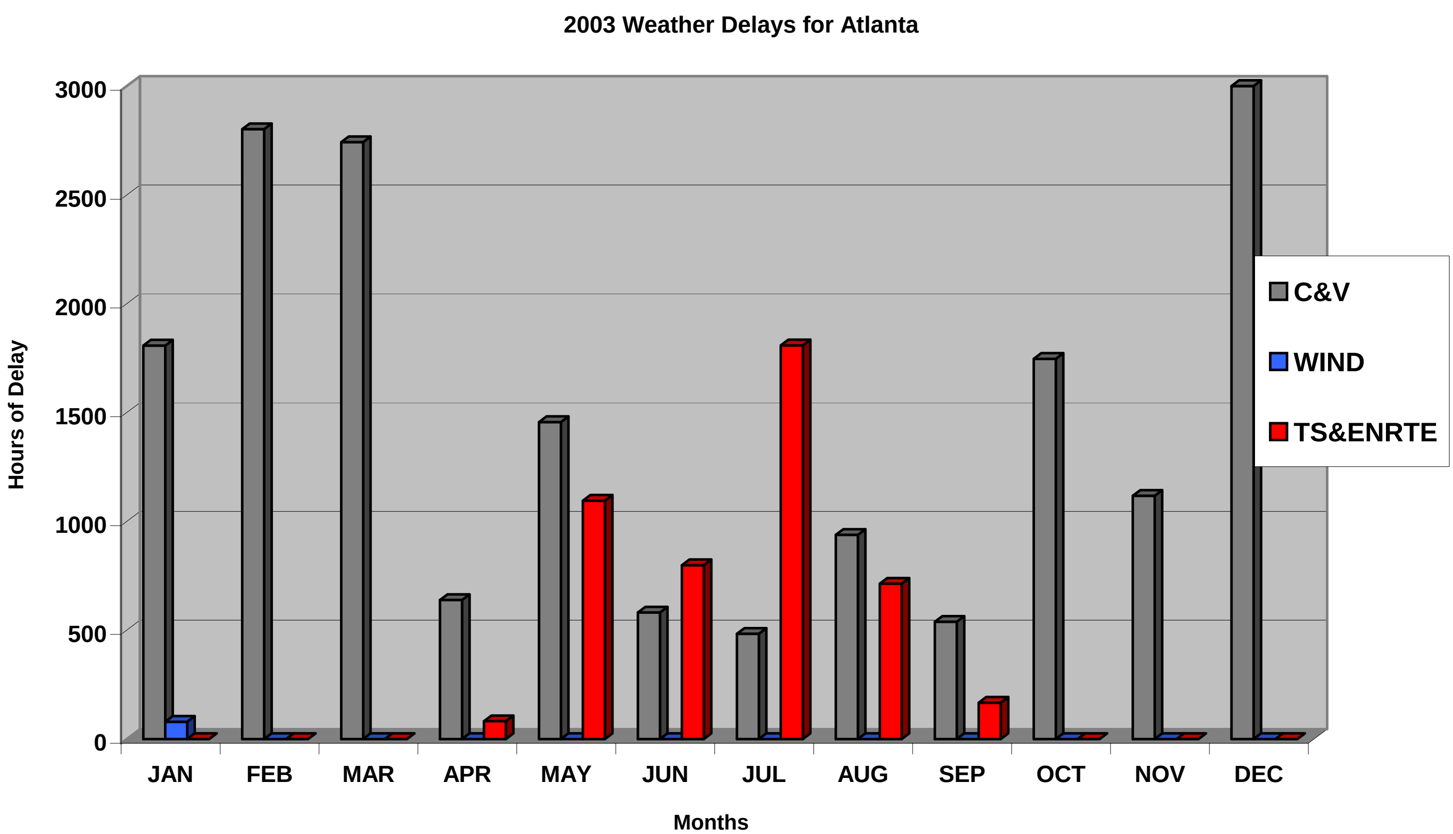

Figure 18. Monthly hours of EDCT delay due to low C/V, wind, and thunderstorms/enroute impacts (TS&ENRTE).

EDCT programs are implemented when it is known that airport capacity will be reduced for a substantial period of time. The airport arrival rate is reduced to a projected arrival capacity and aircraft are given a pre-planned take-off time for their destination airport based on the CDM queue model estimate of when an arrival slot will be available.

It should be noted that:

- There is significant uncertainty as to the appropriate arrival capacity to use when the capacity loss is due to thunderstorms. GDPs are effective in reducing the arrival demand only if put into place well before the planes take off (e.g., at least an hour before the plane is scheduled to arrive at Atlanta). The GDP rates must be based on a forecast of the

Atlanta effective capacity in convective weather several hours in advance of the impact. The ability to forecast convective weather with the required degree of accuracy hours in advance simply does not exist at this time.

- Given the considerable uncertainty in the GDP arrival rate and the desire to avoid excess holding patterns, the forecasted capacity for the GDP is typically lower than the effective capacity that actually occurs. Hence, the GDP itself causes greater delays than would occur from airborne holding near Atlanta.
- The GDP does not reduce delays to the airlines or passengers; it simply changes the location where the delays are incurred.

Departure delays can occur at ATL for a variety of reasons when thunderstorms impact operations. When storms cross over the airport, take-offs can be disrupted until the weather passes the airport. If departure fixes are closed, aircraft either are held or depart via an alternate departure fix, which results in a longer than normal path. Convective weather in the transitional en route airspace can close departure routes and/or result in higher MIT separations along a route. When arrival holding increases due to loss of airport capacity and/or TRACON capacity and/or transitional en route capacity, arrivals are often routed over departure fixes to flush the holding stacks.

All of the above mechanisms result in reduced departure capacity and (depending on the departure demand) can lead to queue departure delays. These delays are compounded if MIT restrictions are in effect for departure flows.

3.3 OTHER SOURCES OF WEATHER DELAY AT ATL

Another major source of weather delay at ATL is low C/V. The benchmark IFR rate in the 2004 FAA Benchmark Capacity Report is 158-162 aircraft per hour. We see from Figure 11 that this rate is exceeded on each of the 8 concentrated arrival/departure pushes at Atlanta. Thus, IFR conditions will surely lead to delays. Figure 18 shows that over 15,000 hours of delay occurred in 2003 at ATL due to EDCT programs for this type of weather. Holding delays and ground stops can also occur when capacities drop unexpectedly due to low ceilings/visibility. Other occasional sources of weather delay at ATL include high surface winds and snow.

One non-convective weather phenomenon that causes delay is vertical wind shear. At Atlanta, a low level jet with winds out of the southwest causes compression for the arrivals on final approach into ATL. This necessitates greater separation between arriving aircraft, thereby reducing capacity. In Chapter 4, we discuss benefits that are achieved through the use of upper level wind information (Terminal Winds) provided by the ITWS.

4. "DECISION/MODELING" DELAY REDUCTION

4.1 INTRODUCTION

In this chapter, each benefit identified in the user interviews is discussed in detail and a description of the benefit is given. For each quantifiable benefit, the model used to quantify the benefit and user inputs to the model are described. All data sources are identified. The chapter closes with a roll-up of the benefits and a description of the economic values used to arrive at dollar estimates of delay reduction.

Two trips by MIT Lincoln Laboratory personnel were made to Atlanta to discuss with users the benefits of ITWS. The first trip was 6-8 October 2003. One Lincoln employee spent a day at each facility (ZTL, Atlanta TRACON, and ATL) interviewing and administering a questionnaire to 10 ITWS users (Appendix D). The questionnaire, developed by MIT Lincoln Laboratory, was based on previous questionnaires used in benefits studies for both ITWS and CIWS. The results of the questionnaire were compiled (Appendix E) and a set of questions was developed to address gaps in our understanding of how to model benefit elements.

Two Lincoln staff members made a second trip to Atlanta on 2-3 December 2003. Detailed interviews were held with five users each at Atlanta TRACON and ZTL. We reviewed the results of the questionnaire with them carefully and asked if there were any inconsistencies in the numbers. In addition, detailed discussions were held on the assumptions used to model the benefits. A visit was also made to Delta dispatch to discuss their web usage of ITWS.

Ideally one would like to have had the time and resources to interview a large number of users, to understand ITWS operational usage, and to understand Atlanta operations well enough to credibly model each identified benefit. Because time and resources did not permit meeting with a large number of users, focus was instead directed at acquiring an in-depth understanding of Atlanta operations from the people with whom we spoke. The small sample of interviewed users introduces uncertainty in the benefit estimates that is not easily quantified.

All users interviewed had nothing but positive comments about ITWS. Some quotes were "This is the best money the FAA has ever spent" and "If the FAA wants to cut programs, this is not the one."

4.2 BENEFITS METHODOLOGY OVERVIEW

Figures 19 and 20 are a convenient way of understanding the breakdown of convection-related benefits at both Atlanta TRACON and ZTL as discussed in Sections 4.3 and 4.4. For each of these facilities, a set of thunderstorm-related traffic flow impacts was identified. For each impact, users identified a decision based on ITWS that improved their ability to plan a response that would minimize the delay. We calculated the number of annual occurrences of each thunderstorm impact and the percentage of time that ITWS was used to improve the management of operations during thunderstorm impact periods[14]. Additionally, Section 4.5 discusses a safety benefit that users identified which did not involve a quantifiable benefit. Section 4.6 summarizes a key airline benefit identified by Delta. Finally, the questionnaires and interviews were used to gather data for quantifying the benefits of the ITWS terminal winds product for Atlanta operations as discussed in Section 4.7.

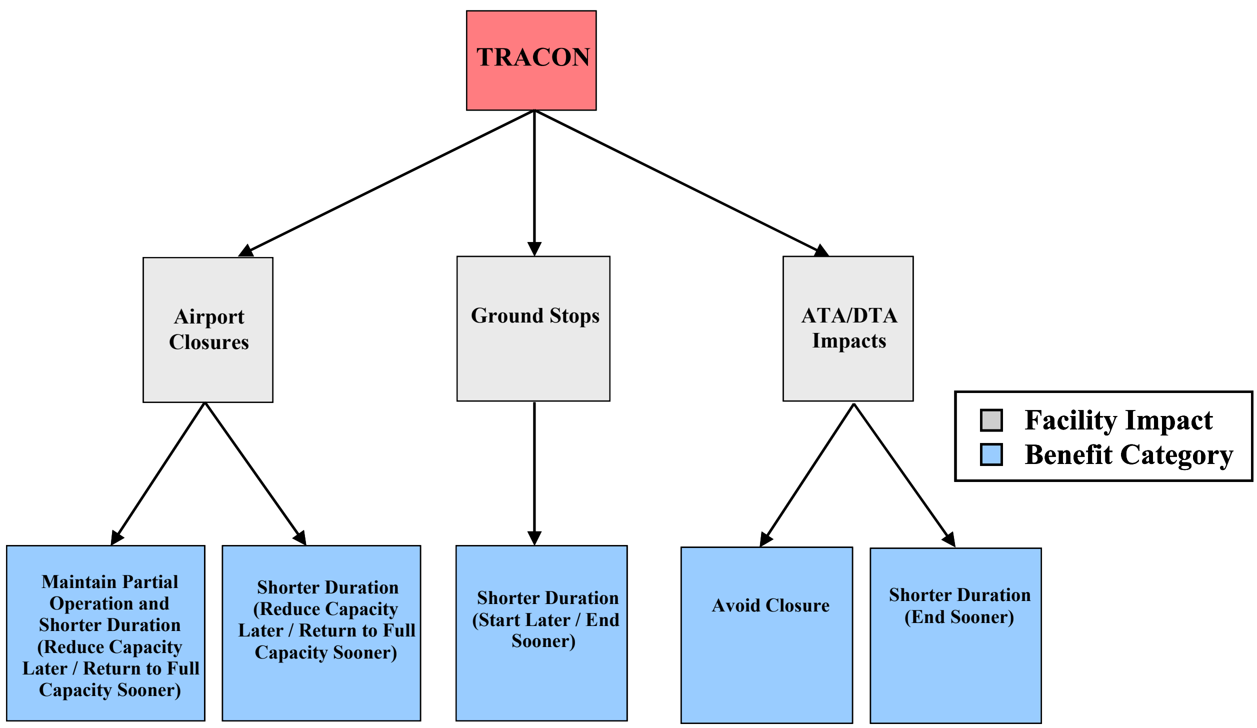

Figure 19. Tree illustrating breakdown of convection-related Atlanta TRACON benefits.

[14] Thunderstorm impact periods include all times convective weather was within 100 nmi of the Atlanta airport. The bulk of these thunderstorm impact periods are not captured by the METAR reports (Chapter 6).

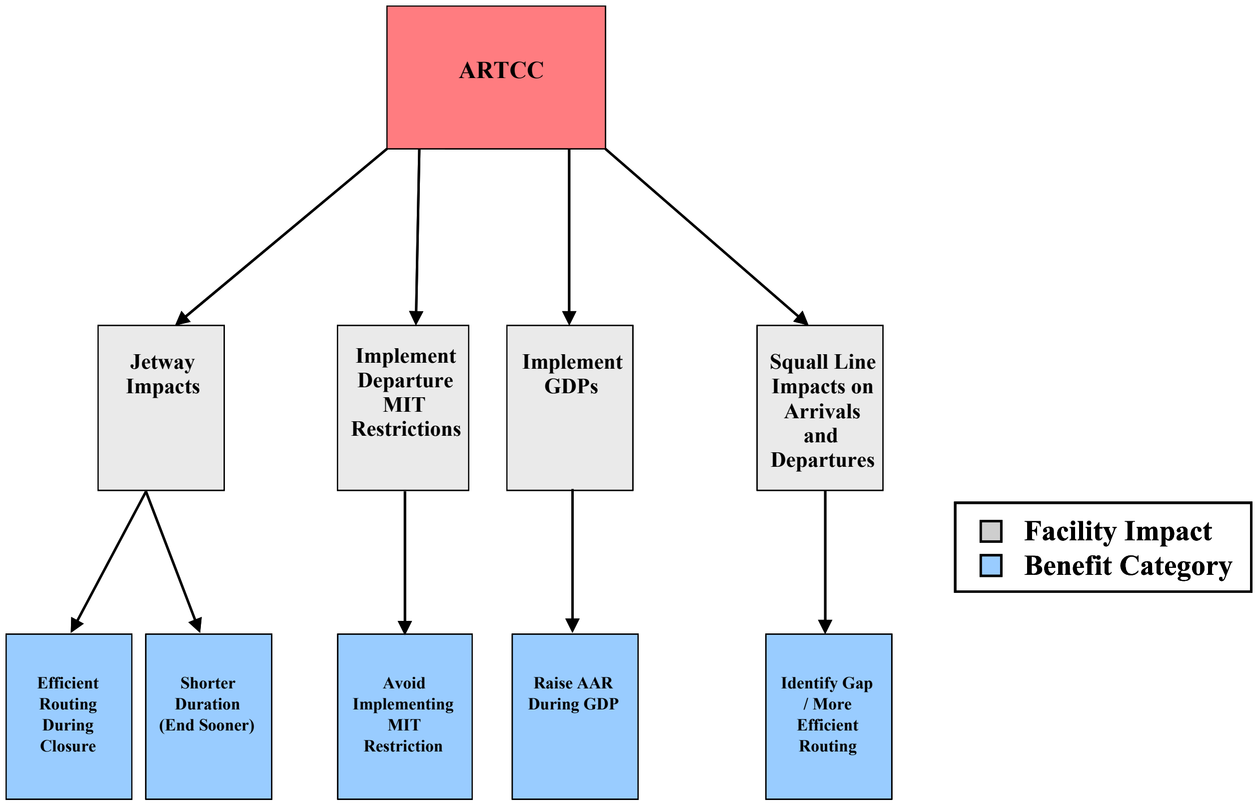

Figure 20. Tree illustrating breakdown of convection-related ZTL benefits.

4.3 ATLANTA TRACON BENEFITS

4.3.1 Impact: Airport Closures

Thunderstorms occasionally track directly over the ATL airfield, preventing any aircraft from landing or taking off. Prior to ITWS, traffic managers did not have the tools to precisely determine the spatial extent and severity of storms over the airport. This made it difficult to determine when landings and/or takeoffs should stop or restart.

There are times when thunderstorms track over the ATL airfield, but only impact a few of the runways, making it possible to continue landing and departing on runways unaffected by the storms. Without a tool like ITWS, it is very difficult to determine from the ground whether the storms can be expected to stay away from runways that are free of weather or even to determine their precise location.

ITWS has proved to be a major benefit in both of these scenarios.

4.3.1.1 Benefit: Shorter-Duration Airport Impacts

With the 30-second update rate of the ITWS ASR-9 Precipitation, Storm Motion, and Storm Extrapolated Position (10- and 20-minute extrapolations) products, traffic managers were able to shorten the amount of time departures and arrivals were stopped when thunderstorms passed over the airport.

Taking an average of eight traffic management responses from the questionnaire, the shorter-duration airport closure benefit was calculated to occur 17 times per year. Traffic managers estimated that, when thunderstorms were at the airport and impacting runway operations, a typical impact lasted 45 minutes pre-ITWS and 30 minutes post-ITWS.

Shorter airport closures reduce delays via two mechanisms. With weather over the airport, airborne aircraft are forced into holding patterns. Shorter-duration airport closures allow for fewer holding delays. In addition, when departures from Atlanta are stopped, long departure queues form and may propagate to gate delays. The shorter duration airport closure benefit has a greater impact on taxi-out delay and a lesser impact on gate delay.

It is also possible that a ground stop will be implemented when there is weather over the destination airport, causing aircraft that have not yet departed for ATL to be held at their origin airport. With fewer arrivals reaching ATL, airborne holding is reduced. However, ground stops cause queues at the origin airports and typically result in a larger overall delay than would occur if aircraft were held in the air. This results from the inability to accurately predict when a ground stop should end.

4.3.1.2 Benefit: Maintain Partial Airport Operation

There are times at ATL airport when the thunderstorms at the airport do not impact both north side and south side operations simultaneously. Prior to ITWS, traffic managers usually did not feel confident enough in the available weather information to continue partial operations with a thunderstorm in such close proximity. Now they feel there are times they can maintain operations on a reduced number of runways rather than shutting down all runway operations.

Based on six traffic management responses from the questionnaire, users estimated that they attained this benefit on average 10 times per year. Just as with shorter-duration airport impacts, they felt that the length of time of direct airport impacts was shortened by ITWS from 45 to 30 minutes on average.

Modeling Description for Both Airport Closure Benefits

A queue model was used to calculate the benefit for both of the airport storm impacts discussed above. In all benefits calculations described in Chapter 4, the demand input to the queue model is the hourly scheduled rate based on a May through August average rate calculated at 15-minute intervals.

The critical piece of data needed in the queuing calculation is the capacity of the airport during thunderstorm impacts. One might be tempted to think that no departures or arrivals operate when thunderstorms are overhead. To test this hypothesis, we analyzed 15-minute traffic counts for arrivals and departures when thunder and rain were reported at the airport. This is reported by METAR as TSRA (thunderstorm with rain). We could have analyzed time periods when thunder was not accompanied by rain (METAR report of TS [thunderstorm]). However, thunder can be heard 5-8 miles from the airport. Unless accompanied by rain, thunder is not an accurate indicator of a storm directly over the airport.

The distribution of actual traffic counts during METAR TSRA times at ATL in 2003 is shown in Figure 21. Data used for traffic counts was taken from the Airport Efficiency section of the ASPM database. Internal studies at MIT Lincoln Laboratory show that these data most closely match actual traffic counts at Atlanta. The mean of the distribution is 28 operations (landings + takeoffs). There are only 6 TSRA incidents with traffic counts below 15, suggesting that there are times when thunderstorms impact the airport but partial operations continue. A similar analysis of 2001 data showed that there were 8 TSRA incidents with traffic counts below 15, or about 12% of TSRA incidents in 2001. Compared with the 6% of TSRA incidents in 2003, this suggests that keeping at least part of the airport open during thunderstorms was more difficult in 2001 than in 2003. This lower frequency of TSRA incidents with traffic counts below 15 post-ITWS provides objective operational data supporting the ATC user feedback that ITWS is a factor in improving the ATL traffic management during convective weather.

To model the benefit of "maintaining partial airport operations" and "shorter-duration airport impact," we consider a single TSRA event (thunderstorm with rain on the airport) capacity of 28 based on the mean of the traffic distribution in Figure 21. This mean includes both types of airport impacts. Modeling a single event with this mean represents an average of the two benefits. In the baseline event (corresponding to a thunderstorm impact on the airport in 2001), the airport capacity is reduced to 28 operations for three consecutive 15-minute intervals, or 45 minutes. In the ITWS benefit event, the airport capacity is reduced to 28 operations for two consecutive 15-minute intervals, or 30 minutes.

The use of the mean of the actual traffic distribution tends to underestimate the benefit since the queue delays are a highly nonlinear function of the capacity in adverse weather. Low capacities in adverse weather (i.e., in cases where the 15-minute count is much less than the scheduled rate) yield delays that are many times greater than the delays that occur when capacity can be kept closer to the scheduled rate.

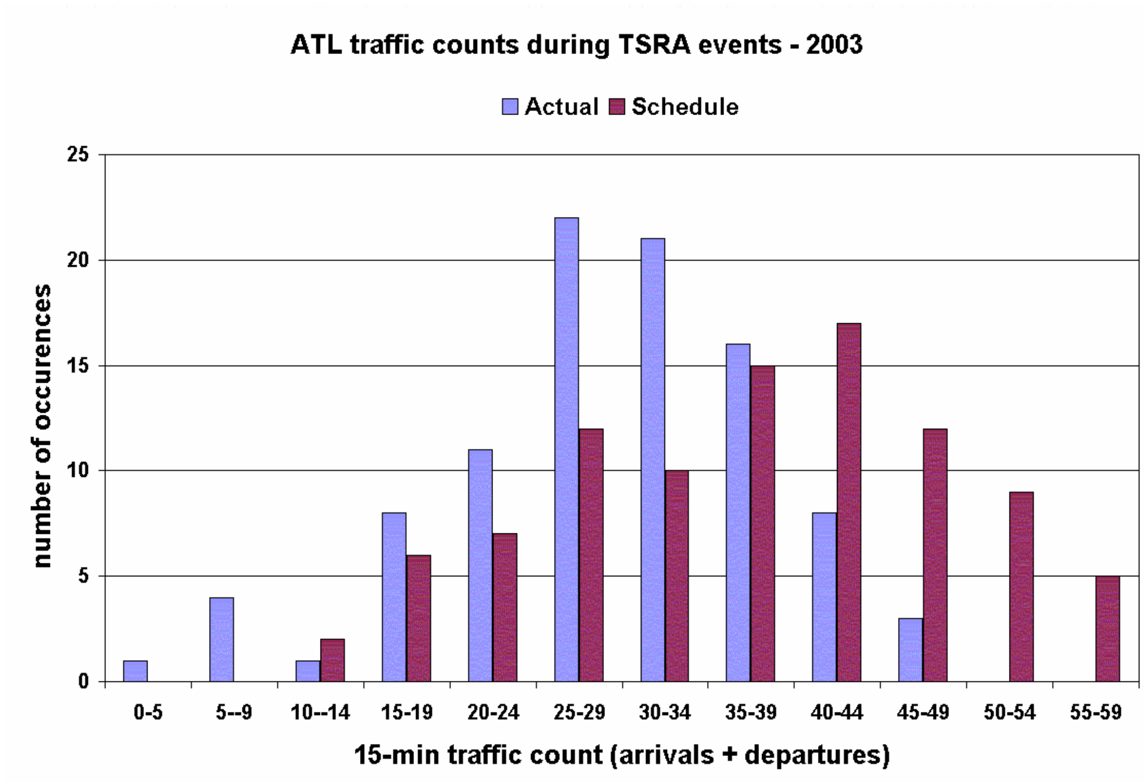

Figure 21. Traffic counts during times of METAR TSRA reports for ATL in 2003. Counts are arrivals plus departures during the 15 minute interval closest to the time of the TSRA report. The mean of the distribution is 28 operations.

At each 15-minute interval from 8:00 AM to 11:00 PM, we calculate the hourly pre- and post-ITWS delay for this benefit category using a fair weather capacity of 50 and a TSRA capacity of 28. Convection is highly dependent on when daytime heating is the greatest (typically in late afternoon), so to account for this we apply the weighting function given in Table 6. The weighting function was derived from an analysis of all thunderstorm observations at ATL over a two-year period. We then compute a weighted-average delay difference over all the intervals. The reason the weighting function is needed is that convection is much more likely to occur during the late afternoon and early evening when traffic volumes are at their highest. In addition, there is a very low likelihood of convection in the morning when traffic volumes are very high for departures. To assume equal likelihood of convection at all times of day would tend to damp out the very non-linear effects that take place when convection occurs during peak traffic volume times in late afternoon, while also significantly overestimating the magnitude of delay from morning convection.

TABLE 6
Weights Used for Obtaining Average Delay Reduction Benefits

Local time	Weight
800-1400	0.20
1400-2000	0.65
2000-0000	0.15

Note: Weights were determined based on METAR analysis for ATL for 2001 and 2003.

The average benefit for the modeling scenario was 42 hours. Users estimated 17 times per year when the benefit of "shorter duration airport impact" was realized and 10 times per year when the benefit of "maintain partial airport operations" was realized. Multiplying the 42 hour benefit by 27 instances annually (17+10) gives a combined benefit of 1134 hours.

4.3.2 Impact: Ground Stops

Ground stops are implemented under a variety of circumstances, all of which involve too much airborne traffic destined for the airport relative to airport and/or TRACON and/or transitional en route capacity. When a ground stop is implemented, aircraft on the ground waiting to depart for ATL are delayed for a specified period of time. Ground stops are common on days with thunderstorms at or around the ATL TRACON. They can be imposed for storms over the airport, for weather forcing the closure of too many fixes, or simply because there is too much airborne inventory.

4.3.2.1 Benefit: Shorter Ground Stops for Planes Destined for ATL

Users told us that better convective information from ITWS gave them confidence to implement shorter ground stops than prior to ITWS. *This benefit was identified on our follow-up visit with users and was not included in the questionnaire survey administered during the first visit*. Shorter ground stops are distinct from shorter airport closures. With shorter airport closures, the benefit accrues to airborne traffic landing at ATL or departures waiting to take off from ATL.

Modeling Description

Traffic managers estimated that ITWS shortened average ground stop time by 15 minutes, with a pre-ITWS ground stop length of 45 minutes. They were unable to estimate the number of times per year ground stops were in place.

To estimate the number of ground stops at ATL, we analyzed traffic management logs obtained from the ZTL traffic management unit for April through September 2003. Appendix C shows the date, start time, end time, and reason for the ground stop (if known) for all ground stops identified in the logs. In several cases, a ground stop was listed but no cause was given.

Radar images from National Climatic Data Center (NCDC) were consulted to verify convection in ZTL airspace.

The number of ground stops for the 2003 full-year period was estimated from the April through September period as follows: (# of GS in April-September [39])/(days with TSRA in April-September [34]) x (days with TSRA in 2003 [45]). This resulted in an estimated 51 thunderstorm-related ground stops in 2003.

A linear model was used to calculate the benefit. The first step was to estimate the number of aircraft affected by a ground stop. Ground stops are usually implemented as either first-tier or second-tier. First-tier refers to traffic departing within centers immediately adjacent to ZTL and second-tier refers to traffic departing within centers immediately adjacent to the ZTL's first-tier centers. A quick OAG analysis showed that approximately 60% percent of ATL arrivals come from first and second-tier centers. This is an average of one aircraft per minute ([100 planes/60 minutes] x 60%). A further breakdown showed that approximately 35% of the traffic was first-tier and 25% second-tier. Thus for second-tier ground stops, one aircraft per minute was affected, while for first-tier ground stops 0.6 aircraft per minute were affected.

For modeling, we assume that every aircraft impacted by a ground stop is independent of all others. If a ground stop is suddenly imposed, a plane that is scheduled to take off at that moment is delayed the entire length of the ground stop. A plane scheduled to depart one minute into the ground stop is delayed one minute less than the length of the ground stop. Therefore, at a take-off rate of 1 plane per minute for a thirty-minute ground stop, the number of delay minutes is 30+29+28…+1 = 465 minutes. Similarly, a 45 minute ground stop yields 1035 delay minutes.

