Project Report
ATC-364

Traffic Management Advisor (TMA) Weather Integration

M. Robinson
H.J. Davison Reynolds
J.E. Evans

10 August 2010

Lincoln Laboratory
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
LEXINGTON, MASSACHUSETTS

Prepared for the Federal Aviation Administration,
Washington, D.C. 20591

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.
ATC-364

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Traffic Management Advisor (TMA) Weather Integration

5. Report Date
10 August 2010

6. Performing Organization Code

7. Author(s)
Michael Robinson, Hayley J. Davison Reynolds, and James E. Evans

8. Performing Organization Report No.
ATC-364

9. Performing Organization Name and Address
MIT Lincoln Laboratory
244 Wood Street
Lexington, MA 02420-9108

10. Work Unit No. (TRAIS)

11. Contract or Grant No.
FA8721-05-C-0002

12. Sponsoring Agency Name and Address
Department of Transportation
Federal Aviation Administration
800 Independence Ave., S.W.
Washington, DC 20591

13. Type of Report and Period Covered
Project Report

14. Sponsoring Agency Code

15. Supplementary Notes

This report is based on studies performed at Lincoln Laboratory, a center for research operated by Massachusetts Institute of Technology, under Air Force Contract FA8721-05-C-0002.

16. Abstract

Time-based flow metering (TBFM) of traffic to capacity-constrained areas such as airport runways and arrival fixes is considered a key element of the Next Generation Air Transportation System (NextGen) operational concept for managing high density air traffic. The principal operational TBFM system today is the Traffic Management Advisor (TMA). TMA is used to optimize the flow of aircraft through various control points (e.g., arrival fixes, final approach fixes, and runway thresholds) so as to maximize airspace capacity without compromising safety.

TMA makes continuous predictions of aircraft estimated time of arrivals (ETAs) at various metering points along the flight's trajectory. Scheduling algorithms use the ETAs to compute scheduled times of arrival (STAs) for each aircraft to specific scheduling points. The desired change in aircraft arrival time to the meter fix is provided to en route controllers who then accomplish speed and/or trajectory changes such that the plane passes over the arrival fix at the desired time. The required arrival fix time adjustment is continually updated as the plane proceeds to the arrival fix to provide closed loop control. During non-convective weather, TMA usage has resulted in increased capacity, reduced aircraft fuel burn, and decreased delay.

If significant convective weather is present, the TMA software currently still assumes that an aircraft will fly the normal fair weather trajectory to a metering fix. However, if an aircraft deviates around a storm, the flying time to a metering point will generally be different from the fair weather flight time. Therefore, the TMA ETAs will be in error. Currently, the TMA usage is often halted during convective weather events because the arrival time adjustments provided to the controllers may be unmanageable or in error.

The results of a study identifying the potential benefits derived from various approaches to integrating weather information from the Corridor Integrated Weather System (CIWS) with TMA are provided in this report. Based on these results, recommendations are provided on near term weather-TMA integration capabilities that would provide enhanced decision support for the operational community that is successfully utilizing TMA in non-severe weather and/or seeking to increase its operational utility in severe weather.

17. Key Words

18. Distribution Statement
This document is available to the public through the National Technical Information Service, Springfield, VA 22161.

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	80	

FORM DOT F 1700.7 (8-72) Reproduction of completed page authorized

This page intentionally left blank.

ABSTRACT

Time-based flow metering (TBFM) of traffic to capacity-constrained areas such as airport runways and arrival fixes is considered a key element of the Next Generation Air Transportation System (NextGen) operational concept for managing high density air traffic. The principal operational TBFM system today is the Traffic Management Advisor (TMA). TMA is used to optimize the flow of aircraft through various control points (e.g., arrival fixes, final approach fixes, and runway thresholds) so as to maximize airspace capacity without compromising safety.

TMA makes continuous predictions of aircraft estimated time of arrivals (ETAs) at various metering points along the flight's trajectory. Scheduling algorithms use the ETAs to compute scheduled times of arrival (STAs) for each aircraft to specific scheduling points. The desired change in aircraft arrival time to the meter fix is provided to en route controllers who then accomplish speed and/or trajectory changes such that the plane passes over the arrival fix at the desired time. The required arrival fix time adjustment is continually updated as the plane proceeds to the arrival fix to provide closed loop control. During non-convective weather, TMA usage has resulted in increased capacity, reduced aircraft fuel burn, and decreased delay.

If significant convective weather is present, the TMA software currently still assumes that an aircraft will fly the normal fair weather trajectory to a metering fix. However, if an aircraft deviates around a storm, the flying time to a metering point will generally be different from the fair weather flight time. Therefore, the TMA ETAs will be in error. Currently, the TMA usage is often halted during convective weather events because the arrival time adjustments provided to the controllers may be unmanageable or in error.

The results of a study identifying the potential benefits derived from various approaches to integrating weather information from the Corridor Integrated Weather System (CIWS) with TMA are provided in this report. Based on these results, recommendations are provided on near term weather-TMA integration capabilities that would provide enhanced decision support for the operational community that is successfully utilizing TMA in non-severe weather and/or seeking to increase its operational utility in severe weather.

TABLE OF CONTENTS

Page

This page intentionally left blank.

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTINUED)

LIST OF ILLUSTRATIONS (CONTINUED)

This page intentionally left blank.

LIST OF TABLES

This page intentionally left blank.

1. INTRODUCTION

Time-based flow metering (TBFM) of traffic to capacity-constrained areas such as airport runways and arrival or departure fixes is considered a key element of the Next Generation Air Transportation System (NextGen) operational concept for managing high density air traffic. The principal operational TBFM system today is the Traffic Management Advisor (TMA). TMA is principally used to optimize the flow of arrival aircraft through various control points (e.g., arrival fixes, final approach fixes, and runway thresholds) so as to maximize airspace capacity without compromising safety[1].

TMA makes continuous predictions of aircraft estimated time of arrivals (ETAs) at various metering points along the flight's trajectory. Scheduling algorithms in the TMA Dynamic Planner use the ETAs to compute scheduled times of arrival (STAs) for each aircraft to specific scheduling points. TMA scheduling is done so that aircraft arrive at meter points within assigned, available slots. The desired change in aircraft arrival time to the meter fix is provided to en route controllers who then accomplish speed and/or trajectory changes such that the aircraft arrives at the scheduling point so as to fit within the assigned slot. The required arrival fix time adjustment is continually updated as the aircraft proceeds to the scheduling point (e.g., fix, runway) to provide closed loop control.

During fair-weather conditions, TMA usage has resulted in increased airport arrival capacity, reduced aircraft fuel burn, and decreased delay (Volpe, 2008). The Federal Aviation Administration (FAA) estimates that TMA usage has resulted in airport capacity increases of 3 to 5 percent, with some airports seeing even higher results (FAA, 2009). Use of TMA has resulted in a significant reduction in the use of Miles-In-Trail (MIT) restrictions to manage airborne arrival flows. MIT restrictions are considered less efficient than the metering constraints of TMA, which are flight-specific and synchronized to the capacity limitations of the meter fix or arrival runway. TMA has also improved common awareness and air traffic management (ATM) predictability, resulting in improved coordination and reduced "no-notice" volume management actions (e.g., unanticipated airborne holding, route closures, etc.).

Increased capacity usage of constrained resources (e.g., runways, arrival and departure fixes) and delay savings achieved with TMA are most significant when traffic demand nears or exceeds the available capacity. Demand often exceeds capacity when adverse weather such as thunderstorms (in en route or terminal airspace) or low ceilings and visibility at the airport restrict the number of available arrival slots. It is during these weather situations where TMA metered operations can provide the most benefit in terms of mitigating airborne delay and facilitating a more predictable air traffic management environment.

If significant convective weather is present, the TMA software currently still assumes that an aircraft will fly the normal fair weather trajectory to a metering fix. However, if an aircraft deviates around a storm, the flying time to a metering point will generally be different from the fair weather flight time. Therefore, the TMA ETAs may be incorrect. If metering point ETAs are inaccurate, then STA metered

---

[1] TMA also can be used to optimize the use of departure fixes, but this is less common. This report focuses primarily on TMA decision support for arrival traffic.

times used by controllers and TMCs to manage airborne delay are also incorrect, resulting in the possible loss of usable slots and/or degraded operational efficiency.