Assuming a ground stop is shortened from 45 minutes to 30 minutes, then at a departure rate of one aircraft per minute to ATL there would be 570 minutes of delay saved. Scaling by 0.6 to account for the fact that the departure rate to ATL from 1st tier airports is 0.6 aircraft per minute, we find that shortening 1st tier ground stops by 15 minutes saves 342 minutes. Since the combined departure rate to ATL from both 1st and 2nd tier centers is 1 aircraft per minute, no scaling factor is needed and we find that shortening 2nd tier ground stops by 15 minutes saves 570 minutes. From an analysis of ATL traffic logs it was estimated that 85% of ground stops were first-tier and the remaining 15% second-tier. Applying these fractions to the total of 51 ground stops occurring annually, the total ITWS benefit of shortening ground stops by 15 minutes is 320 hours.

This model is only an approximation of what actually happens. Often when a ground stop is cancelled, the affected aircraft are not allowed to depart immediately. This might cause sharp spikes in landing demand at ATL[15]. Aircraft may also be embedded in a departure queue and are unable to take off as soon as a ground stop is cancelled. For this reason we believe that our modeling assumptions for this benefit category are quite conservative.

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[15] In a number of cases, the ground stop "rolls over" into a GDP to bound the number of aircraft arriving at the transitional airspace when the thunderstorm impacts have ended.

4.3.3 Impact: ATA and DTA

Impacts to traffic flows to and from the ATAs and DTAs are perhaps the most frequent effect of thunderstorms in the ATL TRACON. ATL has a total of four ATAs and eight DTAs, with all traffic into and out of the airport metered over these fixes. Any thunderstorm in the path of these flows can cause significant disruption. If traffic is light enough, deviations around cells can be tolerated. If the traffic is heavy or the spatial extent of the thunderstorm is large, deviations can disrupt adjacent traffic flows, forcing the closure of an ATA and/or DTA. When a closure occurs, aircraft filed over the closed fix must fly a longer path to an alternate fix, thereby incurring airborne delay. If the alternate fix does not have enough capacity to absorb the additional traffic, holding is initiated and further delay is incurred. If the holding is expected to become significant, arrivals may be allowed to use DTAs. This reduces the departure capacity of the airport/TRACON and causes departure delays.

4.3.3.1 Benefit: Avoid Closure of ATA and/or DTA

Traffic managers cited as a benefit the ability to avoid an ATA and/or DTA closure completely using ITWS. *This benefit was identified in the second visit with users and was not included in the original questionnaire*. “Avoiding fix closure” was possible given the rapid update rate of the ITWS Precipitation, and Storm Motion and Storm Extrapolated Position products. These products enabled traffic managers to see that thunderstorms would miss the fix. Without ITWS, planners might have acted to stop the flow of traffic over a fix altogether due to uncertainty about the thunderstorm’s movement.

Modeling Description

Traffic managers estimated that a typical fix closure lasted 30 minutes. They also estimated that ITWS allowed them to avoid a closure once per thunderstorm event. “Once” refers to one arrival fix or two departure fixes. There are twice as many departure fixes as arrival fixes and departure fixes are typically treated as pairs.

Delay reductions from this decision are both linear (in shorter distance flown) and non-linear (in higher capacity and therefore reduced queues). The linear calculation is straight-forward. On average there are 10 aircraft routed over a fix in a 30-minute period. Traffic managers estimate that each aircraft saves 12.5 minutes in flying time by avoiding a reroute to another fix. (This value was independently verified by Delta airlines during a visit to their dispatch operation.) The total linear benefit for avoiding a fix closure is 125 minutes of reduced flying time.

Based on analysis of radar data combined with thunderstorm observations, it was estimated that thunderstorms affect flows over fixes 95 times per year. ITWS users have greater confidence in the distribution of weather in their airspace and as a result may increase GDP arrival rates. To avoid overlap with the GDP benefit category (estimated at 12 events per year in Section 4.4.3.1), we reduced by 12 the annual number of days when avoiding fix closures could be a benefit. This results in 83 annual occurrences of avoiding fix closures, for an estimated total linear benefit of 173 hours of reduced airborne delay.

Modeling the non-linear impact of closing a fix is difficult. Traffic managers use a variety of techniques to compensate for a closed fix, as outlined in the discussion for this benefit category. We feel the best way to model the full set of possibilities is to model the capacity of the entire TRACON airspace, rather than to consider arrival and departure airspace as independent. As stated in the benchmark capacity report for ATL (FAA, 2001), the fair-weather capacity of ATL is 100 arrivals per hour and 100 departures per hour. These capacities are not independent but fluctuate based on the traffic mix. For simplicity, we assume the full airspace capacity is 50 aircraft per quarter hour with no fix closures. With one fix closure, (i.e. 1 ATA or 2 DTAs) this reduces to 44 ($1/8^{th}$ capacity reduction). Demand is based on the sum of scheduled arrivals and departures for each quarter hour period. Using these capacity values, we calculate the benefit of avoiding a 30-min fix closure at each 15 minute interval between 8:00 AM and midnight.

For example, in the baseline (no-benefit) scenario of a fix closure between 8:30 AM and 9:00 AM, capacity is adjusted from 50 down to 44 for each of the two quarter-hour periods in that time frame and the queuing delay is noted. In the benefit scenario, a fix closure is avoided and capacity remains at 50 for each of the two quarter-hour periods. The difference between the benefit and no-benefit queuing delay determines the delay savings benefit. Taking a weighted average (Table 6) of the delay savings benefits calculated at each 15-minute interval between 8:00 AM and midnight, we find that the benefit is 4.4 hours per event, or 365 hours annually.

Figure 22 shows how the benefit fluctuates according to time of day. There are many times when there are no queue-type benefits because demand does not exceed capacity even with one fix closed. In these cases the benefit reduces to the linear component only. Clearly, the delay impact is very sensitive to the time of day when thunderstorms occur.

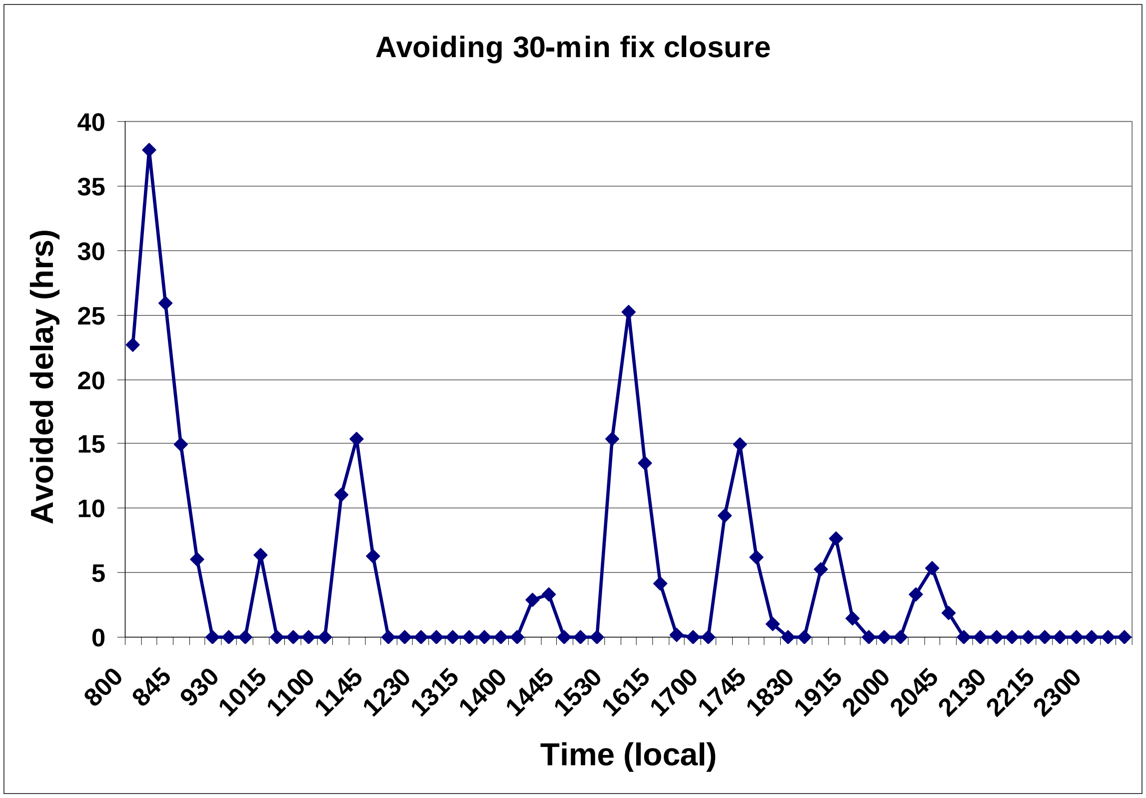

Figure 22. Benefits of avoiding a 30-minute fix closure as a function of time of day when thunderstorms impact a single fix.

4.3.3.2 Benefit: Shorter Duration Impact on ATA and/or DTA

In detailed discussions with users, we were told that a large benefit from ITWS was in the management of the traffic flows over arrival and departure fixes. Traffic managers employ a variety of methods to manage the impacts from thunderstorms. Traffic flows may be slowed (rather than stopped) over thunderstorm impacted fixes. Part of the traffic may be offloaded to other fixes, while a part of the traffic is allowed to deviate around the impacted fix with much greater spacing. Fix balancing can also occur by swapping departure transition areas with arrival transition areas and vice versa.

Traffic managers stated that, using the ITWS storm motion and extrapolated position products, they were able to shorten the duration of impact to traffic flows from thunderstorms affecting ATAs and DTAs. Based on the questionnaire, traffic managers estimated fixes were opened between 7 and 8 minutes earlier than without ITWS information. In other words, capacity returned to normal earlier than when there was no ITWS information. They further estimated that fix impacts of this type occurred 3-4 times during each thunderstorm event.

Model Description

As with avoiding fix closures, we model this benefit using both a linear and a queue model. For the linear model, traffic counts show that 5 aircraft fly over any given fix during a 15-minute period. Opening the fix 7-8 minutes early benefits 2-3 aircraft, avoiding an extra 12.5 minutes of flight time per aircraft. Assuming this benefit is realized 3-4 times per thunderstorm day, and using the same number of thunderstorm days (83) as in fix closures, the total delay reduction using the linear model is 150 hours per year.

For the queuing delay calculation, we assume the airspace capacity for all arrivals and departures is 44 aircraft per quarter hour with one fix closure and no ITWS information. Opening the fix 7-8 minutes early increases the capacity to 47. Using these capacity values, we calculate the benefit of opening a fix early at each 15-minute interval between 8:00 AM and midnight. Taking a weighted average, (Table 6) the benefit is 4.2 hours per event, or 350 hours annually.

4.4 ZTL BENEFITS

4.4.1 Impact: Jetway Closures

When thunderstorms impact jet routes in ZTL airspace, aircraft are vectored around the storms or given reroutes when the route is completely shut down.

4.4.1.1 Benefit: Efficient Reroutes during Closure

Traffic managers told us that ITWS increased their confidence to provide shorter reroutes to aircraft. Some managers felt this was more of a potential benefit; they needed more time to become comfortable with ITWS to make this kind of decision. Although no adjustment was made for this uncertainty, the benefit is sufficiently small that it would not substantially affect the final benefit results.

Model Description

A linear model is used to approximate this benefit. Traffic managers at ZTL (Appendix E) estimate that on average about 12 aircraft per thunderstorm event save between 7-8 minutes of flight time with shorter reroutes. Based on an analysis of surface observations and radar data, the annual number of thunderstorm days is 95. The total benefit is estimated at 148 hours. Figure 14 shows a sample of all over-flights for ZTL airspace and illustrates the potential for any single thunderstorm to cause disruption. The total number of aircraft estimated to benefit from ITWS for this category is a very small fraction of the number of potential flights being affected.

4.4.1.2 Benefit: Opening Jetways Earlier

A benefit that is regularly cited by traffic managers using prototype ITWS and CIWS systems is opening jet routes sooner based on storm motion forecasts. ZTL traffic managers also cited this as a benefit. By opening the jet routes sooner, aircraft avoid reroutes that add to their airborne flight time.

Model Description

We use a linear model to approximate the benefit. Traffic manager's estimate (based on two responses) that there are typically 5 jet route closures on days with thunderstorms. The estimated number of aircraft affected by opening a route early is between 5 and 40 aircraft. We use the lowest end of this estimate (five) because we feel it was more consistent with traffic counts expected on jet routes over a 10-20 minute period. Users estimate that an average of 7-8 minutes of flight-time per aircraft is saved. Using 95 thunderstorm days annually, this results in a total delay savings benefit of 297 hours.

4.4.2 Impact: Departure Route Reduced Capacity

Thunderstorms at a departure fix or at points beyond the departure fix routinely disrupt departure flows out of ATL. In some cases, the thunderstorm itself is not the primary cause of the disruption. Departure delays may be the result of arriving traffic deviating around thunderstorms and into departure airspace. When this occurs, MIT restrictions are imposed on the impacted departure corridors to space the traffic and reduce the airborne complexity. Typical MIT restrictions are 15 nmi, but can be greater depending on the situation. Traffic managers estimate that MIT restrictions are imposed on average between 7-8 times per thunderstorm event.

4.4.2.1 Benefit: Avoiding Miles-in-Trail (MIT) restrictions

Although two users did respond to the MIT benefit category (question 4 in ZTL section of Appendix D), there was considerable user uncertainty as to how to estimate the impact of ITWS on reducing MIT restrictions. Only one user could estimate the reduction in MIT restrictions due to ITWS, although both people interviewed estimated that ITWS helped over 10 times per year. A more in-depth conversation regarding this benefit category was conducted during the follow-up visit. Users felt more comfortable saying that ITWS allowed them to avoid MIT restrictions altogether approximately 10% of the time.

Model Description

Conservatively, most MIT restrictions last at least one hour. The fair-weather capacity over a departure fix (or jet route) is about 12-13 aircraft per hour, while the capacity with a 15 MIT restriction is about 8 aircraft per hour. ATL operates similar to two separate airports in that there are two different runways used for departures. From each runway, aircraft depart over one of four possible fixes.

To model the case of a MIT restriction on one departure fix, we use a 1-hour capacity over a single fix of 11.4 departures[16]. For the case of no restrictions, we use a 1-hour capacity of 12.5

[16] One runway feeds four departure fixes. If there is a MIT restriction on one of the four fixes, then capacity is **only** reduced when two departures are back-to-back over the fix with the restriction. It is assumed that there is a 25% probability that two planes will be back-to-back in the departure queue over the same restricted fix, while there is a 75% probability they won't be back-to-back over a restricted fix. Thus, the capacity is the 0.75 x 12.5 + 0.25 x 8 = 11.4.

departures. Similar to other queuing model calculations, the weighted average benefit is 3.4 hours. Assuming the benefit is achieved 10% of the time (0.7 times per event) over 95 events annually; the total estimated annual benefit is 226 hours.

4.4.3 Impact: Ground Delay Programs

4.4.3.1 Benefit: Increase Arrival Rate in Support of GDP

GDPs are sometimes implemented for ATL when thunderstorms are expected to reduce the capacity of the airport below demand for an extended period of time. Traffic managers told us that ITWS gives them confidence to increase the arrival rate in support of a GDP above what they would have used pre-ITWS. Because they have increased certainty in the timing of airport and fix impacts, they feel more comfortable allowing additional airborne traffic into the airspace.

Model Description

GDPs can be modeled in a straightforward way using a queuing model. The airport arrival rate (AAR) is the capacity. Based on an analysis of logs supplied by ZTL, the average AAR for GDPs in support of thunderstorms is 82 arrivals per hour in 2003 (i.e., the capacity with ITWS in place). Traffic managers feel that this rate was about 3 aircraft per hour higher than pre-ITWS. This is the low end of the range provided by users. Hence the pre-ITWS AAR in support of GDPs is 79 arrivals per hour. We do not have access to traffic management logs for 2001, so this should be verified at a later time. However, the AAR will vary according to the severity, duration, and spatial extent of the thunderstorms. Any proper comparisons between the two years should include a normalization factor.

The other modeling consideration is the duration of the GDP. Based again on the traffic logs, we found two equally probable scenarios for GDPs. In one scenario the GDP lasts three hours from 1800-2100 UTC. In the second scenario the GDP lasts from 1800-0000 UTC. If the arrival rate is increased by 3 aircraft per hour, the first scenario results in a benefit of 12.5 hours and the second scenario results in a benefit of 31 hours. Since both scenarios are equally probable, we take the average benefit (21.7 hours) to compute the annual benefit. Assuming 12 GDPs per year, the annual benefit is 260 hours.

4.4.4 Impact: Squall Line Impacts on Arrivals and Departures

A well organized line of thunderstorms can shut down two or more fixes and/or jetways for an extended period of time. In these squall line impact cases, significant airborne delay can be incurred by aircraft having to fly around the ends of the line of thunderstorms.

4.4.4.1 Benefit: Identify Line Gap and Use More Efficient Routing

If gaps in the line are present and can be utilized, significant airborne delay reduction can be realized from the fewer number of miles flown. The rapid product update (1 minute or less), storm motion estimates, and storm representation provided by ITWS enable traffic managers to more often take advantage of gaps in storm lines. *This benefit was not identified until the second visit to Atlanta and was not in the original questionnaire*.

Model Description

It is estimated that the "utilizing gaps" benefit is achieved 12 times annually and that 40% of the arrival and departure traffic are affected. We use a linear model to capture the benefit. It is assumed that capacity is already reduced by 20% (similar to GDP capacities) due to thunderstorms. Since organized convective events (e.g., squall lines) typically take between 4-6 hours to move through the ITWS coverage region, we assume that the duration of the benefit is two hours. We use 40% of the reduced median 2-hour demand for the period 1400-2000 UTC as the number of aircraft affected by the benefit (130 aircraft impacted). Traffic managers estimate that 12 minutes of flying time are saved by using gaps effectively. The total annual benefit is (130 aircraft) x (12 minutes saved) x (12 annual events) or 125 hours of delay savings annually.

4.5 SAFETY AND REDUCED WORKLOAD BENEFIT: AVOIDING "NO-NOTICE" HOLDING

During the second visit to ZTL, the ARTCC users identified a new ITWS benefit that was difficult to quantify in terms of delays savings. This benefit increased safety and helped reduce controller workload. Prior to ITWS at ZTL, the ARTCC did not have access to information concerning gust front, microburst and wind shear impacts at ATL. Any safety-related information of this nature was relayed by telephone. At times, aircraft would be vectored into the TRACON, only to be warned of microburst and wind shear activity on the airport. These aircraft would execute missed approaches or deviations and would be vectored around other traffic and back into ZTL airspace. In ZTL airspace, the traffic had to be safely merged into a holding pattern. This is known as no-notice holding. Now that ZTL can see on ITWS when ATL is being heavily impacted by thunderstorms and/or microbursts, there are far fewer instances of no-notice holding.

There is no **quantitative** measure of this benefit. The benefit is that controller workload is reduced if the planes are held at the proper location and time using ITWS. As a result, controllers do not have to turn aircraft around mid-stream and insert them into a pre-existing holding stack.

4.6 AIRLINE BENEFIT: AVOIDING DIVERSIONS

ATL is a major hub for Delta Airlines. We spoke with dispatchers at Delta on our visit to Atlanta to see if they felt that the ITWS web site for ATL was a help for their operations. One person interviewed felt that ITWS allowed traffic managers to save an average of 1 diversion for each of 40 convective weather events each year. The cost of a diversion varies significantly and can even result in a savings under certain circumstances. The most costly are diversions occurring late in the evening and requiring overnight accommodations for passengers. Diversion cost is a function of aircraft type and can range from $4000 to $8000. Assuming a typical cost of $6000 per diversion and 40 saved diversions, this equates to approximately $240,000 in savings to Delta.

Figure 23 shows the hourly ITWS web site usage by Delta Airlines for the period 5 August 2003 through 20 September 2004. The data was obtained from the Volpe National Transportation System Center and illustrates that during the 2004 convective season there were regularly over 2000 hits per hour on the Atlanta ITWS web site. One could conclude that there are many other benefits to the airlines that this study did not capture.

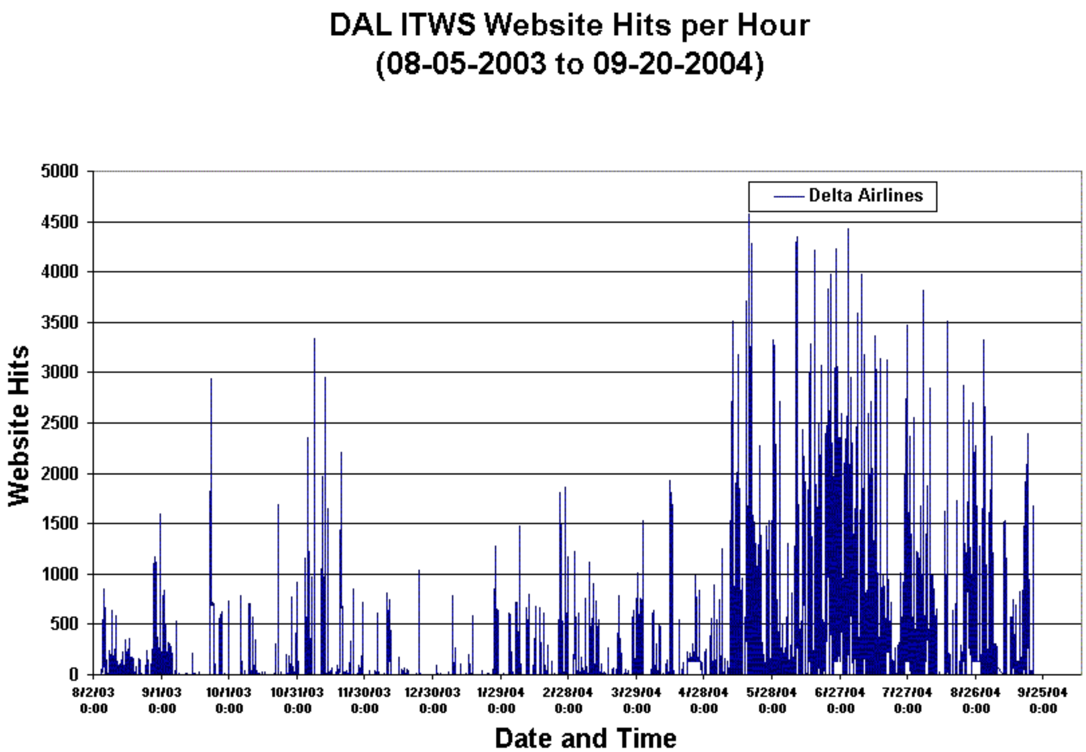

Figure 23. Hourly hits to the Atlanta ITWS web site by Delta Airlines.

4.7 VERTICAL WIND SHEAR BENEFIT: HIGHER ARRIVAL RATE ON DAYS WITH COMPRESSION OF ARRIVAL FLOWS

Compression on final approach occurs when aircraft encounter a headwind, slowing their progress and allowing following aircraft to decrease the gap between flights. In response to this, traffic managers space the aircraft farther apart upstream to achieve the proper spacing on final approach, thereby reducing the effective arrival capacity of the airport. This occurs at ATL during the presence of a low-level jet with winds out of the southwest. However, it is also a problem for other ITWS airports such as LGA and EWR (Allan et al., 2001). When the arrival rate is reduced below demand, airborne holding and GDPs may result. Traffic managers at Atlanta TRACON are responsible for determining the arrival rate for a GDP.

The ITWS Terminal Winds product shows the winds at various altitudes above user-specified locations within the Atlanta ITWS coverage. The terminal winds estimates are derived from Doppler weather radars, the Rapid Update Cycle (RUC) numerical weather prediction model, and aircraft observations. The accuracy and 5-minute update rate make this product the best source of 3-dimensional wind information available in the terminal area. Both the Central Weather Service Unit (CWSU) and traffic managers at Atlanta TRACON use Terminal Winds to determine if conditions necessitate changes in the arrival rate.

All users agree that maintaining a higher arrival rate during compression conditions is a significant benefit. They estimate that the Terminal Winds product allows them to increase the arrival rate by an average of 2 aircraft per hour under these conditions (based on 8 responses from the questionnaire).

Model Description

Based on questionnaire responses, arrival capacity is 11% lower on average during days with compression. Assuming an average arrival rate of 80 aircraft per hour, this results in a pre-ITWS AAR due to compression of (conservatively) 72 and a post-ITWS AAR of 74. Since jet streams are slowly varying weather features, we assume an impact duration of 8 hours and model an equal probability that compression could occur between 0800-1600 or from 1600-0000. Using a queue model with these capacity figures, the total benefit per event (i.e., the average benefit of the two time periods) from Terminal Winds is 33 hours of arrival delay reduction. Traffic managers estimate that on average this benefit is realized 16 times annually, for a total annual benefit of 520 hours of arrival delay reduction.

4.8 SUMMARY OF REDUCED DELAYS AND MONETARY ESTIMATE OF BENEFITS

Table 7 shows a summary of the Atlanta ITWS benefits estimated using the "Decision/Modeling" approach. Rather than restate the work of others, the reader is referred to the CIWS benefits study (Robinson et al., 2004) for a discussion of the model used to convert ATL delay savings in hours to monetary estimates. For downstream delay due to propagation of flight delay, we used the delay multiplier of 1.8 as originally estimated by Boswell and Evans (1999). Based on the study of delay propagation in the American Airlines schedule (Beatty et al., 1999) and the new analysis presented in Chapter 7, we believe that this multiplier is very conservative.

The estimated annual delay savings provided by the Atlanta ITWS is 4,068 hours per year of primary delay and about 7,400 hours per year including downstream delay. An analysis of traffic mix at ATL using OPSNET shows that 72% of their traffic is commercial, 27% scheduled commuter, and only 1% general aviation aircraft. Operating costs are applied using this traffic mix. In addition, we take care to break down each benefit category into delay savings on the ground or delay savings for airborne aircraft. We also use Downstream Model 2 (Robinson et al., 2004), which assumes no airline operating costs associated with downstream delay. Conversion to a monetary value produces an estimated delay savings in excess of $ 23 M per year. It is our belief that this is very conservative. Total monetary benefit rises significantly if there are costs to airlines associated with downstream delay.

TABLE 7
Summary of Benefits Associated with the Atlanta ITWS

Benefit Category[17]	Hours saved	DOC	Passenger Delay Cost
Atlanta TRACON Benefits			
Shorter airport impact and/or recognizing partial airport usage	1134	$1,874,502	$2,529,954
ATA/DTA opens earlier	500	826,500	1,115,500
Avoiding ATA/DTA closure	538	889,314	1,200,278
Higher AAR on days with compression	520	1,074,320	1,160,120
Shorter Ground Stop	320	396,800	713,920
ZTL Benefits			
Avoiding “no-notice” holding	0	0	0
Efficient rerouting in ZTL	148	305,768	330,188
Open route early – avoid reroutes	297	613,602	622,607
Lower MIT restriction	226	280,240	504,206
Raising AAR during GDP	260	322,400	580,060
Identifying line gap	125	206,625	278,875
Airline Benefits			
Avoided diversions		240,000	0
Totals			
Total Primary Delay	4,068	6,790,071	9,075,708
Downstream Delay	3,254	0	7,160,235
Total Benefit	7,322	$6,790,071	$16,235,946

Note: Benefits are in 2003 dollars.

[17] Each benefit is assigned to departure delay benefit, airborne delay benefit, etc. The allocation of benefits to each delay category is not explicitly shown in the table above, but can be inferred from the benefit description. For instance, the benefit category “ATA/DTA opens earlier” is broken down as 50% of benefit allocated to departures and 50% of benefit allocated to airborne arrivals.