Currently, the TMA usage and metering operations are often halted during convective weather events because the arrival time adjustments provided to the controllers may be unmanageable or so significantly in error that TMA may be degrading overall operational efficiency. Moreover, aircraft deviations in a metered flow that are not anticipated or adequately planned for often fall behind their time-metered slot, which can reduce arrival capacity (as available slots go unused) and can result in increased airborne holding (as multiple aircraft arrive in the same meter slot). The lack of weather information in TMA severely limits the ability of traffic managers to make proactive decisions that can mitigate these types of weather impacts on metered traffic flows. The end result of this is often increased controller workload, reduced ATM efficiency, increased airborne holding and aircraft fuel burn, and increased delay and suspended TMA operations.

MIT Lincoln Laboratory supports the FAA's Systems Operations service unit through the development and operation of the prototype Corridor Integrated Weather System (CIWS) (Evans and Ducot, 2006) and the Route Availability Planning Tool (RAPT) (DeLaura et al. 2008). These weather decision support tools provide real time operational support for air traffic decision-making during adverse weather. As part of data packages for investment decision making, a number of studies have been carried out to determine the operational utility of these systems for improving National Airspace System (NAS) operations in severe weather (e.g., Robinson et al., 2010; Robinson et al., 2006). These CIWS and RAPT operational usage studies have focused on CIWS product usage and RAPT impact assessment concepts for a number of traffic flow decisions that are pertinent to the use of TMA in convective weather. These decisions include:

- Determining when aircraft can use weather impacted routes
- Reopening route or fixes more quickly
- Implementing proactive, efficient reroutes

This report presents the results of an exploratory study (a) to assess the current TMA capabilities and procedures for metering operations during convective weather and (b) to identify near-term TMA and CIWS[2] weather integration capabilities that would provide enhanced decision support for the operational FAA community that is successfully utilizing TMA during fair weather and seeking to increase its operational utility during severe weather.

---

[2] CIWS was viewed as the most appropriate candidate for TMA convective weather integration in view of the metered aircraft flight times (less than 2 hours from locked STA to touchdown) and the successful operational usage of dedicated CIWS displays. Although other convective weather forecasts could in principle be used for TMA integration (e.g., the Weather and Research Forecast [WRF] Model [Stobie and Gillen, 2008]), at this point in time, only CIWS has echo tops forecasts – which is critical information and a key factor in en route pilot storm avoidance decision-making (DeLaura and Evans, 2006). Additionally, the FAA plans to provide CIWS products on the TFM display by 2011.

A summary of the current TMA display tools and usage is provided in Section 2. The approach and results of our initial weather-TMA integration assessment are presented in Section 3. Initial concepts for integrating CIWS products and CIWS-derived, scalable traffic impact forecasts into TMA are presented in Section 4. Section 5 examines the potential benefits of the proposed weather-TMA decision support guidance.

This page intentionally left blank.

2. TMA

TMA is an automation aid for traffic managers and controllers at Air Route Traffic Control Centers (ARTCCs) and Terminal Radar Control (TRACON) facilities to manage TBFM operations. The Estimated Time of Arrival (ETA) of arriving aircraft are computed by TMA algorithms that predict aircraft trajectories in real-time. TMA then schedules aircraft to the meter points and the active runway threshold, with the least possible delay. The STA is constantly recomputed with every radar update until a freeze point, called the Freeze Horizon, is reached. Inside the Freeze Horizon, flight-by-flight STA delay assignments from TMA are provided directly to ARTCC controllers as an optimal advisory for maintaining desired aircraft spacing and arrival rates.

The TMA scheduling algorithm is particularly important in considering the impact of convective weather on TMA. To give an initial appreciation of what the scheduler does and how it works, consider the single biggest problem that TMA deals with, which is handling arrival congestion at an airport. Suppose that flights from a number of directions are converging on the airport; since there is arrival congestion, the runway is a scarce resource, and it needs to be used as efficiently as possible. At the same time, the TRACON is constrained as to how many flights it can handle, and each meter fix, which for now can be thought of as an arrival fix, is constrained as to how many flights it can handle. Outside the approach gates (with their meter fixes) there are often outer meter arcs which help control the traffic arriving at the arrival fixes.

The task, therefore, is to merge those streams of traffic and control the flights so that they arrive at the runway (or runways) with minimal spacing so that the highest possible throughput is obtained from the runway. This must be done while satisfying not only the runway constraint but also other constraints in the system (e.g., at arrival fixes and at outer meter arcs). This is a difficult problem since not only are there multiple streams of flights to blend, but the arriving aircraft have different performance characteristics (i.e., fly at different speeds, at different altitudes, and with different descent rates). The TMA scheduler takes into account of all of these factors in its scheduling solution.

A key point in considering convective storm impacts is that there is an implicit slot allocation for aircraft at all constraint points including the arrival fixes and runways. Hence, if a plane is delayed by flying around storms such that it misses its slot at a constraint point and there are no open slots at the constraint point that are readily available, then there may be a need to put the plane in a holding pattern. This may result in further slot allocation problems if aircraft in holding patterns impede other flights which in turn results in more missed slots.

Traffic managers are provided with three different TMA displays:

1. Planview Graphical User Interface (PGUI)
2. Timeline Graphical User Interface (TGUI)
3. Demand Load Graphs

PGUI

The PGUI is the TMA traffic display which shows the location of arrival aircraft en route to the metered airport (Figure 2-1). The PGUI can be configured and "zoomed in" to show arrivals on final approach in the TRACON or "zoomed out" to show all arrival traffic inside the Freeze Horizon, which can extend across multiple ARTCCs. The traffic on the PGUI updates every 12 seconds. The high temporal and spatial resolution of the TMA PGUI has made it a preferred situational awareness tool for monitoring airport arrival flows, particularly for traffic in the TRACON airspace. The TMA PGUI currently does not display weather radar or satellite data. The only displayable PGUI weather information are wind vectors at 13 km grid points from the Rapid Update Cycle (RUC) numerical weather model, updating in TMA once per hour.

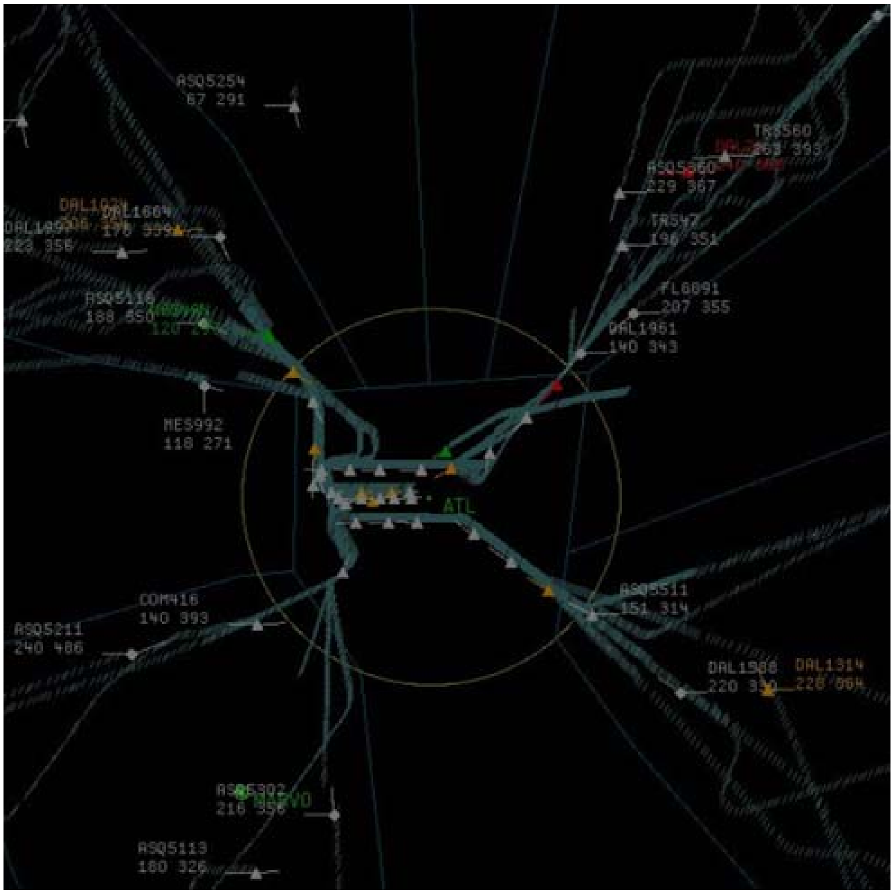


Figure 2-1. TMA PGUI display for ATL metering operations, showing ATL arrival traffic (with flight track history).