4.9 COMPARISON OF BENEFITS WITH PREVIOUS ESTIMATES OF ATLANTA ITWS DELAY REDUCTION BENEFITS

In Section 2.3.1, we noted that the interview/delay modeling approach was used previously in the ITWS operational benefits studies to support Key Decision Point (KDP-3) to begin full scale development. Specifically, delay reduction models were developed on the basis of ITWS operational use at Memphis and Orlando (and, to a lesser extent, using data from Dallas) and then extrapolated to provide estimates for all of the planned ITWS sites. In Table 8, we show the results of that extrapolation. In Table 9, we compare the hours of direct delay saved computed from the KDP-3 study to this study. The results of this study are about 33% less than those estimated in the KDP-3 study. There are a number of reasons for this difference.

- A number of the benefits identified in the KDP-3 study were not assessed in the current study (e.g., landing planes prior to an airport impact rather than holding them, handling of diversions, missed connections).
- A number of elements identified earlier seem to be done less frequently (if at all) at Atlanta than at Memphis, Orlando, and Dallas.
- Some ITWS benefits identified by the ATC users at Atlanta were not significant benefits at Memphis and Orlando (e.g., a higher AAR with a sheared vertical wind profile that causes compression of arrivals, a higher AAR during GDP).

Certain of these differences reflect the differences in the airport operations. Atlanta is much busier than either Memphis or Orlando and uses GDPs to reduce the traffic volume during convective weather. Use of GDPs at Memphis or Orlando was quite rare in the mid 1990's. The spatial extent of the Atlanta holding patterns is certainly much greater than at Memphis or Orlando.

We believe that another important factor is the training provided to the users and the very active participation of individuals at key ATC and airline facilities in the Memphis and Orlando testing. The Memphis and Orlando users were trained by the MIT Lincoln Laboratory local ITWS demonstration system operations team, and ATC users could ask weather situation-specific questions in real time as issues arose. The Orlando tower and TRACON personnel provided key inputs for the development of many of the IOC ITWS features (e.g., the depiction of storm motion, storm extrapolated positions, and display features) and have continued to play important roles in the overall ITWS program since the KDP-3 decision. Additionally, Steve Vail, head TMU at the Memphis ARTCC and Rob Draughon, head TMU at the Jacksonville ARTCC were key contributors to the development of the ITWS operational concept.

By contrast, the Atlanta ITWS training focused primarily on the use of a computer based package that, in our opinion, emphasizes operation of the display features much more than the use of the products for the ATC and airline decisions shown in Tables 8 and 9. There has been some limited operational training at Atlanta TRACON by a very experienced FAA TRACON user from Orlando, but we are unaware of any similar training by an experienced FAA ARTCC user.

During discussions with users at Atlanta TRACON on our second visit, we were told that some of the benefits we asked about were definitely possible with more ITWS familiarity and better training. Hence, it is not surprising that some key ITWS delay reduction benefits identified at Orlando and Memphis (e.g., DTA closure anticipation, ATA reopen anticipation) are not currently being realized at the same level at Atlanta. The benefits opportunities that were identified in the KDP-3 analysis that were not assessed in the current study clearly should be a part of any follow-on program of ITWS benefits analysis at Atlanta as discussed in Chapter 8.

In such a follow on program, data should be gathered on the benefits of ITWS at the Atlanta tower. The principal anticipated benefit from the use of ITWS in the Atlanta tower would be increased efficiency of departure operations when a severe weather avoidance plan (SWAP) was in effect. Based on the NY ITWS experience [Allan, et. al, 1999] we would expect to observe:

1. improved airport surface traffic management (e.g., assigning aircraft to an appropriate departure runway and organizing the departures on a taxiway so that aircraft whose planned route is blocked do not obstruct other departures)

2. providing the tower with common situational awareness of enroute constraints for departures enables the tower to assist the TRACON and ARTCC in identifying and utilizing departure opportunities. This is particularly important when the DTAs have been closed and/or used to handle arrivals.

Another ITWS benefits area that clearly warrants additional assessment is the benefit to the Delta airlines hub operations at Atlanta. Delta was one of the major participants in the development of the ITWS concept in the early and mid 1990's because they were a major airline at Orlando. In that time frame, Delta's access to the ITWS products from the Orlando ITWS prototype was via a dedicated situation display (essentially identical to the demonstration ITWS situation displays used by the FAA facilities). As noted above, Delta is a very significant user of the ATL ITWS products via the CDMnet server operated by Volpe National Transportation System Center[18]. Time did not permit a more detailed assessment of the Delta benefits identified earlier (e.g., avoiding diversions and fewer missed connections) in our study. Recommendations for such an assessment are presented in Chapter 8.

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[18] The Delta access to the Atlanta ITWS is limited to some degree by the communications bandwidth of the CDMnet. If the ITWS products were available on a server connected to the Internet (as is the case with the MIT Lincoln Laboratory-operated ITWS demonstration sites), there undoubtedly would be much greater usage of the Atlanta ITWS products by Delta and other airlines.

TABLE 8
Projected ITWS Delay Reduction Benefits at Atlanta for ITWS KDP-3 Benefits Roll-up with Climatology Adjustment from Bieringer et al., (1999)

Benefit Category	Hours saved
Anticipating DTA closure	668
Balancing DTA traffic	189
Shorter terminal flying distances for departures	20
Fewer occasions of ramp gridlock	155
Anticipating runway shift (thunderstorm)	71
Anticipating runway shift (gust front wind shift)	0
Recognizing that one runway will remain open	1,577
Anticipating airport reopening	189
Landing planes before event rather than holding them	554
Positioning holding aircraft for quicker landings	118
Anticipating ATA reopen	713
Recognizing that ATA will remain clear	701
Anticipating ATA closure	594
More arrivals before AAR reductions	34
Fewer first tier ground stops	71
Shorter ground stops	331
Better recognition of advantageous ground stops	0
Holding jets higher	0
Fewer diversions before airport shutdown	0
Fewer diversions near airport reopening	0
Calling necessary diversions sooner	0
Airline dispatch avoiding specifying alternate airport	0
Improved fueling estimates in marginal weather	0
Improved warning of severe surface winds	0
Improved handling of priority connecting flights	0
Fewer missed connections at hubs	0
Subtotal	**5,985**
Downstream Delay	**4,788**
Total	**10,773**

TABLE 9
Comparison of the Results of This Study with KDP-3 ITWS Benefits Analysis Estimate of Atlanta Delay and Operations Cost Savings

KDP-3 Estimate with Climatological Correction		This Study	
	Hours Saved	**Hours Saved**	
Anticipating DTA Closure	668		Infrequently done by Atlanta TRACON
Balancing DTA traffic	189	250	50% of "ATA/DTA opens earlier"
Shorter terminal flying distances for departures	20	125	Identify line gap
Fewer occasions of ramp gridlock	155		Not assessed
		226	Lower MIT restriction
		269	50% of "Avoiding ATA/DTA closure"
Anticipating runway shift (thunderstorm)	71		Not assessed
Recognizing that one runway will remain open	1,577	1,134	Shorter airport impact and/or recognizing partial airport closure
Anticipating airport reopening	189		
Landing planes before event rather than holding them	554		Not assessed
Positioning holding aircraft for quicker landings	118		Not assessed
Anticipating ATA reopen	713	250	50% of "ATA/DTA opens earlier"
Recognizing that ATA will remain clear	701	269	50% of "Avoiding ATA/DTA closure"
Anticipating ATA closure	594	148	Efficient routing in ZTL
More arrivals before AAR reductions	34		Not assessed
Fewer first tier ground stops	71		Not assessed
Shorter ground stops	331	320	Shorter ground stop
		260	Higher AAR during GDP
		297	Open route earlier – avoid reroutes
Fewer diversions before airport shutdown	0		Not assessed
Fewer diversions near airport reopening	0		Not assessed
Fewer missed connections at hubs ($0.35 M)	0		Not assessed
Higher AAR with sheared vertical wind profile	0	520	Higher AAR on days with compression
Total Direct Hours Saved	**5,985**	**4,068**	

5. ATLANTA ITWS DELAY REDUCTION VIS-A-VIS ATLANTA AND NATIONAL CONVECTIVE SEASON WEATHER DELAYS

One test of the reasonableness of the Atlanta ITWS delay reduction estimates in Chapter 4 is to compare those estimates to the weather delays nationally and at Atlanta. In particular, the ratio of the estimated ATL delay reduction in Chapter 4 to

a. the total weather delay for the NAS and for Atlanta arrivals and

b. the average number of minutes of delay savings per flight during times when convective weather within the coverage region of the Atlanta ITWS impacts Atlanta operations

is of interest for two reasons.

1. The variability (year-to-year, day-to-day, etc.) in the amount of convective weather delays that occur may be viewed as a "noise" that one must consider in attempting to measure ITWS benefits by comparison of delay statistics (as will be done in Chapter 6).
2. These ratios may be viewed as a coarse "reasonableness test" given that concerns have been raised by the FAA independent investment analysis group (Citrenbaum, personal communication, 2004) that the claimed delay reduction for various current and proposed systems is comparable to the amount of convective delays that currently occur.

Since Atlanta was second in the NAS in terms of operations and OPSNET delays from 1997-2003 (Figure 1) and since delays associated with Atlanta convective weather can result in delays at other airports due to "downstream" delay propagation (discussed subsequently in Chapter 7), one is interested in both delays as measured at Atlanta and overall NAS delays.

5.1 TOTAL SUMMER WEATHER DELAY FOR THE NAS AND FOR ATLANTA ARRIVALS

The observed delays in the NAS represent a combination of weather-induced delays and delays due to factors that do not involve the weather, such as airline and FAA equipment malfunctions and congestion. We are interested here in estimating the weather-induced delay. The primary objective for such an estimate is to provide an upper bound on the pool of delays in the NAS that might be possible to be mitigated through systems such as ITWS. A common complaint is that programs are claiming more delay savings than there are minutes to be saved. An objective measure of the upper bound of possible delay savings is therefore important.

One method of estimating weather-induced delay (both direct and "downstream") in the NAS is to first determine the average arrival delay per flight relative to schedule on a "weather free" day. One then subtracts that average "fair weather" arrival delay per flight from the average total arrival delay per flight for all days in the analysis period. This results in an estimate of the average arrival delay per flight that is due to weather.

One of the important elements of our approach is the use of arrival delays relative to schedule as opposed to arrival delays relative to flight plan. On a weather free day, it could be argued that using arrival delay relative to flight plan would be appropriate because it would reduce the impact of winds aloft on arrival delay. However, when convective weather is present or forecasted along a nominal flight path, airlines file flight plans to avoid the weather-impacted areas. The resulting flight path is generally much longer than the nominal flight path (Section 2.4). In this case, the aircraft is delayed relative to schedule but not relative to flight plan. Using "relative to flight plan" in these circumstances results in an underestimate of the weather-related delay.

We also use "two-sided" delays in the computation of the average arrival delays. The sign convention associated with these delays is as follows: flights that arrive late relative to scheduled arrival time have a positive delay while flights arriving ahead of schedule have a negative delay.

Airlines typically base the schedule block time for a flight on a metric (e.g., the median) that is representative of typical block times for that particular flight in the past. (The block time is the difference between when the aircraft leaves the gate at the origin airport and arrives at the gate of the destination airport.) Using a mean or median value for block time implies that some flights exhibit shorter block times (e.g., on weather free days in the NAS when schedules run smoothly) while others exhibit longer block times (e.g., on days when weather significantly disrupts the schedule). One expects that most flights will arrive early on "weather free" days (see Table 10).

ITWS products are most useful during convective weather events. To minimize the contribution of non-convective weather delay events, we focused on the months of May through August in the years analyzed.

Identifying a NAS-wide weather-free day in the summer of 2004 proved to be quite challenging. An initial set of candidate days was suggested by minimum values of the Free Flight convective weather impact index (Post, 2002). These were then cross-checked against the CIWS site operations reports and data provided on the National Oceanic and Atmospheric Administration Real-Time Verification System (RTVS; Mahoney, 2002). Some days with low index values had appreciable weather and were rejected. Finally, it was determined that 4 May 2004 had the lowest average arrival delay for the ASPM airports with no CCFP forecasts being issued over land the entire day and no significant weather appearing on the RTVS web site. However, ORD experienced adverse weather in the form of wind shear, as indicated in the following ATCSCC log for 4 May 2004.

“1837 ORD GDP until 0500z due to WEATHER, WIND SHEAR

PROGRAM AAR: 82/82/82/100/100/100/100

FLIGHTS INCLUDED: ALL CONTIGUOUS US DEPARTURES

CANADIAN AIRPORTS INCLUDED: CYHZ CYOW CYUL CYYZ

DELAY ASSIGNMENT TABLE APPLIES TO: ZAU

AVERAGE DELAY: 39

MAXIMUM DELAY: 92”

A correction was made for the Chicago Midway International Airport (MDW) and ORD ASPM delays on 4 May as shown in Table 10.

To compensate for the weather-related arrival delay at Chicago, the contribution of MDW and ORD to the total minutes of arrival delay relative to schedule on 4 May was removed and replaced by the total minutes of arrival delay relative to schedule at MDW and ORD on 5 May, when no wind shear problems existed. Note that both ORD and MDW had positive average delays relative to schedule on 4 May and negative average delays relative to schedule on 5 May 2004[19]. The end result of the computation is an estimate of **-3.3 minutes per aircraft as the average “fair weather” arrival delay relative to schedule** for the airports considered in the ASPM computations.

TABLE 10
Computation of Minimum Average Arrival Delay (Relative To Schedule) Per Aircraft for the NAS in the Summer of 2004

	Number of Aircraft	Average Delay with respect to Schedule (min)	Sum of Delays with respect to Schedule (min)
5/4/2004 including ORD and MDW	23,539	-2.88	(67,792)
5/4/2004 ORD	1,367	0.49	670
5/4/2004 MDW	411	5.49	2,256
5/4/2004 without ORD and MDW			(70,719)
5/5/2004 ORD	1,384	-4.67	(6,463)
5/5/2004 MDW	404	-1.39	(562)
5/4/2004 + 5/5/2004 ORD and MDW		**-3.3**	(77,743)

Note: The final result (-3.3 minutes) appears again in Table 11.

[19] The change in ORD average delay was over 5 minutes per aircraft while the change in MDW average delay was almost 7 minutes per aircraft between these two days.

We compensated for only primary delays at Chicago. Analyzing and compensating for the "downstream delays" at Chicago on 4 May would have necessitated analyzing the individual flight delays using the results of Beatty et al., (1999). This refinement would have required significant time for marginal additional information.

Computing the weather-related delays for all of the days was straightforward and is shown in Table 11. The use of a factor of 70% as an estimate for the number of air carrier flights represented in the ASPM database was based on a personal communication from Carleton Wine, project lead for the ASPM database. The projected direct arrival delay reduction for Atlanta ITWS (Chapter 4) is about 0.4% of the national excess arrival delay relative to schedule shown in Table 11[20]. By excess arrival delay we mean all arrival delay relative to the minimum delay with respect to schedule calculated on a fair weather day from Table 10.

TABLE 11
Computation of Arrival Delay Due to Adverse Weather at Airports that Report Arrival Delays to the ASPM Database for May through August of 2004

Number of flights	2,815,547
Average arrival delay (two-sided) per aircraft relative to schedule (min)	8.4
Fair weather average arrival delay per aircraft (in min from Table 10)	-3.3
Excess average arrival delay per aircraft (min)	11.7
ASPM-derived excess arrival delay (hr)	549,032
Excess arrival delay assuming ASPM represents 70% of air carrier flights (hr)	784,331

One can continue further and carry out a similar computation for arrivals at Atlanta alone. The results are:

- Average Atlanta arrival delay per aircraft on 5/4/2004 is -6.85 minutes.
- Average Atlanta arrival delay per aircraft for May through August 2004 is 10.84 minutes.
- Number of ASPM arrivals at Atlanta for May through August 2004 is 161,785 flights.
- ASPM-derived arrival weather delay at Atlanta for May through August 2004 is 47,700 hours.

[20] We assume here that approximately 80% of the annual delay shown in Table 7 occurs between May and August.

- **Arrival weather delay relative to schedule at Atlanta from May through August 2004** (assuming that 83%[21] of the air carrier aircraft at Atlanta report delays through ASPM) is **57,469 hours.**

We stress that although the number shown above is an estimate of the weather-related delay for arrivals into Atlanta, the cause of the delays is not necessarily weather in or near Atlanta.

To understand the degree to which other major airports might be a factor in the Atlanta arrival delay, we examined the contribution of DFW, George Bush Intercontinental Airport/Houston, MCO, LGA, EWR, Philadelphia International Airport (PHL), Ronald Reagan Washington National Airport, Logan International Airport/Boston, and ORD to the average arrival delay per aircraft at Atlanta.

It was found that certain of these airports clearly were significant factors in the arrival delays at Atlanta. For example:

- The average arrival delay per aircraft for flights from EWR was 23.4 minutes.
- The average arrival delay per aircraft for flights from PHL was 23.0 minutes.
- The average arrival delay per aircraft for flights from ORD was 19.4 minutes.

Thus, the flights from EWR and PHL had average arrival delays into Atlanta relative to schedule that were over twice the average arrival delay per flight for all ASPM flights into Atlanta. The ORD flights had an average delay about 66% greater than the average arrival delay per flight for all ASPM flights into Atlanta.

The flights originating from the 9 high-delay airports accounted for 17% of the arrivals into Atlanta and 27% of the arrival weather delay per aircraft. The average Atlanta arrival delay per aircraft for the flights from airports other than the nine considered above was 9.53 minutes. This is about 1.3 minutes less than the average arrival delay for all flights.

Since ITWS was in operation at Atlanta throughout 2004, the arrival delays observed were post-ITWS delays. The bulk of downstream delays arising from late arrivals into Atlanta would typically be observed as arrival delays at other airports. That is, a plane arriving late at Atlanta is likely to depart late on its next flight leg, which results in a late arrival at the destination airport. For this reason, one should compare the direct arrival delay reduction from Table 7 with the Atlanta arrival weather delay shown in Table 11.

The projected arrival delay reduction in Chapter 4 is about 5% of the excess arrival delays (relative to schedule) at Atlanta for May through August 2004.

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[21] Delta Airlines reports delays through ASPM and Delta Airlines represents a large fraction of all Atlanta operations. Thus, the percentage of aircraft reporting delays through ASPM at ATL is 83%, rather that the 70% national average.

A similar calculation for 2003 using 5/13/03 as the Atlanta "fair weather" day showed that the projected arrival delay reduction in Chapter 4 is about 7% of the excess arrival delays (relative to schedule) at Atlanta for May through August 2003.

These results suggest that the calculated delay savings due to ITWS detailed in Chapter 4 are not large relative to typical convective weather delays. Additionally, one should make a correction to account for the convective weather that occurs at Atlanta outside the months of May through August. This would have the effect of reducing the ratio of projected arrival delay reduction to excess arrival delay. One approach would be to consider all the months from March through October in estimating the excess arrival delay. However, from Figure 14, it is clear that the additional months would include a number of low ceiling/visibility delay events in the excess arrival delay. The difference this correction was expected to make was marginal, so was not included in this study.

5.2 PROJECTED DELAY REDUCTION AT ATLANTA IN TERMS OF MINUTES PER FLIGHT IMPACTED BY CONVECTIVE WEATHER IN THE ATLANTA ITWS COVERAGE REGION

Another "reasonableness" test that can be applied to the Atlanta ITWS benefits estimate in Chapter 4 is to estimate the delay savings for flights that would be impacted by convective weather within the Atlanta ITWS coverage region.

We have shown that substantial delays due to convective weather can occur for storms within the TRACON and near the ARTCC-TRACON interfaces. In the transitional en route airspace, arriving planes descend and are vectored to the arrival fixes and departures climb to cruise altitude. This airspace is at least another 50 nmi beyond the TRACON boundary. Since the TRACON itself typically has a radius of 40-50 nmi, the region of concern for assessing "terminal" convective weather impacts is inside a circle of radius 100 nmi around the airport.

Typical thunderstorms are only a few miles in diameter. Clearly situations may arise where the airport and its immediate surrounding area experience fair weather while there is operationally significant convective weather within the TRACON and/or the en route transition area. In these cases, weather may impact the TRACON and transitional area operations even though there is no thunderstorm reported at the airport.

Bieringer et al., (1999) use radar data from the Dallas/Ft. Worth and Orlando NEXRADs to develop a radar-based storm-day climatology for the two sites. A radar-based storm day is defined as a day during which convective weather is detected by radar within 10 nmi of the airport. Comparing the station observation data with the radar-based data, they found that radar data indicated 65% more storm days at DFW and 73% more storm days at MCO than were reported by station observations at the respective airports.

The ratio of radar-observed convective weather impact days to station-observed thunderstorm days was even greater for a 50-nmi radius circle (i.e., the TRACON) centered on the airport. There were 2.48 times as many radar-based storm days within the DFW TRACON and 2.01 times as many radar-based storms days in the MCO TRACON than were reported by station observation at each of the airports. Bieringer et al., (1999) attribute the difference in the ratio between the two sites to differences in weather patterns. The Dallas area has more line storms that may enter the edge of the TRACON, while the Orlando area has more air mass type thunderstorms. Air mass storms typically are evenly distributed throughout the TRACON, increasing the likelihood that a thunderstorm will be observed at the airport when air mass storms occur.

These results are a statement about the relative number of days in which thunderstorms occur at some time during the day in various spatial regions (e.g., within 5 nmi or 10 nmi or 50 nmi of an airport) and are <u>not</u> a statement about the relative amount of time storm impacts occur on a given day. For example, a 10 nmi-wide squall line passing through the TRACON at a speed of 25 knots results in a single thunderstorm observation for the day both at the airport and within the TRACON. However, the duration of the thunderstorm impact on the TRACON is 4.4 hours. The duration of impact on the airport is only 0.8 hours. The TRACON impact duration is 5.5 times greater than the airport impact duration. An example of this for a quasi-squall line that disrupted Atlanta on 11 June 2003 is shown in Figure 24. Traffic patterns were disrupted for over 5.5 hours.

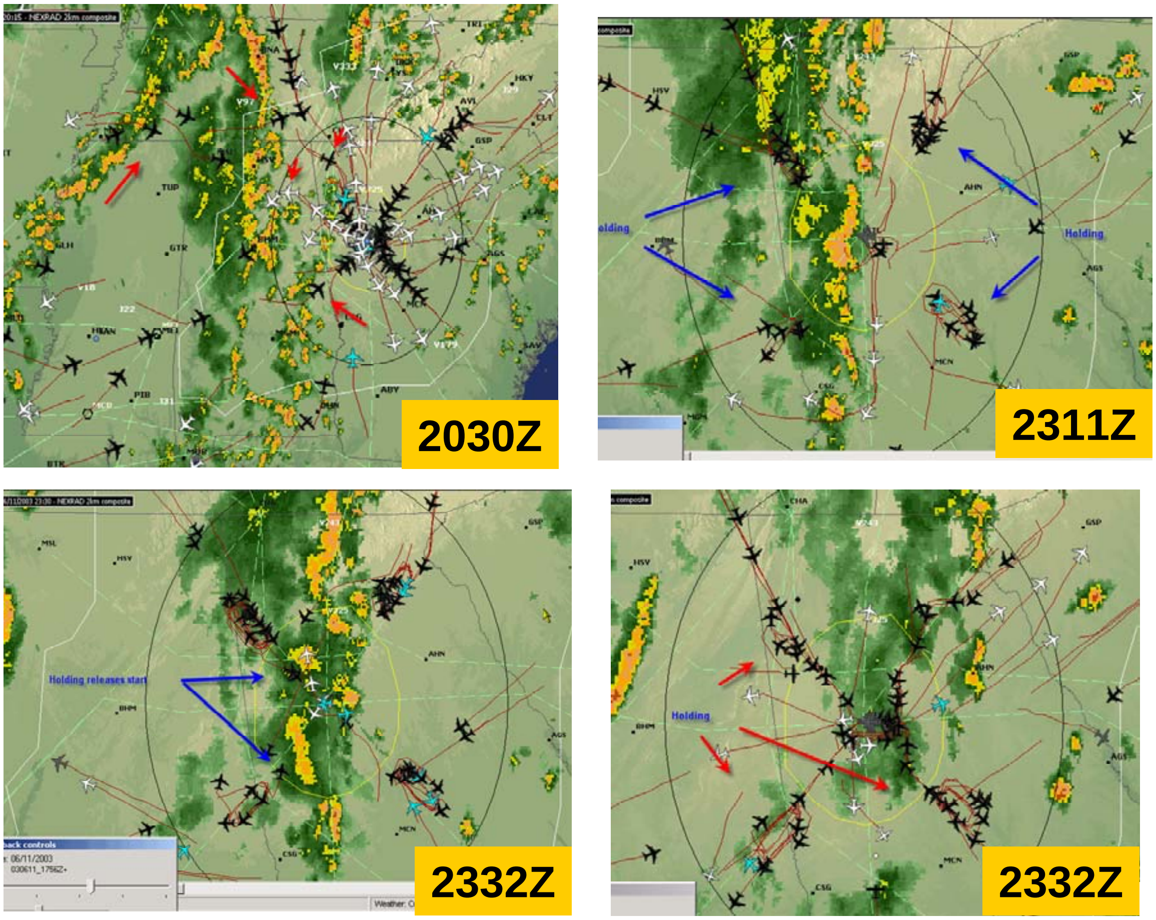

Figure 24. Broken squall line that passed through Atlanta on 11 June 2003. METAR reports occurred for 2153 UTC to 2237 UTC (44 minutes). The traffic patterns for Atlanta arrivals (black aircraft) and departures (white aircraft) were disrupted for over 5.5 hours. Compare traffic patterns shown in this figure to the fair weather patterns shown in Figure 12.

For air mass thunderstorms, the time ratio of airport impacts to TRACON impacts is roughly proportional to the ratio of the area of the storms causing the impact to the area being impacted [e.g., π x (region radius + typical storm radius)^2]. Assuming an air mass storm radius of 4 nmi, the ratio of the total time of storm impacts somewhere in a TRACON (region radius = 40 nmi) to storm impacts at the airport (region radius = 4 nmi) would be about 30:1.

We conducted a study of the relationship between the times the National Weather Service METAR[22] reported a thunderstorm at an airport and times during which convective weather in or near the terminal area was clearly disrupting operations (e.g., causing diversions, significant flight deviations around storms, holding patterns, and/or reduced departure rates). Using ATL METAR data from six such days in 2003, we determined that:

- The median length of time per day with METAR TS reports was 1.38 hours.
- The median time per day during which convective weather within 100 nmi of Atlanta caused traffic disruptions was 8.1 hours.
- The day-to-day variation in the ratio of thunderstorm delay impact time to METAR TS observation time was 2.7 to 28.2 with a mean value of 10.

The Atlanta long term climatology data suggests that on the average there are 47 days per year with a thunderstorm observed at the Atlanta airport. However, it is extremely important to note that **highly disruptive convective weather may be present within the Atlanta ITWS coverage region even in the absence of a thunderstorm observation at the Atlanta airport,** as shown in Figures 25 and 26. Moreover, traffic disruptions due to thunderstorms within the 100 nm radius of the airport are 6 times longer than the length of time thunderstorms are reported within the airport area. It is clear that using length of time that METARs report TS at the airport as a direct measure of the amount of time traffic is disrupted by convection severely underestimates the true amount of time that convection within 100 nm of ATL disrupts ATL traffic.

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[22] METARS reports when thunder was heard at the observing station (i.e., a "TS" observation). The accepted criteria for such reports (Federal Meteorological Handbook, 1988) are:

"A thunderstorm is observed at a station when either
a: thunder is heard, or
b: overhead lightning or hail is observed, but the local noise level is such as might prevent hearing thunder."

The accepted range for auditory detection of thunder is about 5-7 miles. Automated surface observation systems use Automated Lightning Detection and Reporting Systems (ALDARS) that can provide cloud-to-ground lightning reports out to 10 nmi from the airport. ALDARS reports a thunderstorm at the airport only if the lightning is within a 5-mile radius of the airport (FAA, 1999). Hence, the effective detection range for TS observations from either source is approximately 5 nmi.

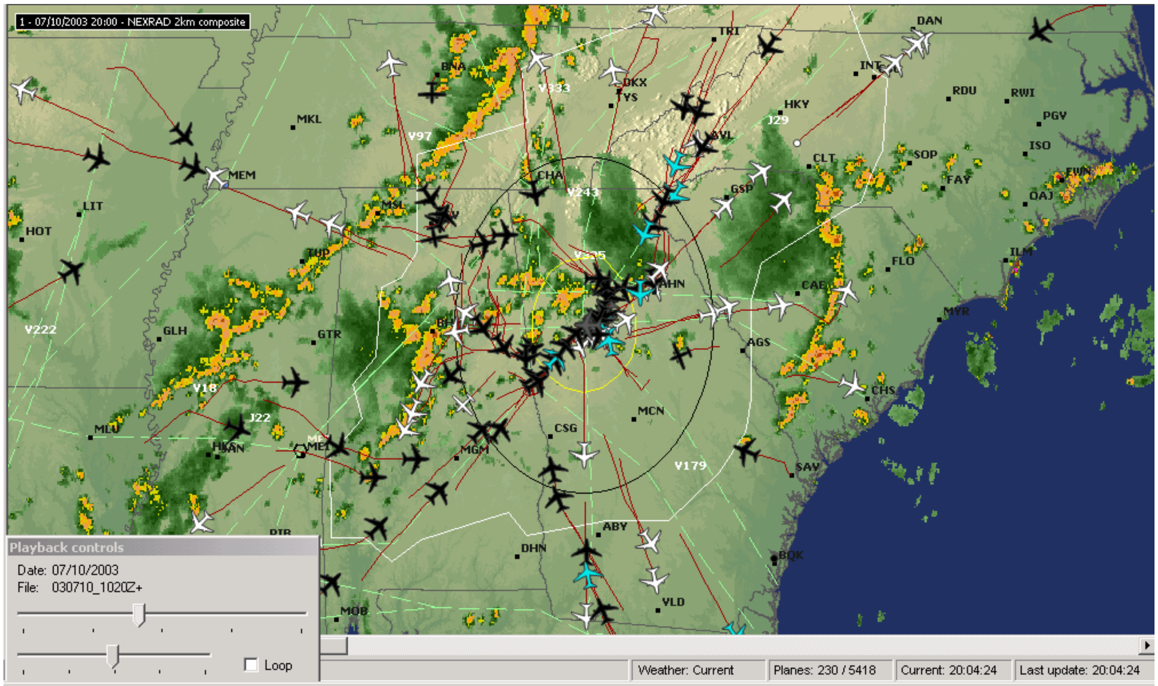

Figure 25. Traffic at 2000 UTC on 10 July 2003.

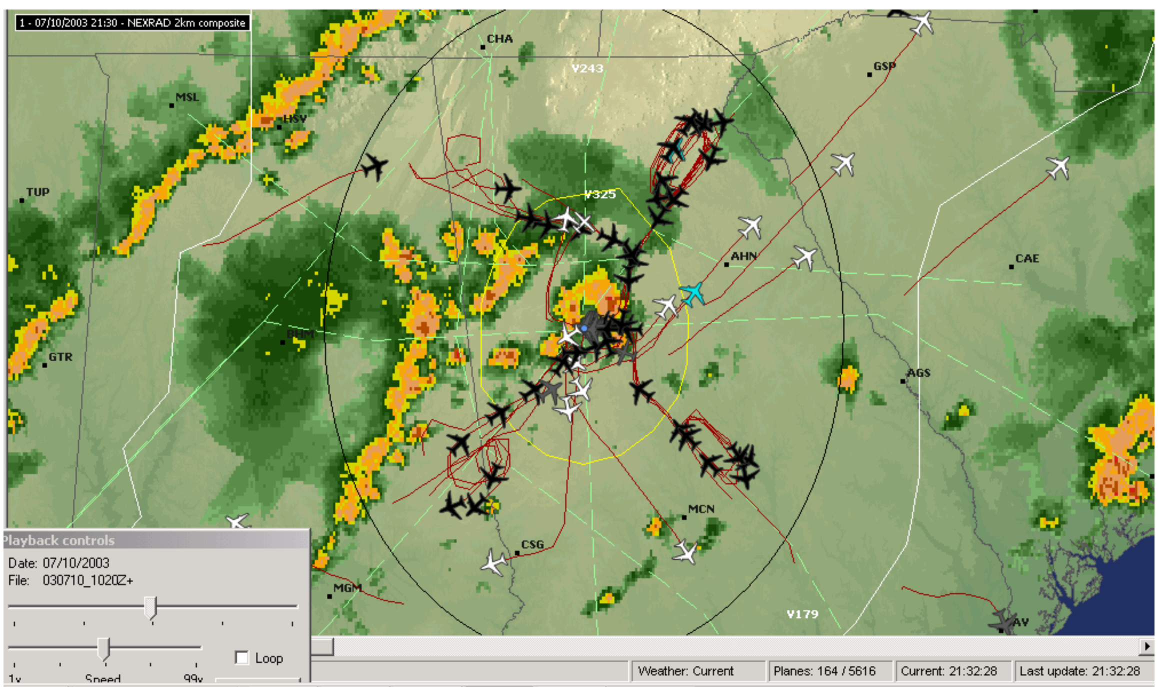

Figure 26. Traffic at 2132 UTC on 10 July 2003. There was <u>never</u> a thunderstorm METAR for Atlanta at any time on 10 July 2003 even though convective weather was in or near the Atlanta TRACON for over 5 hours. Note the very small number of departures and the major holding patterns.

From Figures 25 and 26, it is clear that we need to apply the models established by Bieringer et al., (1999) to estimate the time period during which convective weather is in or near the Atlanta TRACON, given the Atlanta METAR climatology data. This is done in Table 12.

Ideally, we would have multiplied the time duration for storms within 100 nmi by the climatological frequency of storms within 100 nmi. Since Bieringer et al., (1999) did not provide statistics for storms within 100 nmi of the airport; we chose to use their results for storms within 50 nmi of the airport. Since all storms within 50 nmi are also storms within 100 nmi, the approximation in Table 12 clearly understates the duration of weather impacts within 100 nmi of Atlanta. The end results are the estimates shown in bold in Table 12:

- Expected airborne arrival delay savings per aircraft due to better handling of airport storm impacts is 0.33 minutes for all aircraft on a TS day.
- Expected airborne arrival delay savings for non-airport related delay reductions within the ITWS coverage is 0.5 minutes per aircraft on days with convective weather impacts in or near the terminal area.
- Expected minutes of delay reduction per departure on days with convective weather within 100 nmi is 0.67 minutes.

Thus, we see that the expected magnitude of the flight-time change at Atlanta is on the order of 1.1 minutes per arrival aircraft on days with a thunderstorm observation at Atlanta airport and 0.8 minutes per arrival aircraft on days that do not have a thunderstorm observation at Atlanta. This result is useful for the ASPM data analysis reported in Chapter 6 and suggests that the calculated benefits reported in Chapter 4 are plausible.

Convective weather impacts create queue delays. The period of delays associated with a convective weather event at Atlanta can extend well beyond the time period of the weather impact itself (i.e., the time period for which the queue length is > 0 for times t > T in Figure 4). We feel that the delays per aircraft on days with convective weather impacts are the most reasonable metrics for this particular "reasonableness" test. These estimates seem quite reasonable in the context of the many minutes of delay that are clearly occurring in the various figures (e.g. Figures 15 to 17 and Figures 25 and 26) showing flight tracks for arrivals at Atlanta during convective weather conditions.

TABLE 12
Atlanta ITWS Delay Reduction Per Convective Weather Impacted Aircraft for Principal Operational Benefit Situations

Arrival benefits for airport impacts		Source
Atlanta TRACON benefits		
Days per year with thunderstorm observations	47	50-year average (www.weatherbase.com)
Days per year with convective weather impacts within 10 nmi of airport	78	Bieringer et al., (1999) results
Hours of airport operations impacts per thunderstorm day	1.81	Average of continuous METAR times from 22 thunderstorm days at Atlanta in 2003
Hours of airport operations impacts per thunderstorm year	140	50-year average x Bieringer factor x average METAR duration from 2003
Number of arrivals per day at Atlanta	1,310	2003 daily operations
Average arrivals per hour between 6 AM and 11 PM	70	2003 operations
Hours of delay reduction for arrivals associated with airport impacts	567	From Table 7
Minutes of delay reduction per arrival scheduled during airport operations impact times	6.3	Delay reduction divided by (hours of airport operations impacts x arrivals per hour)
Minutes of delay reduction per arrival on days with thunderstorms at the airport	**0.33**	Delay reduction x 60 divided by (arrivals per day x number of airport operations impact days)
Arrival benefits for non-airport impacts		
Number of days per year with convective weather impacts within 50 nmi of airport	94	Bieringer et al., (1999) results
Median time (hrs) per thunderstorm day at Atlanta where there were storms within 100 nmi of ATL	8.1	MIT Lincoln Laboratory analysis of 6 days in 2003
Hours per year with convective storms within 100 nmi of ATL	765	Number of days per year x median duration
Hours of airborne delay reduction for arrivals associated with non-airport convective weather impacts	1027	From Table 7
Minutes of airborne delay reduction for non-airport related convective weather impacts per arrival on days with convective weather within 100 nmi	**0.50**	Delay reduction x 60 divided by (arrivals per day x number of days with convective weather within 100 nmi of ATL)
Departure benefits		
Hours of delay reduction for departures	1375	From Table 7
Delay reduction per departure on days with convective weather within 100 nmi of ATL given in minutes	0.67	Hours of delay reduction x 60 divided by (departures per day x number of days with storms within Atlanta ITWS coverage)

6. RESULTS OF AN EXPLORATORY STUDY OF ATLANTA ITWS BENEFITS QUANTIFICATION USING ASPM DELAY STATISTICS

6.1 INTRODUCTION

In this chapter, we report on the results of exploratory research characterizing the delay reduction provided by the Atlanta ITWS. We compare ASPM delays pre- and post-ITWS at Atlanta. In Chapter 2, we noted that the measured Atlanta delays can be impacted by many factors other than ITWS that are different between the two time periods including:

- Weather differences (both convective and non-convective) within the Atlanta ITWS coverage,
- Demand,
- Fleet mix,
- Policies on management of en route congestion caused by convective weather (e.g., Spring 2000, “growth without gridlock”),
- Airline scheduling and operations procedure changes (e.g., changing the scheduled block time for a flight between two cities and/or deciding when a flight would be cancelled),
- Introduction of other systems (e.g., CTAS, CCFP, traffic flow management), and
- Weather outside the ITWS coverage region (e.g., en route convection, low C/V and/or winds and/or convective weather at the airports that are origins for Atlanta arrivals or destinations for Atlanta departures).

Due to time constraints, we were not able to carry out a complete data analysis effort in which one would:

a. choose the cases analyzed so as to minimize the impact of the factors above, and
b. adjust the delay statistics to compensate for any residual differences.

However, the research did prove very useful by exposing a number of additional issues that need be addressed in a more definitive study.

ITWS was in full operational use in 2003. MIT Lincoln Laboratory and (independently) the FAA selected for study the 2001 period prior to September 11th as the pre-ITWS baseline time period. The work reported here is based on the MIT Lincoln Laboratory study alone.

One of the major challenges in assessing arrival delays at Atlanta (given that ASPM has only limited delay-causality information) is that arrival delays can be affected by both en route weather and weather at the origin airport. Similarly, departure delays can be affected by both en route weather and weather at the destination airport. Atlanta has approximately 2600 operations a day.

Of those operations,

- 7% of the traffic from Atlanta is destined for Florida, which has an abundance of weather impacts in en route airspace and at the terminals.
- 24% of the flights are to the northeast (New York, Washington, Boston, Pittsburgh, and Philadelphia), and
- 13% of the flights are to the north-central region (e.g., Chicago, Detroit, and Minneapolis).

Given that a) many of the airports in the northeast and north-central regions are notorious for delays and b) these regions frequently exhibit major en route congestion problems in convective weather[23] (Robinson et al., 2004), the normalization problem would be very difficult unless one focused on initially analyzing delays that did not involve assessing and compensating for en route and/or terminal weather in this portion of the country.

6.2 FLIGHT TIME ANALYSIS OF ARRIVALS FROM 100 NMI TO TOUCHDOWN AT ATL

To reduce the complexity of the analysis (and following a suggestion by the FAA ATO-P analysts), we focused initially on traffic handling in convective weather near the ITWS domain. Based on the ATC user feedback discussed above, 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 terminal area (within a 60-80 nmi radius). In particular, it was hoped that the change in average flight-times from 100 nmi to touchdown on days of terminal convective activity between 2001 and 2003 could be equated to ITWS delay reduction. Possible differences in the severity of the convective weather events then would be reduced by using many days from the time periods before and after ITWS was introduced. To maintain compatibility with FAA internal studies (Citrenbaum, personal communication) average flight-times would be compared for 22 METAR-identified thunderstorm days each from 2003 and 2001 (Table 13).

An important factor to consider in the design of the ASPM data analysis and interpretation is the magnitude of the expected effect, i.e., the change in flight-times that one would expect based on the user feedback/modeling analysis discussed in Chapter 4. In Chapter 5, we showed that

- The expected airborne arrival delay savings per aircraft due to better handling of **airport** storm impacts is 0.33 minutes.

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[23] Robinson et al., (2004) show that the Washington and Indianapolis ARTCCs that handle the Atlanta traffic into the CIWS domain experienced en route convective weather over 100 days between April and September in 2003.

- The expected airborne arrival delay savings for non-airport-related delay reduction within the ITWS coverage (i.e., out to 100 nmi from the airport but not near the airport) is 0.5 minutes when convective weather occurs in or near the terminal area.

Thus, the expected magnitude of the flight-time change is on the order of *0.8 minutes per aircraft* on days with a thunderstorm observation at the Atlanta airport.

The ASPM flight-times from 100 nmi to touchdown were determined for each of thunderstorm days shown in Table 13 and for non-thunderstorm days shown in Table 14. It is important to stress that the non-thunderstorm days were identified using a combination of Atlanta METARS and weather radar data from the RTVS website[24] (Mahoney et al., 2002). It is well known that there are many days when the Atlanta METAR does not report a thunderstorm but convective activity impacts TRACON operations[25]. Thus, it is very important to use radar data to determine that there truly are no convective weather impacts on airport operations.

In Table 15, we show the comparison of the mean and median ASPM flight-times for the various days in the two years. The difference between average flight-times on thunderstorm days and average flight-times on non-thunderstorm days in 2003 is 3.2 minutes. This corresponds to the post-ITWS average delay per aircraft due to thunderstorms. Since the expected delay reduction on such days is 0.8 minutes, this suggests that the ITWS delay reduction benefit for airborne arrival delay corresponds to about 22% of the pre-ITWS airborne arrival delay due to thunderstorms.

[24] http://www-ad.fsl.noaa.gov/fvb/rtvs/conv/

[25] The results in Bieringer et al., (1999) suggest that for every day there was a thunderstorm observation at the Atlanta airport, there is another day during which convective weather occurred within 50 nmi of the airport without a corresponding thunderstorm observation at the airport.

TABLE 13

ATL Thunderstorm Days (June-August) for ITWS ASPM-Based Delay Analysis

2001		2003	
06/01/2001	07/04/2001	06/03/2003	07/11/2003
06/03/2001	07/05/2001	06/04/2003	07/14/2003
06/04/2001	07/09/2001	06/11/2003	07/15/2003
06/06/2001	07/24/2001	06/13/2003	07/22/2003
06/08/2001	07/25/2001	06/14/2003	07/30/2003
06/14/2001	07/28/2001	06/16/2003	07/31/2003
06/21/2001	07/29/2001	06/17/2003	08/03/2003
06/22/2001	08/04/2001	06/18/2003	08/16/2003
06/25/2001	08/13/2001	06/19/2003	08/19/2003
06/30/2001	08/18/2001	07/03/2003	08/28/2003
07/3/2001	08/31/2001	07/10/2003	08/30/2003

TABLE 14
ATL Non-Thunderstorm Days (June-August) for ITWS ASPM-Based Delay Analysis

2001		2003	
07/14/2001	07/22/2001	06/05/2003	06/23/2003
07/15/2001	08/15/2001	06/09/2003	06/24/2003
07/16/2001	08/21/2001	06/21/2003	06/25/2003
07/17/2001	08/22/2001	06/22/2003	
08/23/2001			

Note: These days were determined based on examining <u>both</u> METAR reports <u>and</u> weather radar data.

TABLE 15

Results of ATL ASPM 100 Nmi-To-Touchdown Flight-Time Analysis (Minutes)

	2001	2003	Delta
Average flight-time, non-thunderstorm	28.2	27.6	-0.6
Average median flight-time, non-thunderstorm	26.7	26.1	-0.6
Average flight-time, thunderstorm	31.8	30.8	-1.0
Standard deviation of daily mean, non-thunderstorm	1.0	1.2	-0.2
Standard deviation of daily median, non-thunderstorm	0.6	0.6	0.0

Detailed investigation showed two major problems with using the ASPM flight-times from 100 nmi to touchdown for benefits analyses plus significant differences between the nature of the convective weather in 2001 and 2003. Thus, for purposes of convective weather delay analysis, the 100 nmi flight time metric appears to be calculated by an algorithm that does not yield accurate results when an aircraft must deviate away from the direct path flight route to avoid convective weather. Consequently, statistics using this metric are less meaningful and reliable.

6.2.1 Algorithm Used to Determine 100 nmi Crossing Time

It has recently been learned that the ASPM-determined time at which a plane comes within 100 miles of the airport is not measured from the time that the plane is within 100 nmi true range from the airport. (i.e., when the plane enters a circle of radius 100 nmi centered on the airport). Rather, the ASPM 100 nmi-to-touchdown flight-time statistic is computed using the assumption that an aircraft flies a great circle route from the origin airport to the destination airport. The flight-time statistic is then based on the time the plane crosses a line perpendicular to the great circle path and at a distance of 100 nmi from the destination airport. This distinction is quite important in convective weather since an Atlanta arrival may be vectored off the origin-to-destination great circle path and cross the perpendicular line at a point much further than 100 nmi true range from the airport.

6.2.2 Inability to Capture the Region in which Airborne Delays are Incurred due to Terminal Weather

The spatial extent of the ATC impact due to weather in or near the TRACON is an important factor. Lamond (2002) shows a number of examples of aircraft held at distances much greater than 100 nmi from an airport when convective weather impacted the airport. Apropos the Atlanta ITWS studies, one of Lamond's examples includes a Delta flight into Atlanta that is held at about 100 nmi. In the holding pattern, the aircraft crosses the 100 nmi boundary several times. This may explain the wide variations seen in flight-times from 100 nmi to touchdown apparent in the ASPM summary data statistics.

Figure 27 shows flight tracks and weather for one of the 2003 "thunderstorm days" in Table 13. Arrivals into ATL are shown as black plane icons with associated tracks in white. White plane icons are departures from ATL. The Atlanta TRACON is the white circle shown in the center. NEXRAD radar reflectivity is shown in green, yellow, and red. A squall line is nearing ATL. Holding patterns are located outside ZTL (light purple line) in Alabama and Tennessee. Clearly, arrivals are being held at distances greater than 100 nmi from the airport due to weather-related loss of TRACON/airport capacity. Such holding patterns also occur on days when convective weather impacts the terminal area, but METAR does not report a TS at the airport (Figure 28). The holding pattern to the northwest is the result of the blockage of the northwest arrival fix by convective weather.

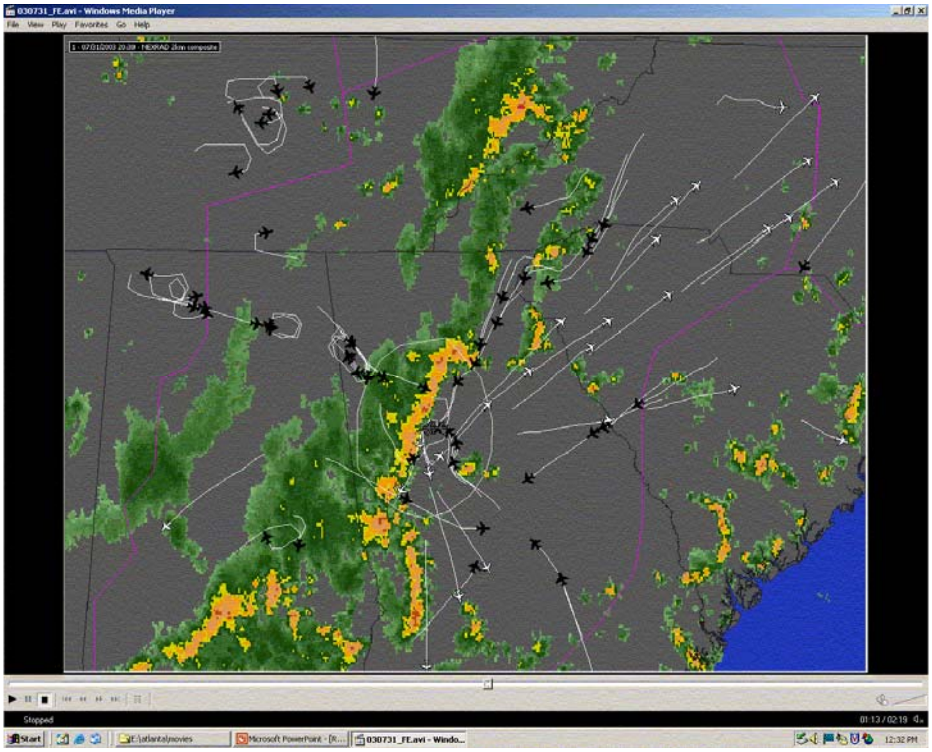

Figure 27. Aircraft tracks and weather at Atlanta at 2030 UTC on 31 July 2003 (one of the Atlanta "thunderstorm day" analysis cases in Table 13).

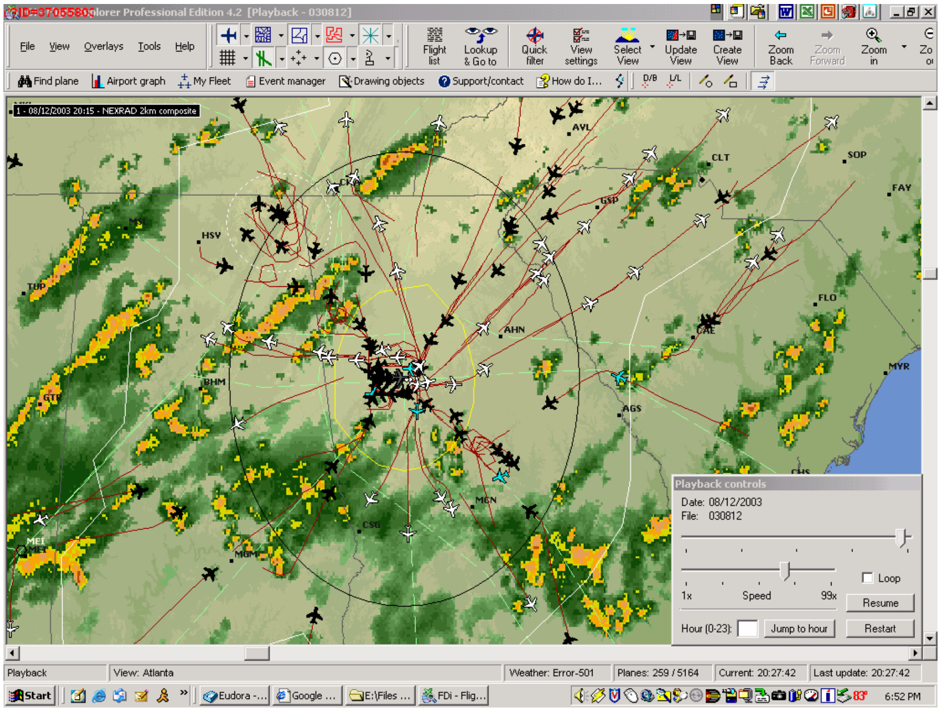

Figure 28. Aircraft tracks and weather at Atlanta on 12 August 2003. Note holding patterns that bracket the 100 nmi distance from ATL.

Recall that Figure 11 indicated that holding at the arrival fixes occurs virtually every weekday at Atlanta near 8 AM and in the afternoon due to congestion at the arrival fixes. Figure 15 showed that the holding patterns can be greater than 100 nmi from the airport on a day with very little convective weather. Hence, both in fair weather and convective weather, there are significant questions as to whether use of flight-times from 100 nmi to touchdown as a metric for capturing delays arising from terminal traffic management in Atlanta is adequate.

In the specific context of the ITWS delay reduction assessment, the deficiencies in the 100 nmi-to-touchdown flight-time metric identified above are definitely significant given that the expected flight-time differences are on the order of a minute.

6.2.3 Addressing the ASPM Data Quality and Interpretation Problems

To improve the accuracy of the ASPM flight-time estimates, we recommend that future analyses of ITWS benefits strongly consider deriving the flight-time estimates from tailored analysis of flight data records that can be retrieved from the ASPM and ETMS data sets and using only flights with OOOI data for certain calculations. This would permit the use of alternative algorithms for estimating quantities such as flight-time from 100 nmi to touchdown that were more appropriate for convective weather situations. By this pair of methodological improvements, it should be much easier to achieve accuracies on the order of a minute in the flight-times from 100 nmi to touchdown.

The problem of holding beyond 100 nmi is not as easily addressed. What one is seeking to do in the flight-time data analysis is to capture the region in which airborne arrival delays due to terminal weather are taken. Two options come to mind.

a) Exclude from the analysis days with holding patterns outside 100 nmi. However, this approach would very likely exclude the analysis of high delay days that are important to keep in the analysis data set.

b) Use a greater range from the airport in analysis. The problem with this approach is that the analysis might be impacted by weather outside the region of the ITWS.

We suggest using a greater threshold (e.g., 200 nmi) for the distance from the airport to handle the cases where airborne holding occurs at ranges beyond 100 nmi. This technique should only be used if it can be determined from radar data analysis that in doing so, one will not be including regions of en route convective weather that are also causing delays.

6.2.4 Differences in the Nature of the Convective Weather between 2001 and 2003

One might imagine that the use of 22 thunderstorm days per year would roughly normalize for the differences in weather between 2001 and 2003. However, this appears to be an erroneous assumption. Although 2001 and 2003 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 (Figure 29). For example, during the period June through August, ATL recorded 16.2 inches of precipitation in 2003 but only 10.5 inches in 2001. The amount of rain was 60 % greater in 2003 than during the same time period 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 TRACON 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 (Mahoney et al., 2002). Our study found that the number of time periods with continuous convective weather at the Atlanta terminal area was <u>significantly</u> higher in 2003.

Assuming that storms in the terminal area reduce the effective capacity of the airport and lead to queues (manifested in airborne holding patterns), it follows from Equation 1 that one might compare severity of the convective weather delay by considering the respective <u>sum of the squared durations</u> of terminal weather events. That metric suggests that the 22 thunderstorm days in 2003 used for the Atlanta ITWS study were **47% more severe** in terms of delays than the 22 thunderstorm days in 2001. **Both the precipitation differences between 2001 and 2003 and the queue delay-derived weather index suggest that the convective weather in 2003 was approximately 50% more severe than the convective weather in 2001.** This similarity in weather impact indices suggests that a direct comparison of delay statistics between 2001 and 2003 is not appropriate unless one either normalizes for the differences in the severity of the weather or compares delay for sets of days that are similar in the severity of ATC delays. Methods for accomplishing such a comparison are discussed in Section 6.3 and Chapter 8.

One could go further in quantifying the differences in the weather severity in 2001 versus 2003. For example, the RTVS validation data is only provided every two hours and the spatial resolution is quite poor. One could obtain high time/space resolution NEXRAD data sets from the NCDC and do a more detailed analysis. However, we think the better approach is to identify analogous convective weather events based on detailed analyses and then compare the ASPM delay for those dates.