TGUI

Traffic managers consider the TGUI display to be the most informative and important TMA decision support product. The TMA TGUI displays traffic volume for each selected meter fix or runway (Figure 2-2). The ETA and STA for each individual flight en route to a specific fix and runway is shown in each timeline. When the STA for a metered flight (right-side of timeline) trails the ETA for that flight (left-side of timeline), the assigned delay associated with this flight that must be achieved by controllers to optimize the capacity of the metered flow is shown in the TGUI next to the STA flight ID. Sometimes, these delay times are negative (see Figure 2-2), which means that the aircraft has fallen behind its scheduled time and it would have to speed up and/or fly a shorter route (e.g., "cut a corner") to return to its scheduled slot. Delay lists derived from these TGUI delay assignments are sent directly to the controller's Display System Replacement (DSR) scopes, where vectoring or speed controls are issued to pilots to ensure STA compliance. In the case of negative delays, controllers are instructed NOT to speed up flights for the purposes of TMA compliance and instead are to ignore these delay times.[3]

Load Graphs

The TMA load graphs are used by traffic managers to assess current and projected traffic demand to select reference points, such as to a meter fix or to the runway (Figure 2-3). Airport or meter fix acceptance rates are also displayed in the load graphs to help traffic managers determine if ATM actions will be required to balance metered traffic demand with capacity. These load graphs are configurable and can show traffic demand by aircraft size (e.g., showing number of "heavy" aircraft – requiring additional wake vortex spacing, which diminishes capacity – expected over the next hour), by anticipated metered delay, by counts or by rate, etc. One manner in which traffic managers use the TMA load graphs is to plan when airport ground stops or ground delay programs may be needed to ensure TMA airborne delay assignments do not become unmanageable.

TMA also provides traffic managers a suite of scheduling actions that can be implemented to reschedule some or all of the metered aircraft in order to manage evolving capacity impacts or demand imbalances. Some of these scheduling actions include changes to meter fix or runway acceptance rates, changes to aircraft separation distance, "find slot" operations, and blocked intervals when a runway or fix is expected to be unavailable (e.g., weather at a fix, or an arrival runway being temporarily used to support a departure push). The use of specific TMA scheduling actions is discussed in Section 3.

Currently, TMA is in operational use at 28 of the 35 Operational Evolution Partnership (OEP) airports in the NAS (Figure 2-4). TMA has been implemented in all 20 FAA ARTCCs. Traffic management coordinators (TMC) and en route controllers in the ARTCC use TMA to support Single Center Metering (SCM) and Adjacent Center Metering (ACM). Single Center TMA allows the ARTCC to meter arrival flows for internal airports only (e.g., Boston airport [BOS] arrivals metered only by the Boston ARTCC [ZBW]). ACM allows additional, neighboring ARTCCs to meter arrival flows to a particular airport (e.g., Newark airport [EWR] arrivals are metered by New York [ZNY], ZBW, Cleveland [ZOB], and Washington D.C. [ZDC] ARTCCs).

---

[3] As a result, flights with negative TMA delay times miss their assigned meter slot, which reduces capacity.

Figure 2-2. TMA TGUI display, showing the ETA (left) and STA (right, with assigned delay) for each flight metered to the Boston Logan airport arrival runway between 45 minutes after the current hour until 30 minutes after the following hour. Flights with blue STAs are inside the Freeze Horizon while yellow STAs depict flights still beyond the Freeze Horizon.