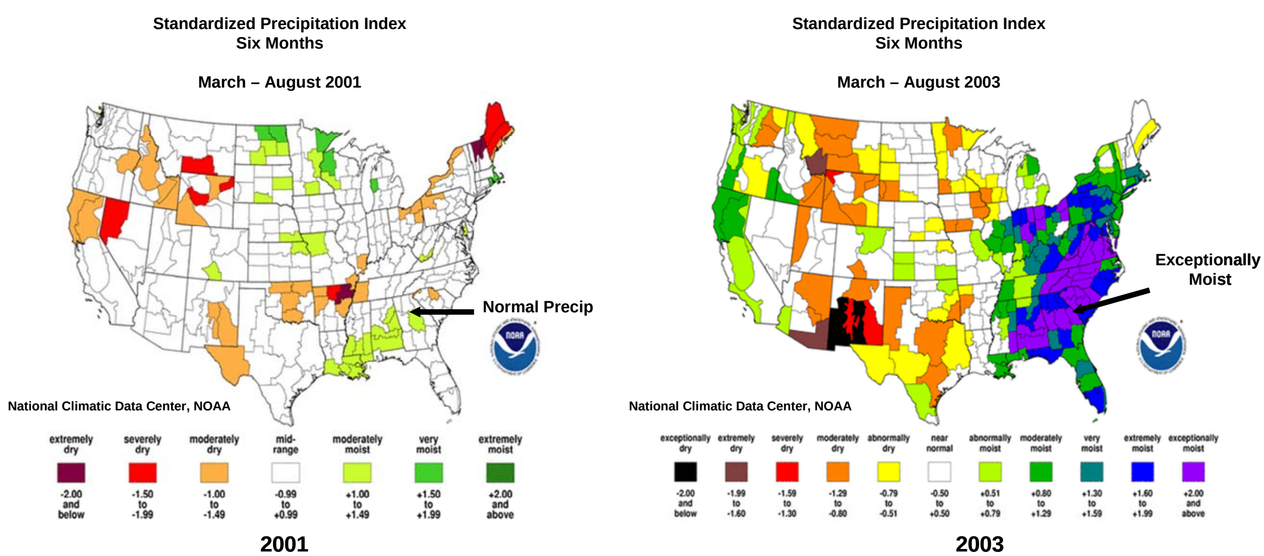

Figure 29. NCDC Standardized Precipitation Index during the six-month period from March through August for 2001 and 2003.

6.2.5 CTAS as a Factor in the ASPM Delay Analysis

A few words of discussion are in order regarding possible convective weather delay reduction provided by CTAS at Atlanta. We did not attempt to estimate the contribution of CTAS at Atlanta to reducing the delays during convective weather events. It may be that CTAS at Atlanta was an important factor in the reduction of the average flight-times on non-thunderstorm days in Table 15. However, given that:

a) Airborne holding patterns occur at Atlanta at peak arrival times during fair weather (Chapter 3) and

b) The current ASPM summary statistics evidently do not correctly capture either the holding patterns or the flight-time from a distance of 100 nmi from the airport to touchdown,

it is unclear whether a fair weather improvement in traffic management for arrivals has occurred at Atlanta. More importantly, even if CTAS does assist in reducing holding patterns (and hence airborne flight-times) in fair weather, it is not clear that CTAS provides a similar benefit in convective weather. The CTAS trajectory computations that are the heart of the CTAS algorithms do not take account of convective weather. The CTAS implicitly assumes that the plane can use the normal routes to the arrival fixes and from the arrival fixes to the runways. If convective weather is present, the CTAS algorithms may well assume that planes can fly through a convective storm. In that respect, one of the arguments made by the NATCA controllers' union at Dallas for having the CTAS Final Approach Spacing Tool (FAST) demonstration halted was that FAST gave erroneous guidance to controllers during convective weather events. We recommend that there should be intensive "blitz" observations similar to those conducted for the CIWS program (Robinson et al., 2004) to study the use of CTAS and ITWS during convective weather events at ZTL. This would provide insights into the utility of CTAS for reducing convective weather delays.

6.3 WHAT CAN ONE DO TO MAKE DELAY STATISTICS COMPARISONS A VIABLE ATLANTA ITWS PERFORMANCE MEASUREMENT TOOL?

6.3.1 Focus attention on specific situations in which one believes that there should be measurable reduction in delays

Since the Atlanta ITWS provides 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[26]. However, one can seek to find predetermined similarities in *degree* of convective impact identified by event duration, *specific* event location, comparable demand/capacity profiles (e.g., time of day, day of week, specific routes/airports involved), and unique city pairs involved.

For example, the distribution of weather in the Atlanta terminal area can be characterized at a high level by impacts on the two sets of airport runways, the four arrival fixes, and the various departure fixes. Even though two events may not have impacts on exactly the same fixes, the likelihood that convective weather will impact a similar number of fixes during different events is much higher than the likelihood that it will be the same fixes. Since the sources of the major traffic flows into a terminal generally have concentrated spatial orientations (e.g., the flow to Atlanta from the northeast is much greater than the flow from the southwest), there may need to be some adjustments to account for the traffic loading differences.

Similarly, one can look at departure delay reduction from Atlanta if one considers cases where weather is "local." Here local means that few if any of the routes to the destination cities are significantly impacted in en route or terminal airspace (e.g., consider only flights that meet this criterion). We would emphasize, however, that such simplifications should be developed as an outgrowth of in depth understanding of the ATC/convective weather dynamics for Atlanta. This understanding should be developed by:

- Discussions with knowledgeable ATC personnel from the Atlanta facilities and
- Confirmation of the utility of simplified capacity models by examination of movie loops of traffic plus convective weather

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[26] A detailed discussion of the rationale will be published elsewhere. However, the gist of the argument is that one can succinctly characterize the ATC impact of a convective weather by assessing which jet routes and fixes have been impacted. TRACONs alone typically have at least 14 such regions, which corresponds to 2**14 possible combinations for a given time. Each of these over 16,000 combinations typically 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 that two separate assignments of convective storm impacts to TRACON locations will agree exactly is vanishingly small.

as opposed to "data mining" only from delay and causality databases with insufficient detail (e.g., using only ASPM summary statistics and METAR data sets). In Chapter 8, we make a number of concrete suggestions for follow-on studies of Atlanta ITWS benefits based on comparisons of ASPM data.

6.3.2 Is a weather impact index a viable option for handling the differences in delays at Atlanta due to differences in the convective weather?

One of the "holy grails" of convective weather performance analysis is a convective weather severity index that enables one to compare delays on a normalized basis (e.g., normalized delay = actual delay/weather severity index). Metrics for the severity of convective weather have been developed by MITRE Center for Advanced Aviation System Development (Callaham et al., 2001) and the Free Flight Program (Post et al., 2002). The common denominator in both of these indices (see Figure 30) is that the index is the space/time sum of the product of a weather severity factor (radar reflectivity or lightning) and the fair weather traffic density at a particular location. Post et al., (2002) show an example of how national delays increased roughly proportionally with increases in the Free Flight convective index. Both of these indices are appealing in that they consider weather and demand simultaneously. However, on closer inspection it is clear that there are significant problems with either of these indices as a tool for detailed quantitative analysis. One problem is that the indices are not sensitive to the manner in which a route is closed. For example, if a squall line is aligned along a single major route, the index would give roughly the same value as if the squall line were perpendicular to a number of major routes that travel in a given direction (e.g., east-west in the Midwest or southwest to northeast along the east coast). However, the disruptive effect is clearly much greater when a number of major routes are blocked than when a single route is blocked.

The functional dependence of both indices (linear in demand, weather coverage, and weather event duration) is completely inconsistent with the functional dependence of queue delays on demand, capacity, and event duration. One needs to have a weather severity index that <u>explicitly</u> considers:

- Capacity of terminal and en route airspace with the actual weather locations (including consideration of the convective weather features demonstrated to be critical for route usage such as storm reflectivity, echo tops, lightning, storm type, and growth/decay) and
- The degree to which rerouting (which leads to a longer-path-flown delay) as opposed to ground holding (use of queues at the departure airport) and/or airborne holding can be used to address the loss of capacity due to convective weather.

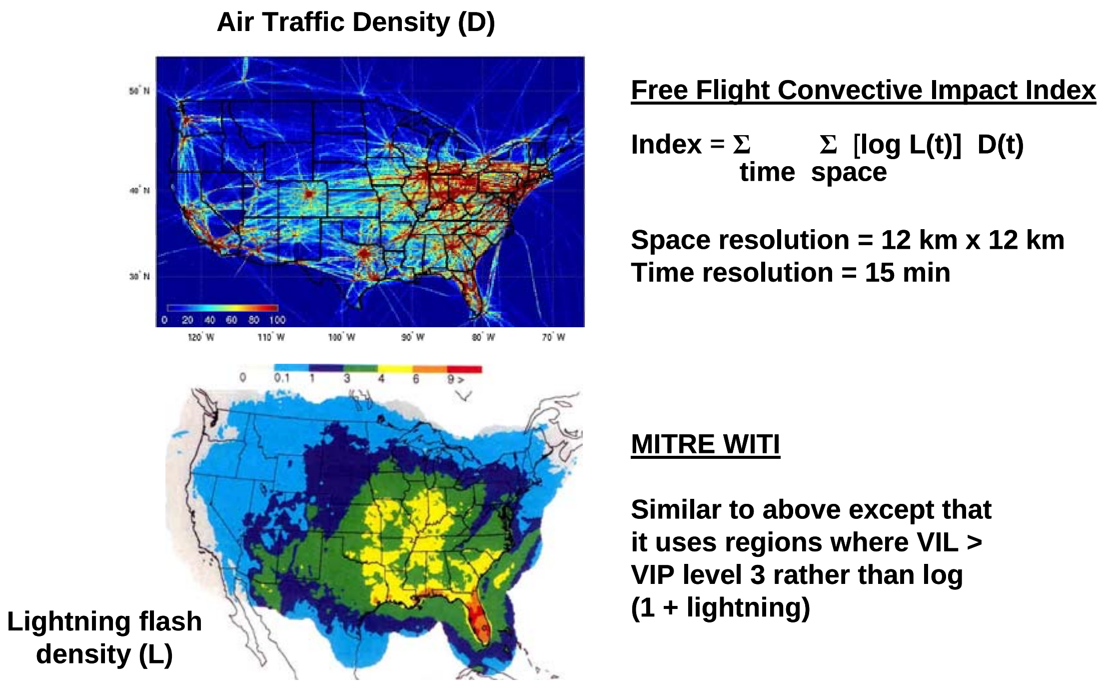

Figure 30. Contemporary convective weather severity indices. The Free Flight Program was developed by CNA (Post et al., 2002) while the Weather Impacted Traffic Index was developed by MITRE CAASD (Callaham et al., 2001).

Developing such an index requires some substantial research and development.

- Adequately validated models for terminal and en route capacity with convective weather do not yet exist.
- Some very preliminary work has been done on approaches for optimizing the use of rerouting and/or holding, but there needs to be many more detailed studies with comparison to actual events.
- Although there has been some useful work on how to model downstream delays, there is some question as to whether those delays should be included in a severity index. One option for handling this might be to consider indices with and without downstream effects.

We believe that the development of such an index would benefit the operational use of convective weather decision support systems and improve the ability to assess the convective delay reduction benefits of individual systems such as the Atlanta ITWS. However, given the magnitude of the effort to develop such an index, it would have to be a major FAA undertaking and could not be developed by the ITWS program alone.

7. STUDIES OF "DOWNSTREAM" DELAY MODEL FOR ITWS

In this chapter, we review the basis of the downstream delay model used for the ATL ITWS benefits results presented above. In addition, we describe new results of ASPM database analyses to substantiate the flight delay propagation model used in this and other ITWS delay reduction studies.

The delay propagation model is important because approximately 44% of the hours of delay reduction and about 31% of the monetary delay savings for ITWS are associated with reducing downstream delays. Downstream delay is the "delay ripple" effect which arises when an aircraft is delayed on one leg of a flight (e.g., due to adverse weather) such that subsequent legs flown by that aircraft that day also are delayed. The delay on subsequent legs is typically[27] manifested as a gate departure delay that is not recovered as the aircraft travels from the origin gate to the destination gate. This results in an arrival gate delay relative to schedule. The late arrival on subsequent legs is reported in ASQP statistics, but is not an OPSNET reportable delay. In cases where the subsequent leg(s) are not weather impacted, the delay on the subsequent legs may not be attributed to the weather that caused the initial delay. Questions were raised by the FAA independent analysis of ATL ITWS delay reduction benefits concerning the magnitude of the downstream delays used in the previous ITWS study. Hence, studies reported here use the ASPM database and further substantiate the downstream delay model used in the ITWS benefits studies.

The next section very briefly reviews the basis for the ITWS downstream benefits model. Section 7.2 presents the results of delay propagation for a major non-hub airline whose flights were delayed departing from MDW in 2004. The results in Section 7.2 confirm that downstream delays can be very significant and suggest that the model used for downstream delay benefits for the ATL ITWS (and ITWS in general) is quite conservative in terms of the magnitude of downstream delays. Section 7.3 discusses the costs associated with downstream delay.

7.1 BASIS FOR THE ITWS DELAY PROPAGATION MODEL

7.1.1 Past Literature on Downstream Delay

Downstream delay or delay ripple has been discussed extensively in the airline and air traffic control literature for over a decade. DeArmon (1992) states that "delay ripple is in general pretty strong" and persists over a number of successive legs. Hartman (1993) cites a case where the number of passengers delayed (down line impact) due to delay ripple was 27 times greater than the initial number delayed. DeArmon et al., (2000) discuss the use of flight cancellations by various airlines to reduce the impact of delay ripple.

[27] Downstream taxi-in delays can also occur on later legs if there is no gate available for the flight when it arrives late at the destination airport.

7.1.2 Studies of Downstream Delay for a Hubbed Airline

A recent study by a group from American Airlines and Oak Ridge National Laboratory (Beatty et al., 1999) looked at the impact on the American Airline operating resources (specifically aircraft <u>and</u> crews[28]) as a result of an initial delay. They examined the actual impact on the American Airlines' operations schedule as a function of both time and amount of delay. As the delay on the initial flight increases, the number of flights affected increases and both aircraft and crew constraints come into play. The down line impact is a highly nonlinear function of the initial amount of delay and when during the day the delay is incurred. The end result of their work is a "delay multiplier" table that characterizes the degree of delay propagation as a function of the time of day and magnitude of the initial delay encountered.

7.1.3 Model for Downstream Delay used for Atlanta ITWS Benefits Study

In this study, we utilize the approach taken in the ITWS delay reduction study conducted by the FAA, the Volpe Transportation Systems Center, and MIT Lincoln Laboratory in 1994-95. Based on the analysis of arrival delays relative to schedule on multiple legs for aircraft passing through LGA, Dr. Steve Boswell of MIT Lincoln Laboratory developed a model in which the amount of arrival gate delay recovered per leg is a random variable (Boswell and Evans, 1997). This model suggests that the initial delay savings should be multiplied by 1.8 to arrive at the net delay savings (That is, the total downstream delay is approximately 80% of the initial delay). The Boswell model considers only downstream delays to the aircraft that is initially delayed and ignores the flight crew constraints that Beatty et al. (1999) consider.

7.1.4 Relationship of Downstream Delay Model used for Atlanta ITWS Benefits Study to the Results of the American Airlines Study

Since Atlanta operations are dominated by the Delta hub operations similar to the American Airlines at DFW, the downstream delays experienced at both hubs should be similar. Therefore, a comparison of the Beatty model and the downstream delay model used here is germane. Beatty's delay multiplier table was used to determine how much delay is needed at various times of the day to result in a delay multiplier value of 1.8. Some representative initial delay values are shown in Table 16. Twenty four minutes of delay at 8 AM in the morning results in the same delay multiplier (1.8) as about 3 hours of delay at 7 PM. A relatively small amount of delay early in the day can propagate throughout the schedule until it has the same impact as a very large delay at the end of the day.

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[28] They also note that there are impacts on passengers, cargo, and gate space caused by delayed flight operations. However, they were not able to quantify the impacts of delays on those other resources and the extent to which impacts on the other resources would further increase the delay impact. As a result of ignoring these other factors in airline operations, Beatty et al., (1999) suggest that their results are very conservative.

TABLE 16
Delays and Times of Day Resulting in a Delay Multiplier of 1.8, Based on Beatty et al., (1999)

Time of Day (Local)	Delay
8 AM	24 minutes
1 PM	1 hour
5 PM	1.5 hours
7 PM	3 hours

When applying the Beatty model, it is very important to consider the downstream delay benefit marginal multiplier, which is the delay multiplier associated with an increase or decrease in delay around a nominal delay value. When a flight is late as a result of earlier delays that day and then encounters an additional arrival delay, the delay multiplier associated with the additional arrival delay is that for the total arrival delay at that time as opposed to the incremental delay on the current leg. For example, if a plane is running late one hour and then encounters a delay of 0.5 hours at 5 PM local time, the delay multiplier is not 1.2 (30 minutes at 5 PM) for the new delay of 0.5 hours, but is 1.8 for the total 1.5 hours of delay (1.5 hours at 5 PM). This is a difference of over 250% in the magnitude of the downstream delay.

Similarly, if ITWS reduces a one-hour delay to 45 minutes for a flight that would have arrived at 2 PM, the delay multiplier associated with the delay reduction of 15 minutes is about 1.7 (45 minutes of delay at 2 PM) whereas the delay multiplier associated with reducing a 15 minute delay to zero delay is 1.09 (0 minutes of delay at 2PM). The downstream delay savings is 10.5 minutes in the first case and 1.4 minutes in the second case for the same delay savings. This distinction is important because in many cases where delays to a flight are reduced by ITWS, the flight may already be running late and/or ITWS did not reduce the delay to zero.

To illustrate, if a GDP is put into place at Atlanta due to thunderstorms in en route airspace and/or in the TRACON, the flight is already delayed when it arrives within the ITWS coverage. If ITWS reduces airborne delay for that arrival after the plane enters the ITWS coverage area, the downstream delay multiplier applied to the portion of the delay that ITWS reduces pertains to the total delay the plane is experiencing at that point.

7.2 EXPERIMENTAL VALIDATION OF THE ITWS DOWNSTREAM DELAY MODEL FOR A NON-HUBBED AIRLINE

We validate the ITWS downstream delay model by considering downstream delay propagation in flights of a major airline for three days in 2004 during which there were convective weather delays at Chicago, but for which there was very little convective weather west of Chicago (as determined from the CCFP verification web site http://www-ad.fsl.noaa.gov/fvb/rtvs/conv/2001/animation/index.html). The airline chosen for this analysis is one of the very few airlines that is financially strong at this time and whose flight scheduling practices are being emulated by a number of other airlines (e.g., Jet Blue and the low cost subsidiaries of major airlines such as United and Delta).

We consider only westbound flights from Chicago to minimize the likelihood of additional weather delays obscuring the propagation of downstream delays[29]. Figure 31 shows the changes in scheduled:

- arrival delay on the preceding leg
- gate departure delay on the next leg
- airborne delay
- gate arrival delay on the next leg

where the flight labeling format is:

314-3= flight 314 on day 3

(This flight arrived at Kansas City International Airport [MCI] 28 minutes late from MDW. It departed the gate at MCI 29 minutes late and arrived at the gate at Albuquerque International Sunport Airport [ABQ] 34 minutes late. The ASPM database shows a block delay of 5 minutes for the flight from MCI to ABQ.)

It is instructive to follow an individual flight on several flight segments on a single day. For example, on day three (6/14/2004), Flight 574 departed MDW and arrived at MCI 128 minutes late. There were three subsequent flight segments:

574-3a= flight 574 aircraft leg "a" on day 3 (MCI to Salt Lake City International Airport [SLC])

574-3b= flight 574 aircraft leg "b" on day 3 (SLC to Seattle-Tacoma International Airport [SEA])

574-3c= flight 574 aircraft leg "c" on day 3 (SEA to Sacramento Metropolitan Airport [SMF])

We see that flight 574 finished the day arriving at SMF 110 minutes late relative to schedule due to inability to make up time on the three legs flown after the initial delay from MDW to MCI. In this case, the downstream delay was nearly three times the initial delay.

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[29] Since convective weather at Chicago typically moves to the east during the rest of the day, it would have been highly likely that flights from MDW to the east or south would have experienced additional delays on later legs.

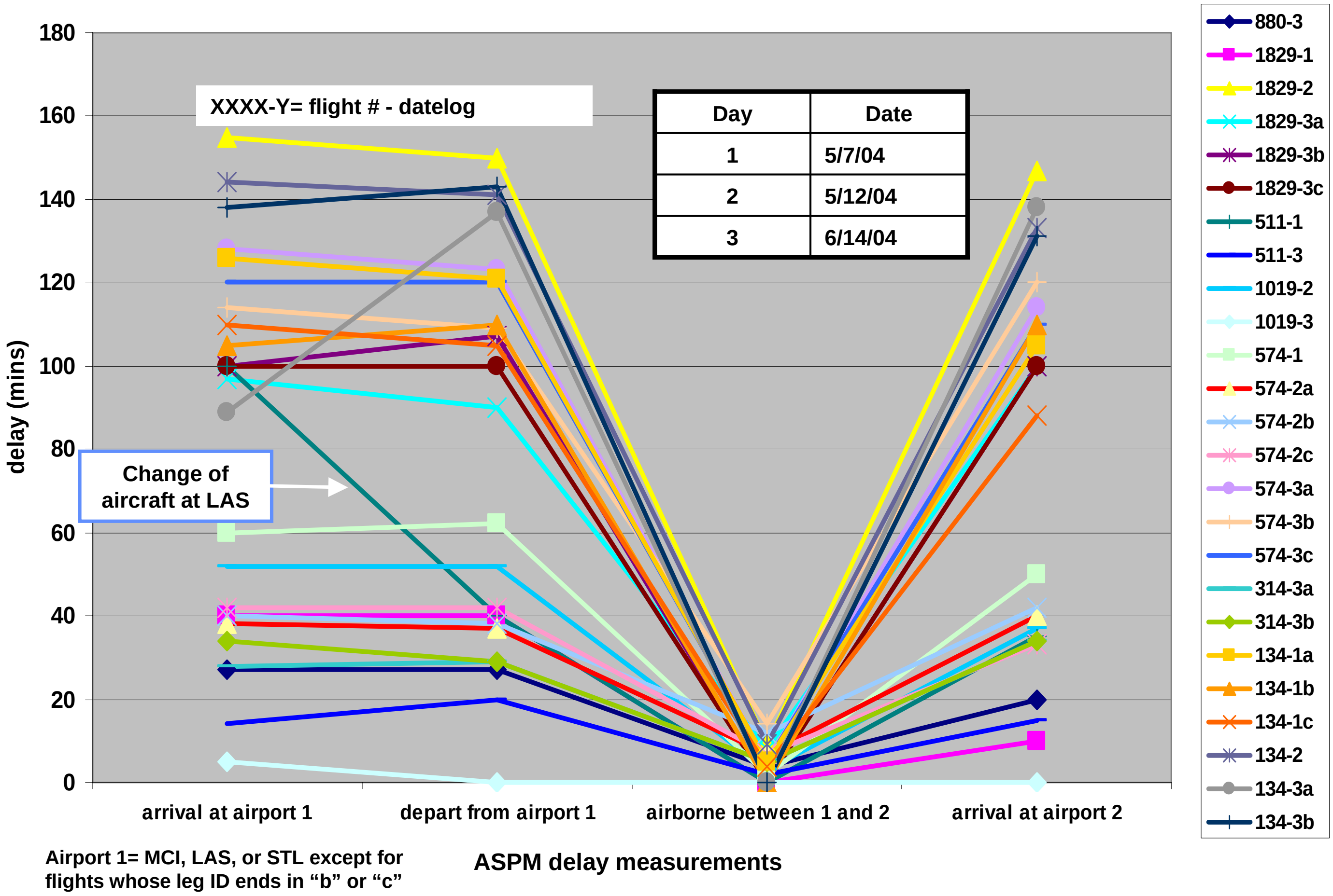

Figure 31. Propagation of arrival delay relative to schedule downstream for flights that were initially delayed at MDW in 2004. These were flights to the west of MDW on a day where the convective weather was at or east of MDW. Relatively little delay was reduced in the turn-around of the aircraft at airport 1.

In Table 17, we show the initial delay and time of day at which the aircraft was scheduled to arrive from MDW for the various flights in Figure 31. Flight 511-1a (from McCarran International Airport/Las Vegas [LAS] to Metropolitan Oakland International Airport [OAK]) shows an anomalous decrease of 65 minutes in gate departure delay on the subsequent leg. That flight arrived in LAS from MDW 100 minutes late. However, there was a change of aircraft tail number at LAS. The following leg experienced a departure delay of 40 minutes from LAS and arrived 35 minutes late at OAK. We believe the airline used another aircraft to fly the next leg. This was the only flight for which there was a change of aircraft. On the other hand, Flight 134 on 6/14/04 showed an anomalous increase in gate departure delay. The reason for this is unknown; possible explanations include late arrival of the flight crew for that leg, mechanical trouble and/or waiting for connecting passengers.

TABLE 17
Comparison of Downstream Arrival Delays Relative to Schedule Resulting from an Initial Delay on Various Flights from Midway to the Indicated Airport

Flight	Initial delay (min)	Initial airport and local time of day	Beatty delay multiplier	Beatty estimate of downstream delay (min)	Sum of downstream arrival delays wrt schedule (min)	Sum of downstream arrival delays/initial delay	Sum of downstream delays/Beatty estimate
1829-3	97	MCI 1:20 PM	2.3	126.1	300	3.1	1.3
574-3	128	MCI 3:20 PM	1.43	55.04	442	3.5	2.4
314-3	114	MCI 2:20 PM	2.3	248.2	250	2.2	1.0
134-2	89	MCI 4:50 PM	1.7	62.3	215	2.4	1.4
134-1	126	MCI 4:50 PM	2	126	303	2.4	1.2
574-2	38	MCI 3:20 PM	1.5	19	148	3.9	2.6
880-3	27	LAS 10:30 AM	1.42	11.34	30	1.1	2.6

The digit following the flight number indicates the date:

Day Date

1. 5/7/04
2. 5/12/04
3. 6/14/04

There are 25 flight legs plotted in Figure 31. Many of them overlap each other thus making it difficult to understand the actual statistical spread in results from Figure 31 alone. Twenty three of the legs plotted in Figure 31 did not display anomalous changes between gate arrival delay and gate departure delay. Detailed analysis of these 23 legs plus an additional 6 flight legs that are not plotted shows the following:

- Unloading and reloading the flight faster to reduce delays was not very effective. The airline was able to make up only a few minutes of delay between the late arrival and the following departure. The mean of the difference between the gate arrival delay and gate departure delay on next leg is 2.7 minutes, with a median difference of 4.0 minutes. The 25% quartile statistic shows no difference between arrival gate delay and gate departure delay on the next leg. The 75% quartile statistic shows a reduction of 5 minutes in gate departure delay relative to the gate arrival delay. The 90% quartile statistic shows a reduction of 8 minutes.
- The combination of unloading and reloading the flight faster and flying faster on the next leg appears to have a small impact on reducing the magnitude of downstream delay. The airline was able to make up only about 7 minutes of the previous-leg arrival delay relative to schedule by the time the plane arrives at the destination on the following leg. The mean of the difference between gate arrival delay relative to schedule at airport 1 and gate arrival delay relative to schedule at airport 2 is 6.6 minutes, with a median difference of 7 minutes.

These results suggest a mean block time savings of 3.9 minutes on the following leg.

Figure 32 shows:

- arrival delay on the preceding leg,
- gate departure delay on the next leg,
- airborne delay, and
- gate arrival delay on the next leg

normalized by the arrival delay relative to schedule on the preceding leg. Relatively little delay is recovered by an expedited aircraft ground turn-around, with the exception of the cases where the initial delay is only 5 minutes or another plane is substituted for the delayed aircraft (e.g., flight 511 on day 1). This follows from observing that the departure gate delays on the following leg are generally greater than or equal to arrival gate delays for the previous leg. As a consequence, the sum of the downstream arrival delays (relative to schedule) is in most cases much greater than 80% of the initial delay.