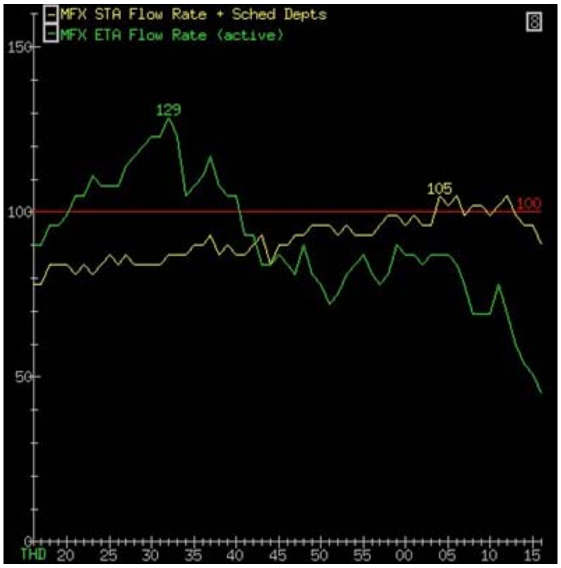


Figure 2-3. TMA load graph for ATL, showing projected ETA and STA flow rates for the next hour. The airport acceptance rate for this period is shown by the red line.

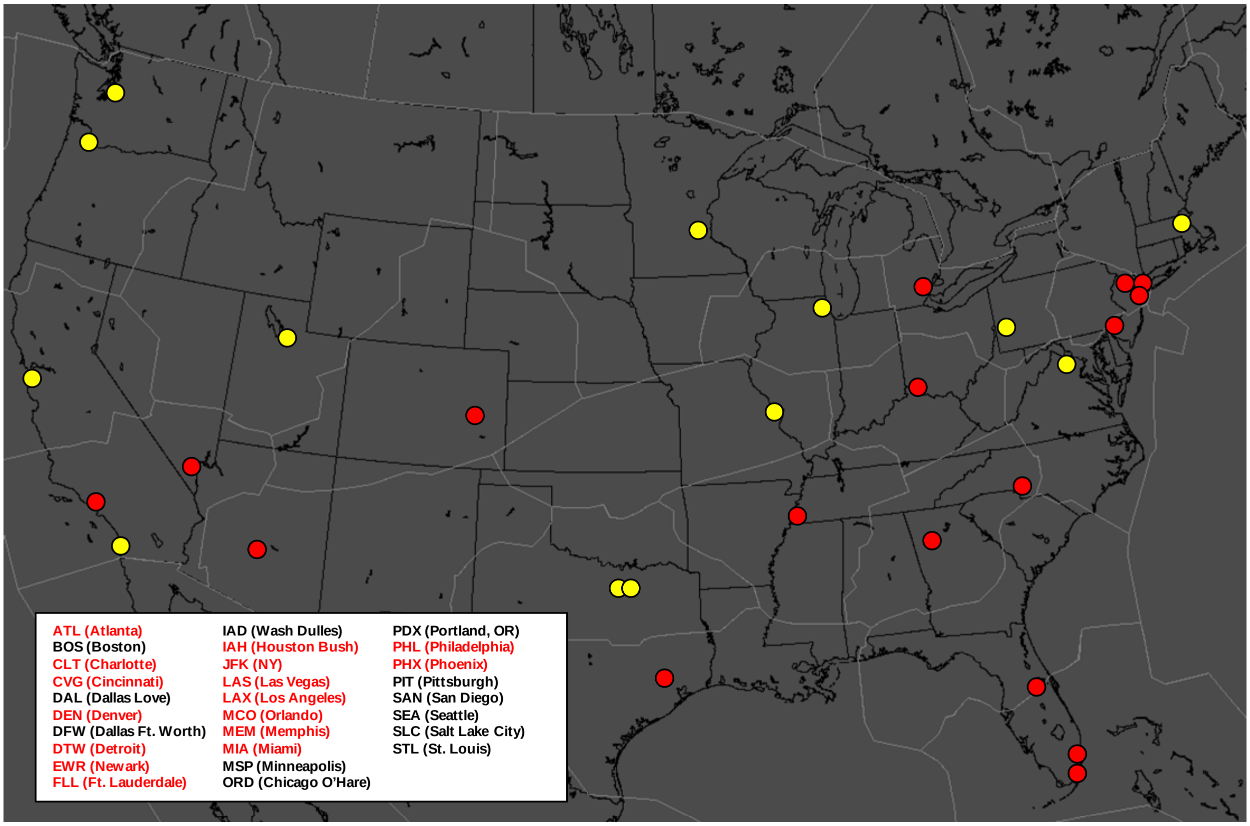


Figure 2-4. Airports where TMA is in operational use (when needed) as of Dec 2009. Airports in red are locations where TMA Adjacent Center Metering (ACM) is supported.