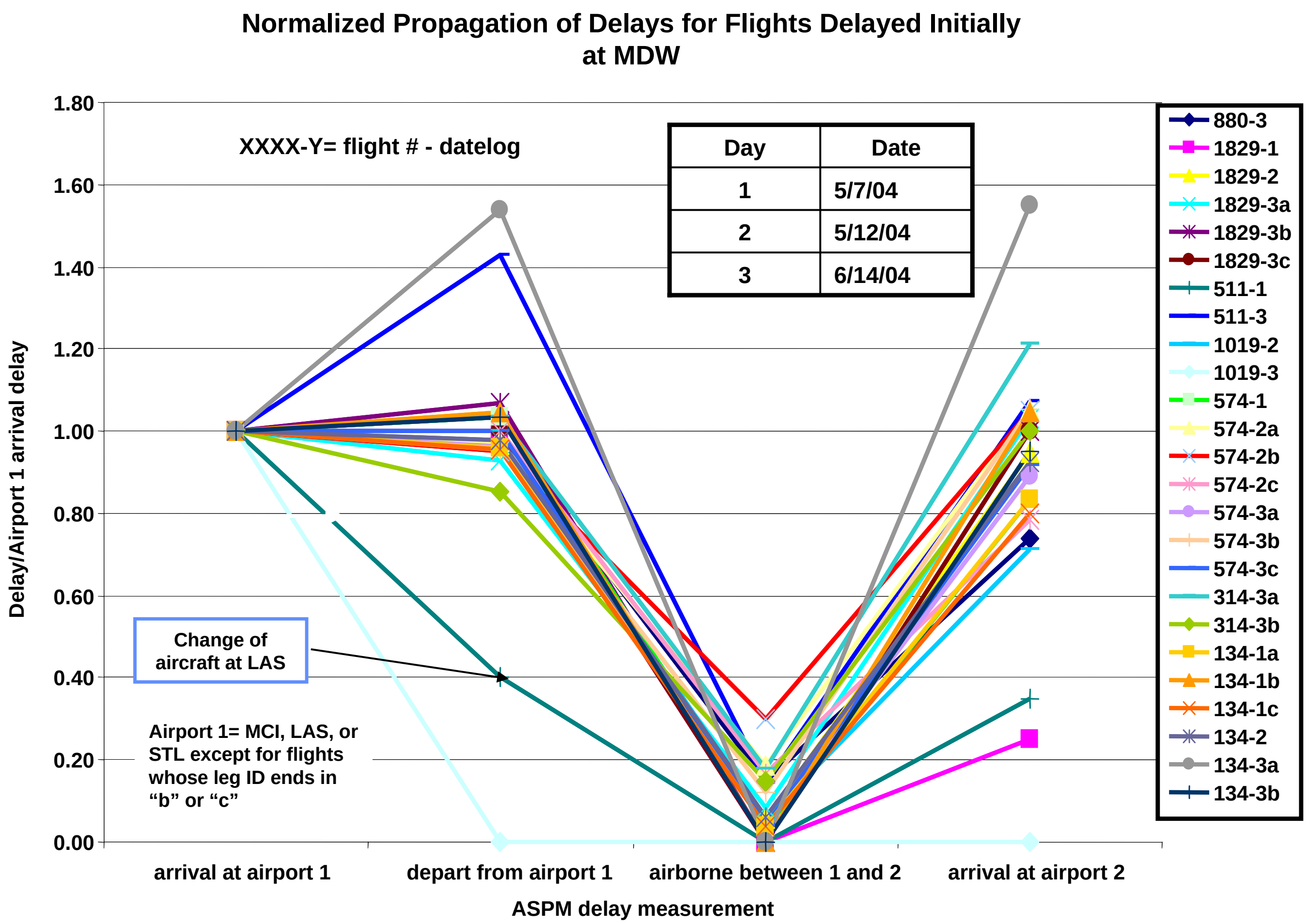

Figure 32. Propagation of normalized arrival delay relative to schedule downstream for flights that were initially delayed at MDW in 2004. These were flights to the west of MDW on a day where the convective weather was at or east of MDW. Relatively little delay was reduced in the turnaround of the aircraft at airport 1.

Table 17 provides a comparison of the sum of the downstream delays for many of the flights studied for several legs with the predictions of the (Beatty et al., 1999) model. In all cases, the sum of the downstream arrival delays relative to schedule was much greater than predicted by either the Beatty model or the model used for the CIWS study (Robinson et al., 2004). By and large, block delays on the later legs were zero, so the results of the two figures and Table 16 both provide substantiation for the model used in the CIWS study and suggest that it is quite conservative. The results provided here are for a limited study, but suggest that there are no significant downstream delay modeling issues that are a high priority for near term ITWS benefits study.

One could also track the propagation of downstream delay for the major airlines operating at ATL with the same approach used to analyze the flights from MDW. However, it may be somewhat difficult to find cases where the flights from Atlanta operate in fair weather for several legs. Many of the Delta flights that depart from Atlanta return to Atlanta later in the day. Hence, it is likely they will experience additional weather delays on the return legs and these delays would be mixed in with the residual downstream delays from earlier in the day.

7.3 MONETARY COST ASSOCIATED WITH DOWNSTREAM DELAY

The monetary cost associated with downstream delay is an important issue that warrants discussion. It is generally agreed that:

- Passengers are definitely affected by downstream delay and passenger time savings should include the downstream delay time savings.
- Aircraft do not fly longer on later flight legs due to the downstream delay propagation. Hence, there is no additional fuel cost associated with downstream delay.

Both of these assumptions are certainly borne out by the ASPM data analysis in the preceding section. However, there seems to be no accepted model for the airline costs associated with downstream delay. The airlines would/may experience costs due to a number of factors.

- There may be crew costs associated with a longer work day. For example the crew that flew the leg on which the initial weather delay occurred may exceed total workday time limits. Under these circumstances, the airline must find a new crew to fly one or more flight legs.
- A crew that flies the plane later that day may have to wait at the crew exchange airport for the aircraft to arrive. Depending on the particular company-union agreement, that crew may or may not be paid for this waiting time.
- Crews that may be destined to crew different flights, and who are flying on the delayed flight as crew members and/or as passengers, are delayed. As a result, their connecting flights may also be delayed.
- Passenger and luggage constraints may result in additional flights being delayed. This is especially true at hub airports; but also occurs for non-hub airlines since their published itineraries show a number of options that involve connections between two flights.
- There is clearly a direct cost to the airline whose flight was delayed if a passenger is transferred to another airline’s flight due to a missed connection.
- The airline with the delayed flight will surely experience additional ground personnel costs (e.g., gate, customer service, and luggage handling personnel) in handling the late flight and its passenger/luggage at the destination airport of each subsequent leg.

There is abundant literature on the details of the disruptions caused by late flights[30], but very little literature on explicit cost models for the disruption. We recommend FAA discussions with the Airline Transport Association to develop a model for airline costs associated with downstream delay.

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[30] Beatty et al., (1999) note that for one of the cases they analyzed, an initial flight delay rippled through 54 subsequent flights due to the combination of crew and aircraft constraints.

8. SUMMARY

This report summarizes the results of an initial study to estimate the yearly delay reduction provided by the IOC ITWS at Hartsfield-Jackson Atlanta International Airport. In this section, we summarize the results of this study and make recommendations for follow-on studies at Atlanta and at other ITWS airports that are more representative of TDWR-equipped airports not receiving an ITWS in the initial ITWS production system deployment. These follow-on studies recommendations are tailored to address two relatively near term ITWS program issues:

- To provide benefits results for an OMB-300 submission to demonstrate that the ITWS program achieves major performance goals, and
- To provide data to substantiate the projected benefits for the ITWS locations that are not a part of the initial ITWS production system deployment (e.g., Dayton, OH and Tulsa, OK).

8.1 RESULTS OF THE STUDY

Specific objectives of this initial study were to:

- analyze convective weather operations at ATL to determine major causes of convective weather delay and how those causes might be modeled quantitatively.
- provide estimates of the Atlanta ITWS delay reduction based on the "Decision/Modeling" method using questionnaires and interviews with Atlanta TRACON and ARTCC operational ITWS users.
- assess the "reasonableness" of the model-based delay reduction estimates by comparing those savings with estimates of the actual weather-related arrival delays at ATL. In addition, the reasonableness of model-based delay reduction estimates was assessed by determining the average delay savings per ATL flight during times when adverse convective weather is within the coverage of the Atlanta ITWS.
- conduct an exploratory study to confirm the Atlanta ITWS delay savings by comparing ASPM delays pre- and post-ITWS at ATL, and
- assess the accuracy of the "downstream" delay model employed in this study by analyzing ASPM data from a major US airline.

All of these objectives were achieved and are briefly summarized below.

8.1.1 Analysis of Atlanta Convective Weather Operations

ATL is the second busiest airport in the country in terms of operations per year. In addition, it is typically one of the top ten airports with the highest number of OPSNET-reported delays per year. Previously, Atlanta ITWS benefits were projected based on the ITWS demonstration system operational use at MEM, DFW, and MCO. It is now clear from the Atlanta ITWS user interviews, ARTCC-provided statistics on airborne holding for ATL arrivals, and our analysis of ATL flight tracks and weather radar data that the delay causality mechanisms at work at ATL are a mixture of those affecting New York and MEM/MCO.

At MEM and MCO, the principal convective weather delay mechanism is aircraft flying longer distances than in fair weather.

At New York, the principal convective weather delay mechanism is queues that arise due to demand exceeding the convective weather arrival and/or departure capacity.

At ATL, there is a mixture of both delay causality mechanisms. Airborne holding is quite common when convective weather closes either arrival fixes or a runway. Departure queues are also common when convective weather closes either departure fixes or a runway. On the other hand, there are many situations where the convective weather is outside the TRACON or between the airport and the arrival/departure fixes but the traffic continues to proceed relatively smoothly, albeit on a longer than normal path.

The fact that airborne and ground queues are a fairly common feature of the ATL operations in convective weather is very important for studies of the delay reduction, since queue delays are very sensitive to changes in capacity, demand, and weather event duration.

8.1.2 "Decision/Modeling" Estimates of the Atlanta ITWS Delay Reduction

Combinations of the "linear" and "queue" model delays were developed for various beneficial decisions identified by the Atlanta terminal (TRACON plus tower) and ARTCC ITWS users. The use of combined linear and queue models to address the benefits for some cases is new. (Previous analyses used one model or the other.) This approach should result in more accurate benefits estimates for the Atlanta environment than in earlier studies.

The terminal users exhibited the greatest number of benefits categories and the greatest magnitude of delay reduction results. Figure 33 summarizes the direct delay savings in hours per year for the principal decisions. **The projected direct delay savings are 4,068 hours per year. The total delay reduction (including downstream delay) is about 7,322 hours per year, which amounts to about $ 23 M per year** when using the conversion factors in Robinson et al., (2004)**.**

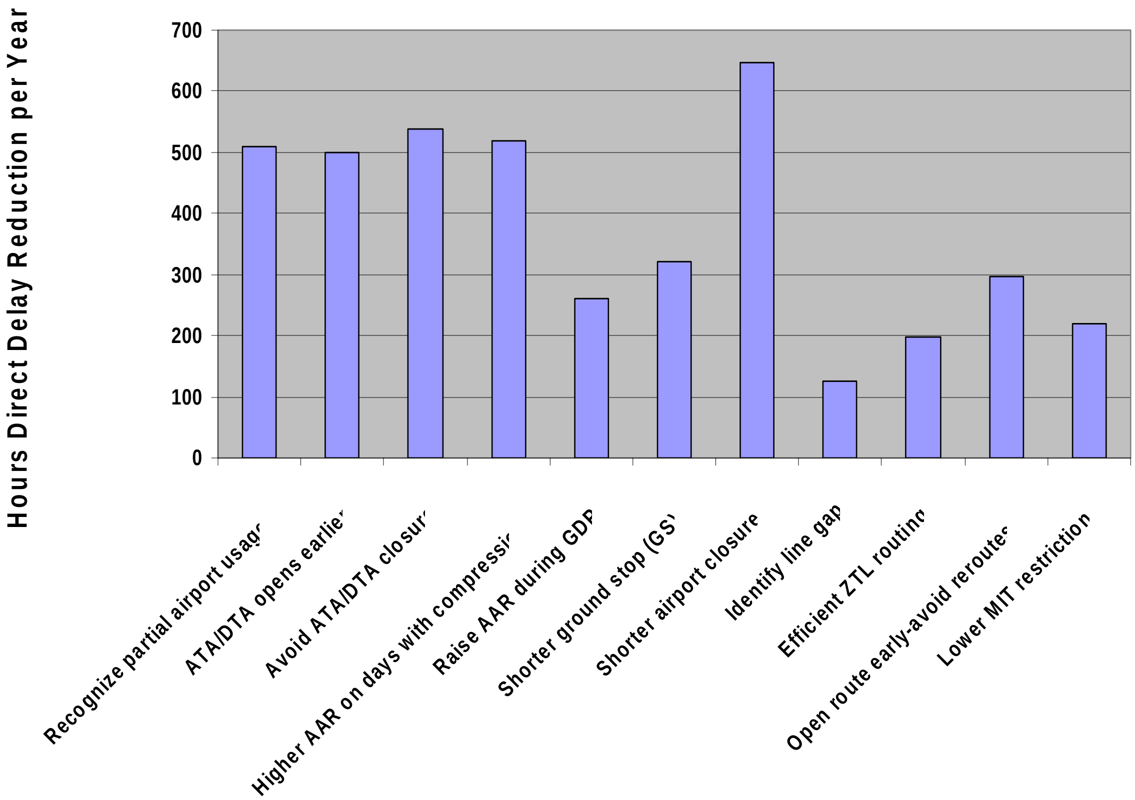

Figure 33. Summary of Atlanta ITWS direct delay reduction (in hours) per year.

These projected benefits are viewed as quite conservative due to:

- Several previously identified benefits not being assessed in this initial study.
- The approximations made in several of the calculations (e.g., the use of the mean of the actual traffic distribution in modeling the airport closure benefits),
- The use of a very conservative downstream delay impact model, and
- Not accounting for cost savings to the airlines from reducing downstream delays.

The results of this analysis were compared to the ITWS KDP-3 estimates of savings at Atlanta in Table 9. Some of the earlier projected benefits are not being fully achieved, but other benefits not previously projected are being obtained. **Overall, the direct hours of delay savings estimated here for**

ATL are about 68% of the savings projected in the earlier report; while another 17% of the KDP-3 projected benefits were not assessed. The difference arises from a combination of several factors:

- Time and resources did not permit assessing all of the previously identified benefits.
- Users at Atlanta were trained differently than the ITWS prototype users at Memphis and Orlando. The Atlanta ITWS training focused primarily on the use of a computer-based package that, in our opinion, emphasizes operation of the display features much more than the operational use of the products. Memphis and Orlando users were trained by the MIT Lincoln Laboratory local ITWS demonstration system operations team and ATC users could ask weather situation-specific questions in real time as issues arose.
- The ATC operations during convective weather at Atlanta are different from the operations during convective weather at Memphis and Orlando. In particular, there is a much greater likelihood for significant airborne queues to develop at Atlanta during convective weather. Hence, the operational utilization of the ITWS products is quite different.
- Some of ATC users of the ITWS at Memphis and Orlando contributed significantly to the development of the ITWS products and operational concept over a two-year period whereas Atlanta ATC was not involved in the ITWS development.

We do not believe that the ratio of the Atlanta ITWS benefits identified in this study to the savings projected from the ITWS KDP-3 assessment (as shown in Table 9) can be extrapolated to other production ITWS locations. Based on our studies of:

1. ITWS at Atlanta and New York, and
2. CIWS at Chicago

we have concluded that these "mega-airport" complexes must each be regarded as unique situations that are neither applicable to each other, nor to less busy airports. Rather, one will need to extrapolate benefits from detailed studies at ITWS sites that are more typical of less congested airports if one is to estimate ITWS benefits at less congested airports.

8.1.3 Assessing the "Reasonableness" of the Atlanta ITWS Delay Reduction Estimates by Comparing Those Results with Other Metrics

One test of the reasonableness of the ITWS Atlanta delay reduction estimates is to compare the 4,068 hours of delay reduction to the total delay reduction that might be achieved at Atlanta. As was noted in Section 2.6, it does not seem possible at this point to estimate with any degree of certainty what the pool of "avoidable" weather-related delay (especially convective weather) is at Atlanta. However, one can provide quantitative estimates of:

- The total weather delay for the NAS and for Atlanta arrivals and
- The average number of minutes of delay savings per flight during times when there are convective weather impacts on ATL operations within the coverage region of the Atlanta ITWS.

We showed in Chapter 5 that:

- The estimated delay reduction by the Atlanta ITWS was about 5% of the “after ITWS” arrival delays (relative to schedule) due to weather at Atlanta in 2004 and about 7% of the “after ITWS” arrival delays (relative to schedule) due to weather at Atlanta in 2003,
- The expected airborne arrival delay savings per aircraft due to better handling of **airport** storm impacts is 0.33 minutes.
- The expected airborne arrival delay savings for non-airport-related delay reductions within the ITWS coverage is 0.5 minutes per aircraft when convective weather impacts in or near the TRACON.
- The departure delay savings are approximately 0.67 minutes per aircraft when convective weather impacts in or near the TRACON.

Considering the many minutes arrivals spend in holding patterns at Atlanta when there is convective weather (as shown in Figures 16, 17, 24, 26, 27, and 28), the above estimates suggest that the projected ITWS delay reduction is not unreasonable.

8.1.4 Confirming the Delay Reduction Estimates through the Analysis of Operational Data (e.g., Delay Statistics)

Two types of operational data were assessed. In 2003 on days when convective weather was reported at ATL [i.e., there was a thunderstorm with rain (TSRA) station observation], the fraction of 15-minute periods when the number of operations (i.e., arrivals + departures) was less than 15 was reduced by 50% in 2003 compared to 2001 (Chapter 4). This is particularly noteworthy given that the convective weather that occurred at ATL in 2003 appears to have been more severe than the weather in 2001 (Chapter 6). This lower frequency of TSRA incidents that result in abnormally low Atlanta operations rates provides objective, quantitative operational data supporting the ATC user feedback on ITWS benefits.

In Chapter 6, we compared the ASPM flight times from 100 nmi to touchdown at Atlanta for 22 days in 2003 and 22 days in 2001 when thunderstorms were reported at ATL. Although the average flight time in 2003 was about 1 minute less than the average flight time in 2001 (which is about what had been predicted), **we do not view this as confirming the results described in Chapter 4.** Many factors were different between the two years, including the severity and duration of the convective weather, the introduction of CTAS at Atlanta at the same time as ITWS, and the very significant data quality problems with the ASPM flight times from 100 nmi to touchdown.

The ASPM data quality problems include the inability to capture a significant fraction of the airborne holding delays due to convective weather in the Atlanta terminal area, the deficiencies in the algorithm used to compute a distance of 100 nmi from the airport, and the inaccuracy of the touchdown times for aircraft that do not provide OOOI data. Hence, we concluded that significant research and development into methodologies for using the ASPM data would be needed before it could be viewed as an accurate assessment tool for the ITWS at Atlanta.

When thunderstorms occur at the Atlanta airport, the effective capacity of the airport is often reduced. A comparison of Traffic counts during the time periods when the Atlanta surface report (METARs) indicated a thunderstorm with rain was present supports the user statement that ITWS reduced the frequency of airport closures. Specifically, the fraction of TSRA incidents with 15 minute arrival plus departure counts was reduced from 12% in 2001 to 6% in 2003. The lower frequency of TRSR incidents which result in abnormally low Atlanta operations rates provides objective operational data supporting the ATC user feedback on ITWS benefits.

8.1.5 Assessing the Accuracy of the Downstream Delay Model Used in this Study with Operational Data from a Major US Airline.

A significant fraction of the Atlanta ITWS benefits (44% of the delay hours, 31% of the monetary value) are associated with downstream delay reduction. The model used here (which stated that the total downstream delay was equal to 80% of the initial delay) was derived from operational data at LaGuardia airport in the early 1990's. In view of the substantive changes to the NAS since the early 1990's, the downstream delay model applicability to more contemporary aircraft scheduling and disruption mitigation systems might be questioned.

ASPM arrival delay statistics for a major US carrier (one of the very few that is currently profitable) were analyzed to determine whether the downstream delay model used is realistic. Downstream delays were analyzed for three different days in 2004 when it was reasonable to assume that subsequent arrival delays arose primarily from the initial delay. The results show that the model of downstream delay significantly underestimates actual downstream delays.

Since the downstream delay model is germane to many weather delay reduction systems other than ITWS (e.g., CIWS, TFM-M, URET, WARP), the FAA should develop an improved model for downstream delay that can be used for a wide variety of delay reduction benefits studies. Additionally, the FAA needs to work with the airlines to develop and validate an airline cost model for the downstream delays.

8.2 RECOMMENDATIONS FOR ADDITIONAL STUDIES OF ITWS DELAY REDUCTION AT ATLANTA

User responses to questionnaires and interviews suggest that the Atlanta ITWS is delivering significant operational benefits, including a delay reduction well in excess of the cost of the system. There are several approaches one could take to further substantiate and refine the results reported here.

Given the differences between the ITWS usage at Memphis and Orlando (as encapsulated in the KDP-3 ITWS benefits projections for Atlanta) and the delay savings documented in Chapter 4, we strongly recommend considering additional operational usage training on ITWS. This training should take advantage of the experienced ITWS users at facilities such as MCO and Jacksonville ARTCC. Also, the current ITWS training material should be augmented with material discussing the operational use of the products. For example, one might include flight tracks with weather (see the discussion below) that illustrate the usage of the various ITWS products based on feedback from users at other ITWS sites who have had years of experience with the system. By the same token, some of the new ITWS benefits observed at Atlanta should be incorporated into the ITWS training for new sites.

8.2.1 Studies of Candidate ITWS Benefits that were Not Assessed in this Study

In Section 4.7, we noted that there were a number of ITWS benefits observed at Memphis and Orlando that were not assessed at Atlanta due to time and resource constraints. It would be very useful to conduct follow up interviews to determine if these benefits are being achieved at Atlanta. Interviews should also be conducted with the Atlanta tower and Delta airline ITWS users. This could be combined with the additional training and onsite benefits observations that we have already recommended.

8.2.2 Observations of Atlanta ITWS Product Usage during Convective Weather Events

Observations of the ITWS product usage during actual convective events at Atlanta, coupled with post event detailed analyses of flight track data and weather radar, would be highly beneficial. This technique was used successfully for the CIWS program (Robinson et. al., 2004). The analyses can be independently verified by outside parties and can help resolve some of the more complicated modeling issues that we had to address. These observations should be carried out at the tower, TRACON and ARTCC (ZTL) and at Delta Airlines.

One of the major issues that could not be resolved either from the interviews or analysis of ASPM statistics is the utility of CTAS in reducing delays during ATL convective weather events. For example, convective weather may reduce the arrival rates to a value well below the ATA capacities such that there is little benefit from optimal sequencing. Also, the CTAS guidance may be in error since CTAS does not recognize the presence of severe convective weather. By observing the use of CTAS and ITWS during convective weather events, getting immediate feedback from the ATC users, and employing post event analysis of flight tracks and weather, it should be possible to provide realistic bounds on the marginal benefit of CTAS during convective events.

Another important issue is managing arrivals in cases where the arrival rate drops significantly due to storms on or near the runways. As was noted in Table 9, a number of proactive measures used at Memphis and Orlando (e.g., positioning holding aircraft for quicker landings) were not assessed in this initial study.

Observations of departure operations during and immediately after airport thunderstorm impacts would be helpful in quantifying the period of time required to commence full operations after a departure runway is closed (including the amount of taxi time). Also, there were a number of departure related benefits observed at Memphis, Orlando and New York that were not identified as Atlanta benefits in this study.

8.2.3 Comparison of Flight Tracks and Weather Before and After the Atlanta ITWS was Installed.

We also recommend that there be a comparison of flight tracks and NEXRAD data recordings from events before and after the ITWS was installed at Atlanta. This would further substantiate the user feedback that they are doing a better job of managing key convective delay situations such as preventing the use of some or all of the runways and managing storm impacts on ATAs and/or DTAs.

The metrics that one would use are fairly self evident from the benefits discussions in Chapter 4. For example, when the storm impacts end on a runway, one would compare the time to resume full arrival and departure operations on that runway before and after the ITWS was introduced. Similarly, one would compare the amount of "dead time" after storm impacts end on an ATA or a DTA. In particular, it would be important to identify where holding patterns were established. The use of summary landing rate statistics from ASPM may not capture all of the important dependencies, especially since the 15 minute averaging time used in ASPM analysis is comparable to the expected reduction in "dead time" with ITWS in operation.

The model used in section 4.3.3.1 considers queue delay reductions using combined arrival and departure operations. Alternatively, one could consider a queue model which treats ATAs and DTAs as separate capacity assets used respectively for arrivals and departures unless there is explicit sharing (e.g., a DTA used for arrivals). The frequency of these two approaches could be assessed by flight track analyses.

Some experience at accomplishing such an analysis is being accumulated in the CIWS program benefits studies. Hence, analysts for the Atlanta ITWS should take advantage of the CIWS experience at conducting such comparisons. These flight track/weather comparisons should also be useful as an augmentation to the current ITWS training for new sites.

8.2.4 Comparison of ASPM Delay Statistics for Carefully Selected Cases Before and After the Atlanta ITWS was Installed

Comparing ASPM delay statistics before and after the ITWS was introduced will clearly be quite challenging since a large fraction of the Atlanta convective weather delay arises from queues. Since queue delay is very sensitive to differences in demand, effective capacity, and the duration of the events, it will be both very difficult to find comparable benefits and to normalize for the differences in these key parameters.

Since the Atlanta ITWS provides products over a limited domain, we recommend searching to identify "similar" situations for comparisons. One approach to finding "similar" situations is illustrated in Figure 34.

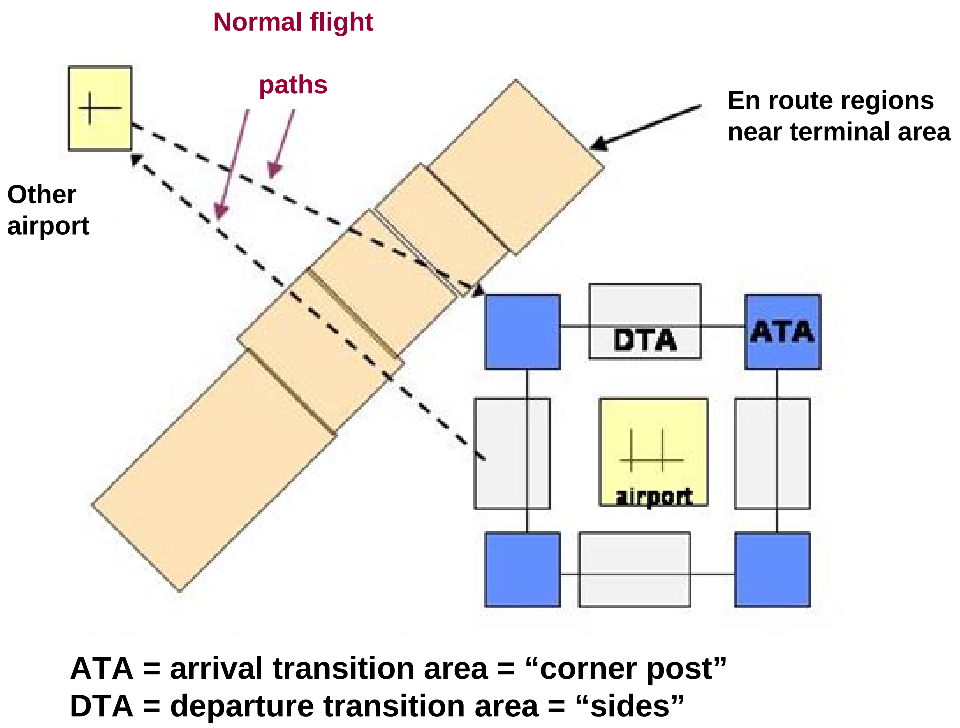

Figure 34. Simplified representation of convective weather impacts on terminal area.

The distribution of convective weather in the ITWS coverage region may be characterized at a high level by impacts on the airport runways, the ATAs, the DTAs, the region between the airport and the ATAs/DTAs, and by a small number of regions in the transitional en route airspace between a distant airport and the test airport. Even though two events may not have impacts on exactly the same fixes, the likelihood that convective weather will impact a <u>similar</u> number of fixes on different events is much higher than the likelihood that it will be the <u>same</u> fixes. Since the sources of the major traffic flows into a terminal generally have concentrated spatial orientations (e.g., the flow to Atlanta from the northeast is much greater than the flow from the southwest), adjustments to account for the traffic loading differences may be needed if one cannot find identical fix impacts.

Similarly, one can look at departure delay reduction from Atlanta by considering weather events/flights where the terminal area impacts are similar and the other convective weather is "local." "Local" here means that few if any of the routes to the destination cities are significantly impeded in en route or terminal airspace (e.g., consider only flights that meet this criterion).

The Atlanta ITWS product data (e.g., ASR9 and NEXRAD precipitation, alerts and storm motion information) have been archived at MIT Lincoln Laboratory as a byproduct of validating the Lincoln software to create web-browser-viewable images for the Atlanta ITWS. However, these images have never been assessed to determine if they are in fact usable for benefits studies.

There clearly are no ITWS products from the "before" ITWS time frame. If the Atlanta ITWS product archive is usable for benefits studies, it would be necessary to obtain NEXRAD base data (i.e., "archive 2") from the NCDC and create appropriate NEXRAD precipitation and storm motion products for time periods of potential interest. Automatic algorithms could then process the data and output a digital time series for days when the various regions discussed above are or are not impacted significantly by convective weather at the given time. This "reduced space" realization would convert the actual weather spatial pattern at a given time into a number whose value indicates where the weather impacts were. Hence, the comparison of two days to identify periods of similar weather would be reduced to tests of whether strings of numbers in two time series are identical or had runs of numbers that are similar (e.g., corresponding to only one ATA and one DTA being weather impacted).

Once time periods are identified when the convective weather impacts are identical or highly similar between different data sets, one would then need to examine the scheduled demand for those time periods and the previous history of weather impacts prior to these time periods[31] to see if the delays could be reasonably compared.

Finding cases where both en route and terminal convective impacts are similar is very difficult. It may be necessary to choose arrivals (or departures) that do not have en route impacts between the Atlanta terminal area and the other airport. Comparing arrival flight times from an appropriate distance from the Atlanta airport (e.g., 100 nmi to 200 nmi) to touchdown can reduce the region of en route weather that

[31] For example, if two days have an identical weather impact for 30 minutes, but one day has significant holding patterns at the beginning of the impact period, then clearly there would be major complications in attempting to compare the delays for aircraft scheduled to land during the periods of identical weather.

needs to be considered[32]. Similarly, for departures, one can look at the taxi out time and flight time to an appropriate distance from the Atlanta airport (e.g., 100 nmi to 200 nmi).

We strongly recommend that such a procedure be validated by:

- Comparing delays on pairs of days where ITWS was (or was not) in operation so one could experimentally assess the accuracy of this approach to achieving comparable statistics, and
- Reviewing flight track/weather data on these days to ascertain whether the convective weather impacts were in fact as postulated in the automated analysis[33].

Having validated the process for multiple pairs of days with "no ITWS" and multiple pairs of days "with ITWS", one could then proceed to the comparison of delays for ITWS/no ITWS days. Again, analysts would review flight tracks overlaid on NEXRAD data to determine there were no odd features of the respective days that had not been identified in the automated weather impact analysis procedure.

We strongly suggest that any additional ASPM delay statistics analyses for Atlanta closely examine departure delay statistics. Unpublished studies carried out by the FAA in the late spring suggest that June through August departure delays at Atlanta after 13 UTC decreased nearly 3 minutes per flight from 2001 to 2003. This is greater than the projected ITWS departure delay savings (0.42 minutes per aircraft) computed in Chapter 5. This suggests that Atlanta ITWS users may be achieving a greater departure delay reduction than is indicated in Chapter 5. However, some of the departure delay reduction accrues from reduced departure gate delays. There may be other factors involved in the departure delay reductions such as weather differences at the destination airports and the use of CIWS by Washington DC ARTCC in 2003 versus 2001. The possible impact of these other factors could be mitigated by weather event-specific choice of the flights whose departure delays could be assessed. For example, one could choose flights whose paths do not traverse the CIWS domain and which experience no operationally significant convective weather between the Atlanta ITWS coverage region and the destination airport runways.

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[32] In Chapter 6, we noted the importance of also choosing a large enough distance from Atlanta airport to insure that holding patterns due to convective weather within the Atlanta ITWS coverage were captured.

[33] For example, one of the challenging issues in this methodology is how to set a threshold on the fraction of convective weather covering an ATA or DTA region in order to declare that the ATA or DTA was closed. If the flight track data shows that the predicted usage of the region was quite different than postulated, then clearly some refinements to the blockage model would be needed.

8.2.5 Comment on the Multiple Use of Flight Tracks Plus Weather as an Analysis Tool in ITWS Benefits Analysis

In both of the discussions above, an important element of the analysis has been the review of flight track plus weather data for the test periods. It might appear that these two uses of flight track plus weather data are duplicative. However, there are some important differences that should be emphasized. When one is comparing delay statistics in a situation that involves queues (either airborne or ground), it is very important that the arrival and departure demand, weather durations, prior queue conditions, and the convective weather terminal capacity impacts be similar. By contrast, flight track plus weather data can be used to demonstrate that certain beneficial decisions (e.g., starting arrival operations promptly after convective weather impacts have ended on the runways) are being made better after ITWS without requiring that the duration of the runway closure, arrival demand, and prior airborne holding be similar.

8.2.6 Validation of the Terminal Winds Benefits on Days when there is Significant Arrival Compression due to Vertical Wind Shear

At Atlanta, a low level jet with winds out of the southwest causes compression for the arrivals. The use of the ITWS terminal winds product to achieve higher landing rates during such conditions was a significant but unexpected benefit. Such situations would be fairly easy to identify from archived RUC data. One could then compare the landing rates with and without the Atlanta ITWS to determine if the stated improvement of about 2 aircraft per hour was being achieved. The delay reduction benefits can easily be determined by using the queue model with time varying capacities (i.e., the version of the queue model used for Appendix A).

8.2.7 Validation of Delta Airline Benefits from Use of Atlanta ITWS Products

Interviews with additional Delta dispatch users and the development of a real time benefits decision capture process at Delta (e.g., via email from the Delta dispatch users) would help validate the benefits results reported in Section 4.5.2. An important objective would be to validate the frequency with which diversions were avoided. It would also be desirable to further validate the improvement by comparing Delta diversion rates at Atlanta before and after the Atlanta ITWS was installed. These rates undoubtedly have some relationship to the size of the airborne holding patterns that arise from Atlanta terminal area convective activity and hence could be quite sensitive to the exact details of the respective weather events and the arrival demand at the time of convective weather impacts. We would add that diversions may not only be reduced directly by airline usage of ITWS, but indirectly when holding times are reduced due to FAA usage of ITWS. This is because diversions are quite sensitive to the length of time aircraft must hold.

It also appears that there may be additional airline operations benefits that are being generated by the Atlanta ITWS. Specifically, a concentrated effort should be undertaken to determine if some of the other airline operations benefits identified at Memphis and Orlando (see Section 4.9) are also being obtained at Atlanta. The ITWS program office should consider providing training for major airlines when the ITWS is installed at the respective airline's major hubs to further enhance the ITWS benefits to the "FAA's customer".

8.3 RECOMMENDATIONS FOR STUDIES OF ITWS DELAY REDUCTION AT OTHER ITWS SITES

8.3.1 Studies Germane to Potential Benefits for Planned ITWS Sites that were not Part of the Initial ITWS Deployment

The planned ITWS sites that are not a part of the initial ITWS production system procurement are typically airports with far fewer operations than Atlanta. Given the very important roles of queues in the delays at Atlanta, it is not clear that validation of delay reduction estimates for Atlanta would also validate the estimates for these lower volume airports. On the other hand, it may be far easier to carry out delay model validation for these less busy airports since the overall convective weather delays at these airports are not likely to be as sensitive to small changes in demand or weather severity as is Atlanta. Also, the issue of CTAS as a factor in convective weather delay reduction would not be as significant. One obvious candidate for such studies would be Kansas City, a less busy airport that has had an ITWS for several years. Another candidate would be Charlotte, NC, which is a new ITWS site.

Several other ITWS production sites currently in operation were considered (St. Louis and Houston). However, these present significant challenges in data normalization. At St. Louis International Airport (STL), the drop in demand when American Airlines stopped using STL as a hub makes before and after ITWS comparisons difficult. In addition, CIWS coverage overlaid the St. Louis terminal after the STL ITWS was installed. It will be difficult to determine which system was being used to manage transitional en route airspace, including handling of weather impacts on ATAs. Houston is a complicated busy TRACON with a major hub (IAH) that probably would have many of the queue issues experienced at Atlanta. Miami is a major hub and has very different convective weather than the TDWR airports that are not part of the initial ITWS production deployment. Hence, our discussion on this topic will focus on Kansas City or Charlotte as a specific example of a general approach.

We recommend a multi-phase program of benefits assessment at Kansas City or Charlotte consisting of:

- Improved training
- A review of recorded flight tracks and convective weather events before and after ITWS was installed.
- Interviews of the tower, TRACON and ARTCC users.

- Real time convective weather observations[34] during weather events with post-event analyses of the flight tracks and weather to provide quantitative confirmation of benefits that could be independently reviewed (as with CIWS), and
- A comparison of ASPM delays before and after ITWS was installed for weather events that typify the high benefits situations identified in the interviews and real time observations. As in the case of Atlanta, the flights to be used for the delay comparisons and ASPM delay metrics would be chosen to minimize the impact of non-ITWS factors (e.g., en route weather, overloads of en route sectors by "strategic reroutes" of transcontinental flights, and/or weather at the other airport).

Given the much lower volume of operations, it is expected that Kansas City or Charlotte will have a smaller likelihood than Atlanta of queues due to convective weather. If true, this would significantly reduce the sensitivity of the delay results to small differences in weather and/or demand.

The one possibly complicating factor for Kansas City is that Kansas City is in a region that is known to experience severe squall line convective activity. Such squall lines can easily block a significant fraction of the TRACON and en route airspace, producing major queues. Since such squall lines are also relatively frequent at some of the other ITWS airports not in the initial production deployment (e.g., Oklahoma City and Tulsa), the Kansas City assessment would be germane. At Charlotte, strong squall lines are most likely in early spring or, early fall. Hence, we would strongly recommend stratifying the data analysis by type of convective weather event[35].

We recognize that the above program of assessment is relatively ambitious. However, it will be the basis for significant production deployment decisions as well as laying the groundwork for subsequent OMB-300 analyses. It is expected that results of the intensive Kansas City or Charlotte analyses will suggest ways that the analysis could be simplified for subsequent ITWS production system benefits assessments.

We also strongly recommend a review of the ITWS training provided in the context of:

- Operational feedback received thus far from the operational ITWS users, and
- The differences between the benefits observed at Memphis and Orlando compared to Atlanta (Section 4.9).

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[34] The observations of weather events at MCI should be carried out in 2005 if possible, since there is a reasonable likelihood that the CIWS coverage might be extended in 2006 to include the MCI terminal area. Since CIWS provides 2-hour convective forecasts that are significantly better than the current Kansas City 20-minute forecasts, there would be a complicating issue of which system was being used for decisions related to convective weather impacts on the ATAs and DTAs.

[35] The initial ITWS benefits assessment had different delay benefits coefficients for the different convective weather regimes.

to determine whether additional operationally oriented training may be warranted at all the production ITWS sites.

It should be noted that the MIT Lincoln Laboratory-operated ITWS and CIWS demonstration sites have provided refresher training by staff that are very familiar with the system products and their operational use at the beginning of each storm season because there are often personnel changes, etc. Additionally, such training provides an excellent opportunity to obtain feedback on product issues that should be addressed to more fully achieve the operational benefits possible with the ITWS.

8.3.2 Assessing the Benefits of IOC ITWS Systems Deployed within the Coverage Region of the CIWS Demonstration System

In the period 2003-2005, there have been and will be a number of ITWS production system installations within the current CIWS coverage (e.g., Chicago, Boston, Detroit, and Cincinnati). This will present some significant challenges for ITWS benefits assessment.

Since CIWS does not provide a terminal winds product, there definitely should be an assessment of the benefits of the ITWS terminal winds product at Chicago and Boston. This product is expected to contribute significantly toward reducing delays during cases of low ceiling and visibility when there are strongly sheared winds aloft; conditions that occur frequently at those facilities. The benefits assessment would involve using RUC recordings, plus ceiling/visibility recordings, plus runway usage data to assess the delay reduction benefits. If runway usage data is not available, it could be inferred from flight track data. Since the benefits for these cases definitely involve the reduction of queues (e.g., by allowing the terminal to set a higher GDP rate than they would otherwise), the measured delays will definitely be a very strong function of the demand for the specific times. However, adjusting the measured delays to account for differences in demand should be quite straightforward and easily verified by independent analyses.

An ITWS convective weather benefits assessment at these sites will, however, be quite complicated since the CIWS demonstration system:

- Will have been in operation longer at those locations than the production ITWS,
- Provides significantly better forecast capability than the IOC ITWS, and
- Has much more intensive training than is provided for the IOC ITWS.

Hence, there will be a very difficult benefits allocation problem if it is necessary to measure the convective weather benefits provided by the IOC ITWS using operational data.

The CIWS benefits study (Robinson et al., 1999) noted that in the absence of an ITWS, CIWS was used as an ITWS surrogate to support many of the operational benefits decisions discussed in Chapters 2 and 4. However, the benefits that could be attributed to an ITWS were excluded in estimating the benefits for CIWS and thus can be credited to ITWS. The rationale for this decision is that ITWS would be regarded as part of the “baseline NAS” for a production CIWS deployment and therefore CIWS should not claim those benefits. One could imagine trying to establish a pre-ITWS baseline at these locations by looking at traffic handling and delays before CIWS commenced operations (e.g., in 1999 and 2000). However, all of the post-ITWS time periods would be periods when CIWS was in operation.

We recommend that convective weather IOC ITWS benefits assessments not be conducted at CIWS demonstration locations unless the CIWS demonstration system is not in operation during the post-ITWS evaluation period.

APPENDIX A
CONFIRMATION OF QUEUE MODEL DELAY ESTIMATES USING OPERATIONAL THUNDERSTORM DATA FROM ATLANTA

Data reported in the Airline System Quality Performance (ASQP) database (which preceded the ASPM database) are used to provide confirmation of the queue model based on operational data. The ASQP database provides the scheduled arrival times and delays for individual flights. Data from a thunderstorm event at Atlanta Hartsfield International Airport (ATL) on April 27, 1994 are used to construct a demand and capacity rate profile. From these, the computed delays can be compared to the actual delays.

Table A-1 shows the demand and capacity time series data used to construct the scenario. We assume that the ASQP scheduled arrivals represent the demand from 1600 to 0100 and the ASQP actual arrivals represent the effective airport capacity for all times except 0100. The effective airport capacity at 0100 is assumed to be 53 (the effective capacity in the preceding hour). Figure A-1 shows the model results for this scenario.

Figure A-2 compares the actual and computed delays. The trend of computed delays agrees well on an hour-by-hour basis with the actual delays, but there are obvious small underestimates at 2100 followed by overestimates at 2200 and 2300. The model assumes that the aircraft were landed in the order that they were scheduled. If this is not the case, delay for aircraft landing ahead of schedule is reduced while delay for aircraft landing later than scheduled order is increased. Thus, some time periods show shorter actual delays than the computed delays, while other periods exhibit longer actual delays than computed delays. However, the overall sum of the delays to the individual aircraft should be similar.

The computed accumulated delay (i.e., $\sum$ [# a/c scheduled to land in a given hour x average delay in that hour]) is 312 hours, which is within five percent of the ASQP-reported accumulated delay of 325 hours. We regard this as excellent agreement given the very coarse capacity-model time resolution used in a period where there are very large hour-to-hour changes in the effective capacity.

TABLE A-1

Data Used to Compute Queue Model Estimates of Plane Delays at Atlanta

Time (LST)	Scheduled Arrivals	Actual Arrivals*
1600	61	53
1700	35	33
1800	41	48
1900	34	12
2000	38	33
2100	34	19
2200	36	16
2300	34	24
0000	28	53
0100	5	53

*Note: Actual arrivals are used as a surrogate for effective capacity. Value at 0000 is used as the effective capacity for 0100.

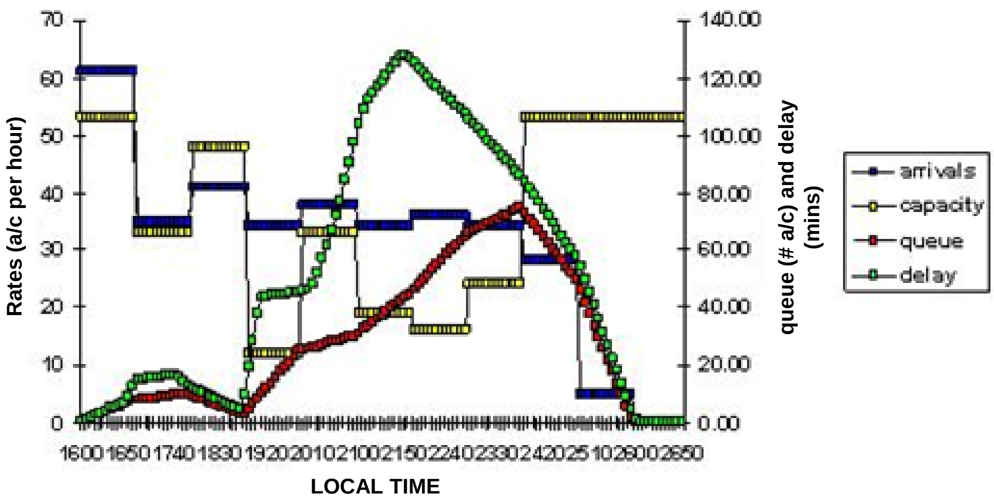

Figure A-1. Queue model results using scheduled arrivals as demand and actual arrivals as capacity. Local times beyond 2400 are the next day (e.g., 2500 = 0100 the next day).

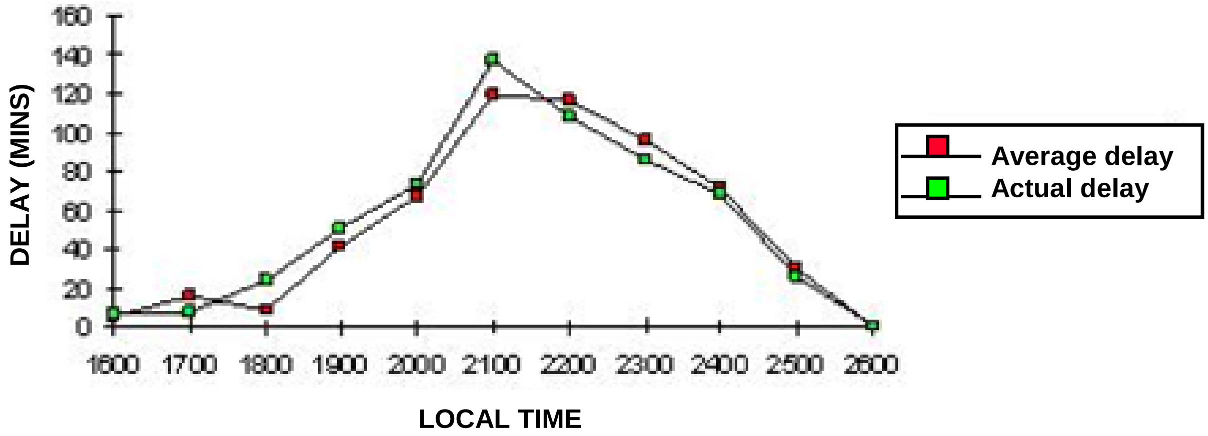

Figure A-2. Comparison of actual average delay to queue model estimates average delay for aircraft scheduled to arrive in a one-hour period (as reported by ASQP). Differences reflect the use of average demand and capacity for 1 hour periods and swapping of planes.

APPENDIX B
CAUSES OF CONVECTIVE WEATHER DELAYS

It is important to have an in-depth understanding of the cause of convective weather delays if one is to design benefits quantification systems including the use of delay statistics. In this section, we will briefly review insight developed from our analysis of delays over the past decade.

Historically, one finds three major theories of convective weather delay causality in the literature:

– blockage of routes between terminal areas by en route weather (e.g., the FAA/airline "Spring 2 K" effort, Post et al., 2002 and Callaham et al., 2001),

– thunderstorms near or over airports (Bond, 1997)[36], and

– reduced airport capacity associated with low ceiling-and-visibility conditions at the airport during thunderstorms.

However, it is now clear from the detailed studies of convective weather delays and traffic handling at Dallas, Memphis, New York, and the northeast quadrant of the US over the past decade that <u>none</u> of the above theories <u>alone</u> provides an adequate explanation.

CONVECTIVE WEATHER IMPACTS WITHIN THE TERMINAL RADAR APPROACH CONTROL (TRACON)

The typical structure of traffic flows between major terminals[37] and the surrounding airspace is shown in Figure B-1. Planes enter (blue dashed arrows) the Terminal Radar Approach Control (TRACON) at corner fixes and depart (green arrows) through fixes on the sides of TRACON. Overall TRACON width is typically 100 nmi. Within the TRACON, there are a variety of routes from the corner fixes to the runways. The transitions between TRACON and en route are relatively inflexible due to facility differences and the structure of the en route sectors (purple lines). Within the TRACON, there is a great deal of flexibility to vary routes between the airport and the arrival and departure fixes.

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[36] It should be noted that Bond suggests that such delays cannot be reduced by a change in Air Traffic Control technology because aircraft cannot fly safely in thunderstorms.

[37] This structure applies at nearly all of the major terminals that encounter convective weather delays with the notable exception of the New York terminal area, which has a much greater number of arrival and departure transition fixes.

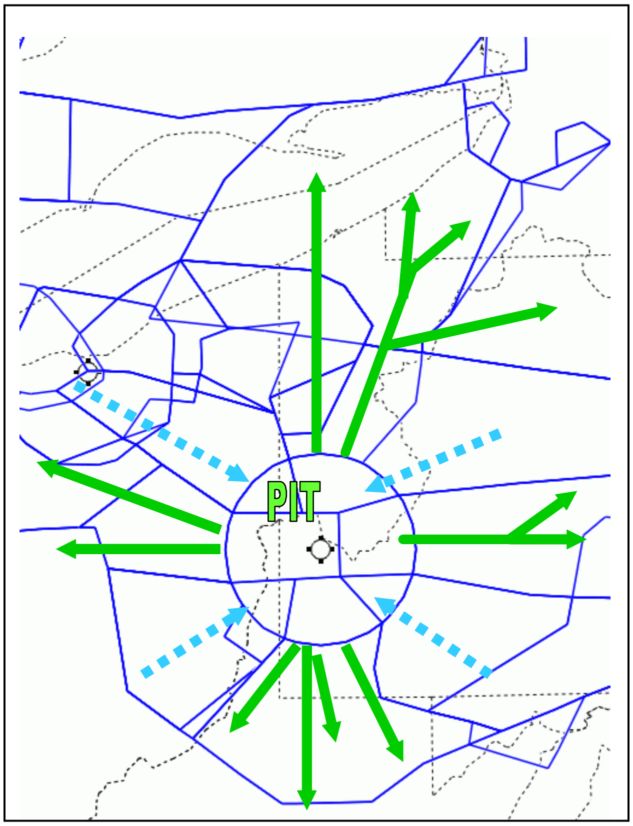

Figure B-1. Typical terminal area arrival and departure route structure.

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 <u>not</u> close <u>all</u> of the runways very often. R. Ferris of Lincoln Laboratory conducted a study of terminal operations during convective weather events at Orlando International Airport (MCO) and Dallas-Ft. Worth (DFW) airports. In only one of 20 storm day cases examined did arrival and departure traffic stop 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.

Rhoda et al., (1999 and 2002) found that a very high percentage of arriving aircraft are more likely to fly through high-reflectivity storms (typically VIP level 3 or higher) if they are within 10 nmi of the airport. The same aircraft likely will not fly through such storms if the storms are located at one of the arrival fixes shown in Figure B-1. Experience at the ITWS demonstration sites (Orlando, Dallas-Ft. Worth, Memphis, and New York) over the past decade shows that arriving planes will frequently penetrate disorganized convective storms (e.g., air mass) when landing, but generally will not penetrate vigorous squall lines moving across the airport. Moreover, air mass storms typically only block one of the runways at a time at major airports (e.g., MCO, DFW, Chicago O'Hare International Airport, or Atlanta) so that arrival and departure operations can continue on the other runways. Since vigorous squall lines typically are over the airport for a relatively short period (e.g., less than 30 minutes[38]), the overall time that the runways are not used is a relatively small fraction of the time that the squall line is disrupting terminal operations. Thus, convective weather at or very near the airport may reduce the traffic flow but typically will not halt the flow of arrivals and departures completely.

REDUCED CAPACITY AT MAJOR AIRPORTS DUE TO INSTRUMENT METEOROLOGICAL CONDITIONS (IMC)

If the Instrument Meteorological Condition (IMC) capacity of an airport is the main constraint, then convective weather forecasts could do little to reduce the delays. Experience at the ITWS demonstration sites shows that the capacity reductions associated with convective weather within 100 nmi of the airport are generally much greater than the airport capacity reduction associated with IMC conditions. A study of high-delay thunderstorm events at Newark Liberty International Airport (EWR) revealed that half of the events had only Visual Meteorological Conditions (VMC) throughout the event, with the duration of VMC time exceeding IMC time duration for another 18% of the events (Allan et al., 2001). On the other hand, the highest EWR delay events also had a higher fraction of IMC conditions. It is our observation that IMC conditions rarely are the main constraint during a convective event in or near a TRACON. However, IMC at the end of a convective weather impact event is an important factor in the magnitude of queue delays (discussed below) that occur. Such conditions can significantly extend the delay recovery period if a Ground Delay Program or Ground Stop Program is put into effect to reduce the arrival demand at the airport.

STORM IMPACTS ON THE TRACON-EN ROUTE ARRIVAL AND DEPARTURE FIXES

Planes at the TRACON arrival and departure fixes (Figure B-1) are typically flying at altitudes of less than 20,000 feet, so they cannot fly over convective storms. In addition, at these fixes pilots typically will not penetrate storms with weather level three or higher (Rhoda et al., 1999 and 2002). It is difficult to dynamically change the location of these transition fixes during a convective weather event because both the TRACON and ARTCC have designed their internal route structures and procedures based on the fix locations. The result is that storms at the transition fixes will stop the flow of traffic through that fix. When an arrival fix is closed, the arrivals that would normally use that fix are either routed to another arrival fix (e.g., from the northeast to the northwest fix in Figure B-1) and/or departures are halted while the departure fix is used to handle arrivals.

Rerouting to another arrival fix, although preferred procedurally, causes delays from two mechanisms.

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[38] A 10 nmi wide squall line moving at 30 mph would traverse the 4 nmi diameter circle that typically covers an airport's runways in about 30 minutes.

1. Planes fly a longer distance than would have been the case had the convective weather not been present (this is the "linear delay" model discussed in Chapter 2).
2. There may be queue delays at the other arrival fixes if the arrival demand at that fix exceeds the fix capacity (as occurs at Atlanta and is discussed in Chapter 2.) In Chapter 2, we discuss the behavior of queues and note the very nonlinear relationship of delay to demand, capacity, and weather event duration.

TERMINAL DELAYS DUE TO EN ROUTE LOSS OF CAPACITY RESULTING FROM CONVECTIVE WEATHER

When convective weather shuts down key en route sectors in congested airspace, airborne traffic is typically given priority because of fuel constraints and the disruption that holding patterns cause in congested areas. As a result, departures on the ground are heavily restricted and long departure delays frequently occur. The delays that arise when convective weather causes an en route loss of capacity are particularly difficult to model. A given en route sector may be used to handle flights from many different city pairs and there may be multiple flow constraints for flights between a city pair.