Whether using TMA as a Single Center or as part of ACM, time-based metering often requires significant effort from numerous operational controller and traffic management positions for TBFM coordination and execution. This increased workload can be particularly severe at traffic facilities supporting multiple TMA operations (e.g., N90 and ZID). However, when operated correctly and when weather conditions are favorable, the extra effort needed to manage TMA is deemed worthwhile, as increased airspace management predictability and increased capacity often contribute to an overall workload decrease in the operational ATC system (Figure 2-5).

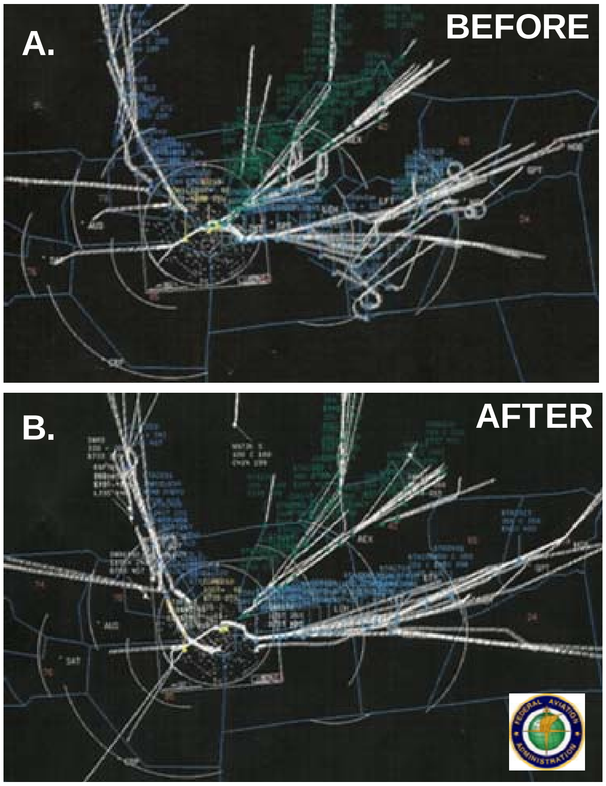


Figure 2-5. Arrival traffic to Houston George Bush Intercontinental Airport (IAH) during a fair-weather period (A) before and (B) after TMA and time-based metering was in use in Houston ARTCC (ZHU). The streamlined arrival flows and limited holding with TMA increased both IAH landing rates (capacity benefit) and ATC productivity (workload benefit). This figure is provided courtesy of the FAA.

Unfortunately, off-nominal conditions can quickly disrupt the highly-coordinated TMA environment. Unanticipated impacts on metered flows can introduce metered-slot uncertainty across multiple FAA facilities, making the ATC environment unpredictable. Eventually, this often results in an unmanageable TMA operation that must be suspended. Most unanticipated TMA impacts are the result of adverse weather, most notably thunderstorms. The motivation of this weather-TMA study is to identify weather-TMA integration weather concepts that would support proactive TMA actions that may help maintain a predictable and manageable traffic metering operation during adverse weather conditions.

3. WEATHER-TMA INTEGRATION ASSESSMENT

The elements of our Weather (WX)-TMA integration assessment were as follows:

1. Identify sites for focused evaluation of TMA operations
2. Conduct site surveys and provide CIWS training
3. Conduct (a) interviews with TMA SMEs and (b) analyze baseline TMA operations during convective weather
4. Observe and evaluate TMA operations in real-time during convective weather at selected sites
5. Provide “storyboard” concepts for adding weather decision support information to the TMA PGUI, TGUI, and load graph displays
6. Assess potential benefits of integrated WX-TMA decision support

The results of tasks 1–4 are presented in this section. The proposed concepts and potential benefits for WX-TMA decision support integration are presented in Sections 4 and 5.