As shown in Figure B-2, one must explicitly consider the NAS as a complicated network in seeking to understand the delays. Convective storms can block multiple en route sectors. Rerouting aircraft through weather-free sectors can result in overloads and queues in those sectors, including major problems for departures from the terminals inside the sectors. This "NAS as a network" concept is nicely illustrated by a major FAA operational initiative for the summer of 2004: the "growth without gridlock" approach to coping with the loss of en route capacity due to convective weather. This initiative is described (McCartney, 2004) as follows: "If the waiting time for takeoff hits 90 minutes at a U.S. airport, the FAA slows down departures from other airports so that the clogged airports can launch more jets. In addition, express lanes are set up for the delayed flights…. Storms in one part of the country might delay your flight even though it's sunny where you are, where you are going, and even in-between."

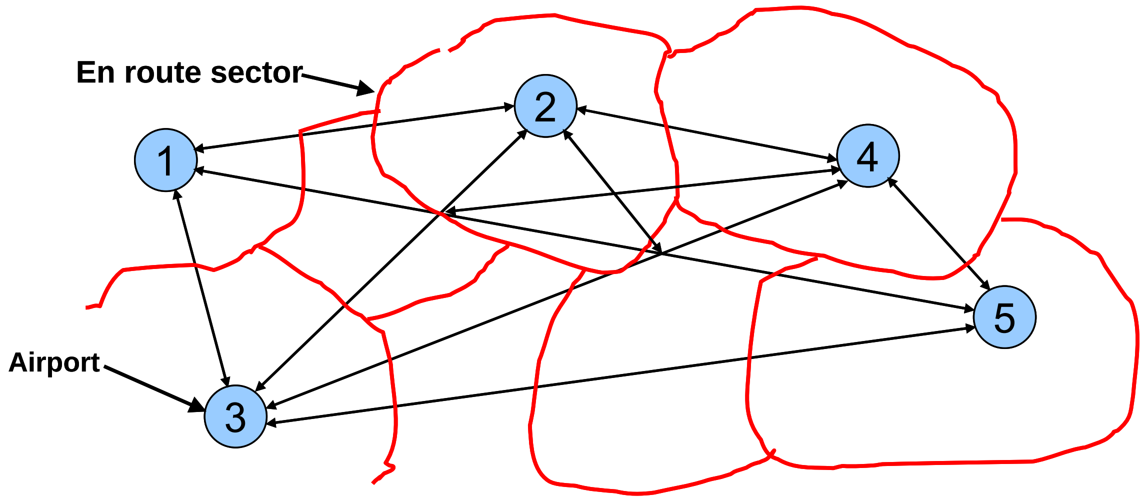

Figure B-2. The National Air System (NAS) as a network.

There is no convenient quantitative closed-form expression analogous to Equation 1 for the delays that arise when there are multiple queues as in Figure B-2. What one can say is that the delays are surely a very nonlinear function of both the duration of the event, the various city pair demands, and the various sector capacities. Since the system is typically operating in a very <u>nonlinear</u> mode, it is not easily possible to decompose the delay that occurs into terminal and en route contributions, i.e., the overall delay with both terminal <u>and</u> en route convective weather impacts is <u>not</u> equal to the delay with only terminal impacts plus the delay with only en route impacts.

TERMINAL DELAYS ARE IMPACTED BY NON-TERMINAL FORECASTS AND "STRATEGIC DECISION MAKING"

The dynamics of the NAS network under time-varying, unpredictable perturbations due to convective weather are quite complicated and not well understood conceptually by many of the people who must manage it in real time. Hence, the decision-making process for adapting to convective weather impacts is itself an important factor in delay causality. Figure B-3 illustrates the overall operational decision-making process for managing convective weather impacts. The Operational Decision Loop must be executed in a time period commensurate with a) the time scale over which the weather changes and b) the ability to accurately forecast the weather impact. If this cannot be achieved, then the plans that are executed will not be an appropriate solution for the weather situation.

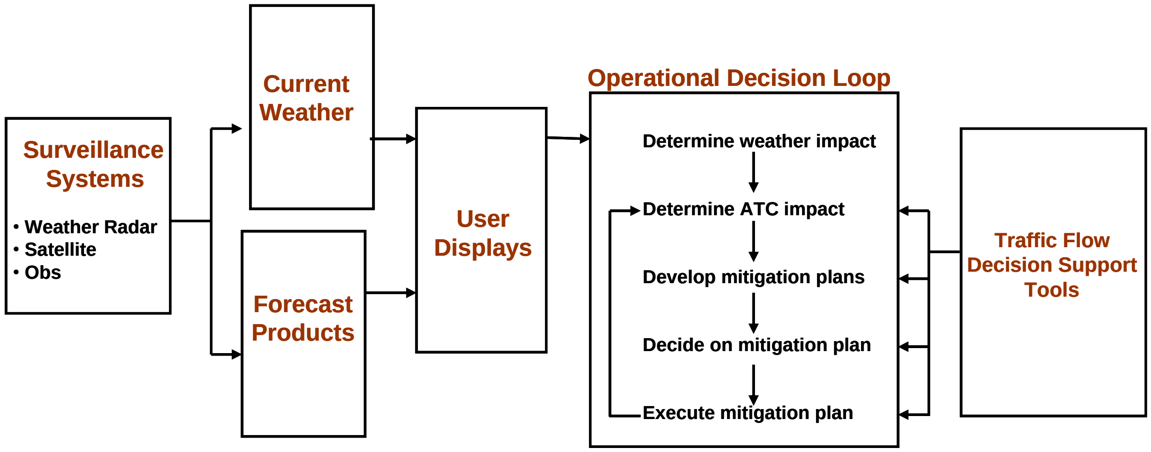

Figure B-3. Overall convective weather impact mitigation process.

DELAYS EARLIER IN THE DAY MAY IMPACT TERMINAL DELAYS AT ATLANTA

When an aircraft is delayed on one leg of a flight (e.g., due to adverse weather), it experiences delay on the next leg (and subsequent legs) flown that day. In cases where the subsequent leg(s) are not weather impacted, the delay may not be attributed to terminal weather even though the initial cause of the delay was weather impact on one leg of flight. The delay that occurs on subsequent legs is not a block-time delay [block time delay = actual block-time - flight plan block-time]. Rather, typically it would be a gate departure delay.

A study by American Airlines and Oak Ridge National Laboratory (Beatty et al., 1999) looked at the impact on airline operating resources (specifically aircraft and crews) that results from a first-leg delay. They examined the actual impact on the American Airlines operations schedule as a function of both time and amount of delay. They found that as the delay on the initial leg increases, the number of flights affected increases as well. The downstream impact is a highly nonlinear function of the initial time of occurrence of the delay and the amount of delay. The researchers developed a "delay multiplier" table that characterizes the degree of delay propagation as a function of the time of day the delay occurs and magnitude of the initial delay encountered. The "delay multiplier" ranges from as high as 4.0 (for delays greater than two hours early in the day) to a very small number for evening delays. For mid afternoon (e.g., 2 PM) the delay multiplier for a one hour delay is approximately 1.8 (i.e., the downstream impact is about 80% of the convective weather-induced initial delay)[39]. Delayed flight operations also impact passengers, cargo, and gate space. However, impacts of delays on those other resources and the

[39] It is interesting to note that a delay multiplier of 1.8 was also determined by Boswell and Evans (1997) from analysis of flights through LaGuardia International airport.

extent to which those impacts would further increase the delay could not be quantified. As a result, (Beatty et al., 1999) suggest that their results are very conservative.

To summarize the key points made in this appendix:

1. Terminal related delays are caused by convective weather impacts on the airport and on the airspace well away from the airport (especially the boundary between terminal and en route airspace).
2. Principal delay-generating mechanisms are (1) aircraft flying longer paths than desired due to the need to avoid convective weather and (2) the queue delays that arise when demand is greater than effective capacity.
3. Queue delays have a very nonlinear dependence on key factors such as the effective capacity of an ATC facility when impacted by convective weather, the demand, and the duration of the capacity impact. In contrast, the "longer path flown" delays tend to be linear in demand, weather event duration, and spatial extent of the adverse weather.
4. Convective weather impacts on highly congested en route airspace lead to very complicated, poorly understood multiple queues in the "NAS network". Since terminal and en route impacts contribute to most of these total 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.
5. The planning/mitigation plan execution process to cope with NAS network problems is a major factor in the delays that occur. Since effective execution of this process requires multi-hour convective forecasts of an accuracy that is currently unachievable, the convective weather-related delays that occur represent a very complicated combination of the actual weather characteristics, the convective weather forecasts, and the decision-making process.
6. The "delay ripple effect" arises when an aircraft and/or flight crew are delayed on one leg of a flight (e.g., due to adverse weather), which results 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 the initial delay.

APPENDIX C
ATLANTA AIR ROUTE TRAFFIC CONTROL CENTER (ZTL) GROUND STOP LOG

ZTL Ground Stop Log April-August 2003			
Entry	**Reason--if any**	**Start Time**	**End Time**
GS		4/7/2003 23:40	4/7/2003 0:45
GS		4/21/2003 20:45	4/21/2003 21:45
GS	ENRTE TSTMS, 2	5/3/2003 22:43	5/3/2003 1:39
GS		5/3/2003 17:30	5/3/2003 18:15
GS		5/5/2003 19:56	5/5/2003 20:26
GS		5/5/2003 22:09	5/6/2003 23:00
GS		5/6/2003 17:44	5/6/2003 21:00
GS	TS	5/6/2003 20:13	5/6/2003 21:09
GS	TSTMS	5/6/2003 21:56	5/7/2003 22:47
GS--ZTL1	TSTMS/VOL	5/7/2003 1:58	5/7/2003 2:51
GS-	TSTMS ENROUTE	5/15/2003 11:26	5/15/2003 12:08
GS	VOL & ENRTE	5/15/2003 18:56	5/15/2003 19:31
GS	VOLUME & WX	5/16/2003 18:54	5/16/2003 21:00
GS		5/18/2003 18:15	5/18/2003 20:08
GS		6/3/2003 11:15	6/3/2003 12:15
GS		6/11/2003 19:07	6/11/2003 19:44
GS	TSTMS	6/12/2003 22:37	6/12/2003 23:47
GS	TSTMS	6/13/2003 17:49	6/13/2003 19:30
GS		6/14/2003 17:53	6/14/2003 18:45
GS		6/17/2003 0:34	6/17/2003 0:52
GS	TS	7/10/2003 17:15	7/10/2003 18:15
GS	GRIDLOCK	7/10/2003 20:18	7/11/2003 23:00
GS		7/14/2003 21:00	7/14/2003 22:19
GS		7/15/2003 20:55	7/15/2003 21:10
GS	MICROBURST/WIND	7/15/2003 22:56	7/16/2003 23:20
GS		7/16/2003 19:15	7/16/2003 19:53
GS	TSTMS	7/22/2003 17:04	7/22/2003 19:40
GS		7/23/2003 10:50	7/23/2003 11:55
GS	TSTMS LIMITED	7/31/2003 19:57	7/31/2003 21:17
ZTL	TSTMS	7/31/2003 22:42	7/31/2003 22:50
GS		8/3/2003 17:45	8/3/2003 18:20
GS	WX/VOL	8/3/2003 19:00	8/3/2003 19:30
GS	WX DEV/VOL	8/3/2003 19:51	8/3/2003 20:25
GS	WX....TSTMS	8/6/2003 18:43	8/6/2003 19:30
GS	TSTMS	8/16/2003 18:25	8/16/2003 18:59
GS	TSTMS, CENTER	8/16/2003 19:57	8/16/2003 20:40
GS	TSTMS	8/17/2003 23:51	8/17/2003 0:20
GS	TSTMS	8/18/2003 18:31	8/18/2003 18:55
GS	TSTMS WIND	8/28/2003 20:57	8/29/2003 23:00

APPENDIX D
QUESTIONNAIRE

Note: some of these questions are to obtain a basic understanding of the operations of the Atlanta terminal area. Being provided with training material (e.g., ZTL TMU training material) on ATL operations prior to conducting the interviews would be most helpful.

TRACON Benefits Questions

1. On average, how many days per year do thunderstorms impact your operations?

   20-30 __ 30-40 __ 40-50 __ 50-60 __ 60-70 __

   a. What percentage of those days do you feel ITWS is a substantial benefit?

   0-20%__ 20-40 __ 40-60__ 60-80 __ 80-100__

2. How many key departure fixes are there? ___

   a. What are the average hourly rates over those fixes during a SWAP?

   10-20 __ 20-30 __ 30-40 __ 40-50 __ 50-60 __

   b. During good weather?

   10-20 __ 20-30 __ 30-40 __ 40-50 __ 50-60 __

3. How many key arrival fixes are there? ___

   a. What are the average hourly rates over those fixes during a SWAP?

   10-20 __ 20-30 __ 30-40 __ 40-50 __ 50-60 __

   b. During good weather?

   10-20 __ 20-30 __ 30-40 __ 40-50 __ 50-60 __

4. Of the arrival/departure fixes, approximately how many are on average closed during a convective weather event?

   1-2 __ 2-3 __ 3-4 __ 4-5 __ 5-6 __

5. On average, how long does your typical SWAP last?

   0-2 hrs __ 2-4 hrs __ 4-6 hrs __ 6-8 hrs __

6. Is ATL sometimes shut down with thunderstorms at the airport? If yes:

   a. How many times a year on average might this happen?

   0-3 __ 3-6 __ 6-9 __ 9-12 __ 12-15__ 15-18 __ 18-21 __ 21-24 __ 24-27 __ 27-30 __

   b. Do you feel ITWS allows you to better preplan closing the airport when this occurs?

   If so:

   - How many minutes would be saved in the Ground Stop start time by being able to anticipate when the airport will close?

     5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __

   - On average how many minutes of holding might this save for each aircraft?

     5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

   c. Do you feel ITWS allows you to preplan opening the airport when a ground stop occurs? If so:

   - How many minutes earlier might you end a Ground Stop based on ITWS information?

     5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

   - How many minutes less would a plane have to hold on average by using ITWS to pre-plan opening the airport?

     5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

7. Are there instances where you have a partial airport shutdown (e.g. storms on north side of airport)? If so:

   a. How often does this occur?

   1-3 __ 3-5 __ 5-7 __ 7-9 __ 9-11 __ 11-13 __ 13-15 __ 15-17 __ 17-19 __

   b. How many more times a year might you be able to keep the airport at least partially open now that you have ITWS to inform you on exact motion/location of thunderstorms?

   1-3 __ 3-5 __ 5-7 __ 7-9 __ 9-11 __ 11-13 __ 13-15 __ 15-17 __ 17-19 __

   c. On average, by what percentage would the arrival/departure rate drop when the airport is partially impacted?

   10% __ 20% __ 30% __ 40% __ 50% __ 60% __

d. How many extra minutes on average would you be able to keep the airport at least partially operating based on ITWS information?

0 __ 5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __

8. Aircraft are often routed around thunderstorms inside the TRACON during a convective event.

   Does ITWS allow you to more accurately route arriving/departing aircraft based on its rapid update rate and storm motion information? If so:

   a. How many minutes on average per aircraft do you estimate this would save (i.e. a shorter route than there would be with no ITWS)?

   5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

   Fixes may open and close during a convective event. ITWS can be used to plan when these fixes will open using the 20 minute Storm Extrapolated Position.

   a. How many times might you use ITWS to preplan opening a fix during a convective event?

   1-2 __ 2-3 __ 3-4 __ 4-5 __

   b. How many minutes earlier on average would you re-open the fix based on ITWS?

   0-5 __ 5-10 __ 10-15 __ 15-20 __ 20-25 __

9. Do you feel departure capacity when there is severe convective weather in or near the TRACON has been increased because of ITWS? If so:

   a. What percentage increase in departure capacity do you feel has been achieved?

   0-2% __ 2-4% __ 4-6% __ 6-8% __ 8-10 % __

10. Do the winds aloft adversely affect your operations such that the arrival rates you can achieve are lower than normal —presumably primarily in winter months?

    Yes ___ No ___

    a. Are ITWS Terminal Winds a help? Yes ___ No ___

    b. If you sometimes have compression on final approach, how much lower does this make your arrival capacity?

    1-3% __ 3-5% __ 5-7% __ 7-9% __ 9-11% __ 11-13% __ 13-15%

c. How many extra aircraft per hour do you think Terminal Winds helps you land if you have compression problems?

1-2 __ 2-3 __ 3-4 __ 4-5 __ 5-6 __ 6-7 __ 7-8 __ 8-9 __ 9-10 __

d. How many days per year do you estimate arrival rates are lowered because of rapidly varying winds aloft?

5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __

En route Center Benefits Questions

1. Ground delay programs (GDPs) are sometimes used to help manage arrivals during convective weather events. If ZTL sets the arrival rates for GDPs

   a. Do you feel ITWS has made you more comfortable in raising the expected hourly arrival rate above the rates you typically set in the past? If so:

   - By how many aircraft per hour do you raise the arrival rate based on ITWS?

   1 arrival ___ 2 arrivals ___ 3 arrivals ___ 4 arrivals ___ 5 arrivals ___

   b. ITWS projects storm movement out to 20 minutes. In the case of a well-organized line of storms, are 20 minutes enough time to let you preplan ending the GDP (if there is one) early? If so:

   - How many times a year—on average—might this occur?

   1-3 __ 3-5 __ 5-7 __ 7-9 __ 9-11 __ 11-13 __ 13-15 __ 15-17 __ 17-19 __ 19-21 __

2. Aircraft are frequently rerouted when their planned route is impacted by a convective event.

   a. Does ITWS allow you to more accurately reroute aircraft based on its rapid update rate and storm motion information? If so:

   i. How many minutes on average per aircraft do you estimate this would save (i.e. a shorter reroute than there would be with no ITWS)?

   5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

   ii. How many aircraft would you estimate achieve this benefit during a convective weather event?

   5-20 __ 20-40 __ 40-60 __ 60-80__ 80-100 __

3. In addition to more accurate rerouting, ITWS may aid in avoiding reroutes by giving 20 min forecasts of when jetways will reopen when thunderstorms move off them.

   a. On average, how many times during a convective event would ITWS help keep routes open or help routes open earlier?

   1-2 __ 2-3 __ 3-4 __ 4-5 __ 5-6 __ 6-7 __ 7-8 __ 8-9 __ 9-10 __

b. How many aircraft per route (on average) would be affected by routes being opened earlier? If ITWS helps you preplan opening the route 20 minutes earlier, this might be the number of aircraft to fly along the route over a 20 minute period.

5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __

c. How many minutes on average of delay would this save per aircraft?

5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

4. If MIT are used to reduce traffic on impacted jetways, how much might MIT be reduced because of accurate ITWS information?

   5-10 __ 10-15 __ 15-20 __ 20-25 __

   a. How many days per year would ITWS help you achieve a lower MIT restriction?

   1-3 __ 3-5__ 5-7 __ 7-9 __ 9-11 __ 11-13 __ 13-15 __ 15-17 __ 17-19 __

5. On what fraction of the days on which thunderstorms occur is ITWS useful in identifying the starts of weather impacts on arrival and departure fixes so that you could proactively reroute planes before the weather impact starts?

   0% 20% 40% 60% 80% 100%

6. How many aircraft would have a more efficient route due to ITWS showing the direct route would be usable

   0 1-5 5-10 10-15 15-20 20-30 30-40 40-50 50-60 >60

7. How many minutes on average per aircraft of delay do you estimate this would save?

   Can't estimate 1-5 5-10 10-15 15-20 20-30 30-40 40-50 50-60

8. On what fraction of the days with thunderstorms is ITWS useful in identifying cases where reroutes can be avoided because the forecasts show the weather will not impact the arrival and/or departure fixes?

   0% 20% 40% 60% 80% 100%

   On such days where ITWS is useful:

   a. How many aircraft would have a more efficient route due to ITWS showing the route through the desired fix would be usable?

   0 1-5 5-10 10-15 15-20 20-30 30-40 40-50 50-60 >60

   b. How many minutes on average per aircraft of delay do you estimate this would save?

Can't estimate 1-5   5-10   10-15   15-20   20-30   30-40   40-50   50-60

9. On average, how long does your typical SWAP last?

   0   30 mins   1 hr   2 hr   3 hr   4 hr   5 hr

10. Is ATL sometimes shut down with thunderstorms at the airport?

    a. If so, how many times a year on average might this happen?

    b. Do you feel ITWS will be useful next year in anticipating closing the airport when this occurs?

    c. If so, how many fewer aircraft would you expect to hold in at higher altitudes in en route airspace because of ITWS information?

    d. On average how many minutes of holding at higher altitudes might be achieved for each aircraft?

    e. Do you feel ITWS is useful in anticipating reopening the airport?

    f. If so, how many minutes earlier would you be able to commence landing aircraft at the airport because of ITWS information?

    g. Are there instances where you have a partial airport shutdown (e.g. storms on west side of airport) and if so how often does this occur?

    h. If there are such instances, how many more times a year might you be able to anticipate that the airport will remain at least partially open now that you have ITWS to inform you on exact motion/location of thunderstorms?

    i. If so, on average, how many aircraft might be saved from a holding pattern because of the ITWS precipitation and forecast products benefit?

       5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __

    j. How many minutes on average might they have held without ITWS?

    5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

11. One ITWS product is storm echo tops. Fuel burn can be reduced if the holding stack is closer to the airport, and ITWS can show whether holding above a low-topped storm is feasible. Do you envision getting this benefit from ITWS?

    If so:

    a. How many times a year do you achieve this benefit?

1-2 __ 2-3 __ 3-4 __ 4-5 __ 5-6 __ 6-7 __ 7-8 __ 8-9 __ 9-10 __

b. On average, how many aircraft in the holding stack would benefit?

1-2 __ 2-3 __ 3-4 __ 4-5 __ 5-6 __ 6-7 __ 7-8 __ 8-9 __ 9-10 __

c. On the average, how much flying time might be saved per aircraft by holding near the airport?

5-10 __ 10-15 __ 15-20 __ 20-25 __ 25-30 __ 30-35 __ 35-40 __ 40-45 __

APPENDIX E
QUESTIONNAIRE RESULTS

Questionnaire Results

	ZTL		A80					ATL	
Question	**User 1**	**User 2**	**User 1**	**User 2**	**User 3**	**User 4**	**User 5**	**User 1**	**User 2**
1a	180	90	80	60-70	90	90	60-70	60-70	60-70
1b	n/a	80-100	80-100	80-100	100	100	80-100	0-20	60-80
2a									
2b									
3a									
3b									
4			1--2	can't est	1--2	2--3	n/a	1--2	1--2
5	n/a	0-2	0-2	2--4	0--2	0--2	n/a	0-2	0--2
6a		n/a	18-21	12--15	6--9	12--15	12--15	12--15	12--15
6bi		20-25	12	15--20	15--20	ZTL	n/a	ZTL	10--15
6bii		25-30	10--15	15--20	can't est	n/a	n/a	10--15	5--10
6ci			n/a	15--20	n/a	ZTL	n/a	ZTL	10--15
6cii			n/a	15--20	n/a	n/a	n/a	10--15	10--15
7a			5--7	5--7	3--5	5--7	17--19	n/a	25
7b			3--5	5--7	9--11	7--9	7--9	20	11--13
7c			n/a	50%	can't est	can't est	20%	60%	n/a
7c			5--10	10--15	can't est	can't est	15--20	10	can't est
8a			10--15	15--20	no	10--15	5--10	15	n/a
8b			3--4	4--5	3--4	1--2	2--3	4--5	n/a
8c			5--10	10--15	5--10	can't est	0--5	10--15	n/a
9			n/a	0-2%	8--10	2-4%	n/a	2--4	can't est
10a		yes	yes	yes	yes	yes	yes	yes	yes
10b		1--3	13-15	25%	5--7	3--5	3--5	10-15%	15%
10c			2--3	1--2	1--2	can't est	n/a	no	1--2
10d			5--10	30-35	5--10	can't est	n/a	10--15	15--20
11									

	Questionnaire Results - Section 2	
	ZTL	
Question	User 1	User 2
1a	5	3
1b	15-17	30
2a	5--10	5--10
	5--20	5--20
3a	9--10	1--2
3b	5--10	30-40
3c	5--10	5--10
4a	5--10	can't est
4b	17--19	11--13
5a	100%	100%
5b	5--10	30-40
5c	can't est	15-20
6a	100%	100%
6b	1--5	15-20
6c	5--10	15-20
7	2	2
8a	45-60	20
8b	yes	yes
8c	no	no
8d	0	0
8e	100%	yes
8f	10--15	10
8g	2/3 of time	15
8h	2/3 of time	n/a
8i	20-25	10--15
8j	30-35	15-20
9a	no	no
9b	no	no
9c	no	no

GLOSSARY

AAR	Airport Arrival Rate
ABQ	Albuquerque International Sunport Airport
Acronym	Definition
ALDAR	Automated Lightning Detection and Reporting System
ARTCC	Air Route Traffic Control Center
ASOS	Automated Surface Observing System
ASPM	Aviation System Performance Metrics
ASQP	Airline System Quality Performance
ASR	Airport Surveillance Radar
ASR-9	Airport Surveillance Radar – Model 9
ATA	arrival transition area
ATC	Air Traffic Control
ATCSCC	Air Traffic Control Systems Command Center
ATL	Hartsfield-Jackson Atlanta International Airport
BOS	Logan International Airport (Boston)
C/V	ceiling/visibility
CDM	Collaborative Decision Making
CIWS	Corridor Integrated Weather System
CTAS	Center-TRACON Automation System
CVG	Cincinnati/Northern Kentucky International Airport
CWSU	Center Weather Service Unit
DFW	Dallas-Ft. Worth International Airport
DTA	departure transition area
DTW	Detroit Metropolitan Wayne County Airport
EDCT	Estimated Departure Clearance Time
ETMS	Enhanced Traffic Management System
EWR	Newark Liberty International Airport
FAA	Federal Aviation Administration
FAST	Final Approach Spacing Tool
GDP	ground delay program
GS	ground stop
IAD	Washington Dulles International Airport
IAH	George Bush Houston Intercontinental Airport/Houston
IFR	Instrument Flight Rules
IOC	Initial operational capability
ITWS	Integrated Terminal Weather System
KDP	Key Decision Point
kft	thousands of feet
LAS	McCarran International Airport (Las Vegas)

LAX	Los Angeles International Airport
LGA	LaGuardia Airport (New York)
LLWAS NE	Low Level Windshear Alert System Network Expansion
LST	local standard time
mb	millibars
MCDRS	Meteorological Data Collection and Reporting System
MCI	Kansas City International Airport
MCO	Orlando International Airport
MDW	Chicago Midway International Airport
METAR	Meteorological Actual Report
MIA	Miami International Airport
min	minutes
MIT	Miles-in-Trail
MIT Lincoln Laboratory	Massachusetts Institute of Technology Lincoln Laboratory
MSP	Minneapolis-St Paul International Airport
NAS	National Airspace System
NCDC	National Climatic Data Center
NEXRAD	Next Generation Weather Radar
NLDN	National Lightning Detection Network
nmi	nautical miles
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
OAG	Official Airline Guide
OAK	Metropolitan Oakland International Airport
OMB	Office of Management and Budget
OOOI	Out/Off/On/In
OPSNET	Air Traffic Operations Network
ORD	Chicago O'Hare International Airport
P_d	Probability of Detection
P_{fa}	Probability of False Alarm
PHL	Philadelphia International Airport
PHX	Phoenix Sky Harbor International Airport
RTVS	Real-Time Verification System
RUC	Rapid Update Cycle
SEA	Seattle-Tacoma International Airport
SEP	Storm Extrapolated Position
SFO	San Francisco International Airport
SLC	Salt Lake City International Airport
SMF	Sacramento International Airport
SOC	Systems Operation Center
STAR	Standard Terminal Arrival Route
STL	Lambert-St Louis International Airport

SWAP	Severe Weather Avoidance Program
TDWR	Terminal Doppler Weather Radar
TEB	Teterboro Airport
TMU	traffic management unit
TRACON	Terminal Radar Approach Control
TS	thunderstorm
TSRA	thunderstorm with rain
UTC	Coordinated Universal Time
Z	Greenwich Mean Time or Coordinated Universal Time
ZME	Memphis ARTCC
ZTL	Atlanta ARTCC

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