3.1 SELECTED SITES FOR WX-TMA STUDY

The four sites identified by the TMA Program Office, the TMA National Workgroup, and MIT Lincoln Laboratory for consideration in the WX-TMA integration study were

1. Atlanta
2. Boston
3. Chicago
4. Dallas-Fort Worth

The sites were selected because they each satisfied specific criteria required to support this study. These site-specific criteria are shown in Table 3-1.

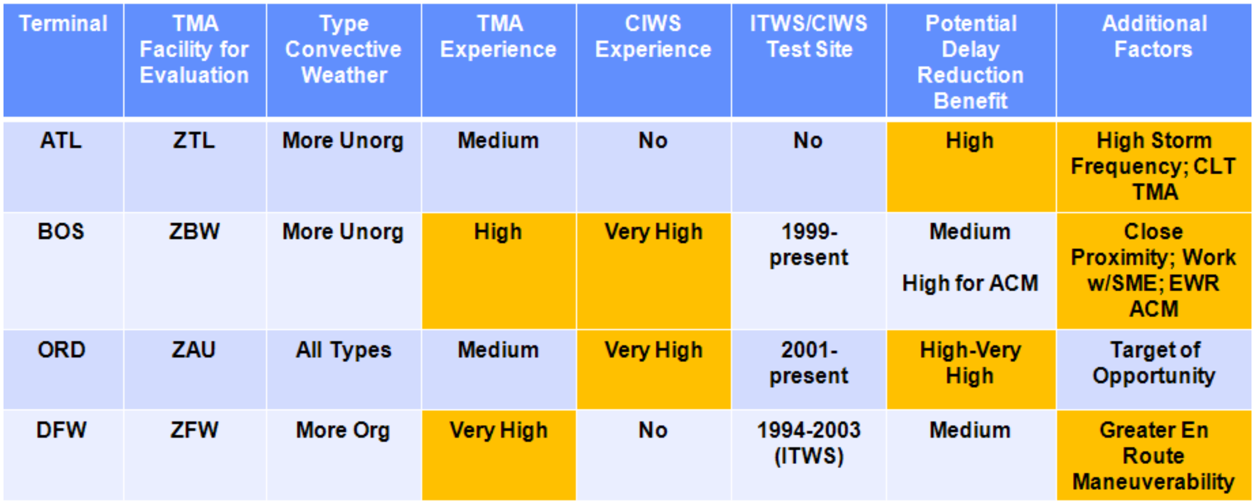
Assessments of TMA usage in convective weather based upon these collective sites were anticipated to be robust, given (a) the mix of TMA and CIWS user experience, (b) the adequate variability in the predominant types of convective weather, (c) the different levels of anticipated potential benefits, and (d) the variability in airspace and metering operations (e.g., degree of routing flexibility, support for ACM, etc.) across the four sites.

Since TMA is primarily an en route metering tool, the parent-ARTCC for each selected terminal site was designated as the TMA evaluation facility: Atlanta (ZTL), Boston (ZBW), Chicago (ZAU), and Fort Worth (ZFW) ARTCCs. At each of these facilities, a site survey was conducted to determine if the location of the TMA equipment was near enough to CIWS displays (or Internet-ready PCs capable of displaying CIWS web) for users to assess the potential expanded capabilities of TMA with CIWS weather products directly available on the TMA displays.

A summary of the TMA site survey and CIWS training results are shown in Table 3-2. CIWS is available at both ZAU and ZBW Centers. Unlike in ZAU, where the CIWS display is well-placed immediately adjacent to the TMA displays at the Traffic Management Unit (TMU) arrival position (see Figure 3-1), the ZBW BOS TMA position is located just outside of the TMU – where it is not possible for the TMC managing BOS TMA to view the CIWS display in the TMU area. Therefore, in support of this WX-TMA integration task, the TMA program office purchased a CIWS display for the ZBW TMA position for BOS. This display was deployed in June 2009.

At ZFW and ZTL, where dedicated CIWS displays are not available, CIWS web training was provided to familiarize traffic managers with the CIWS products that may be integrated with TMA to improve the efficiency of metering operations. The CIWS web site was displayed via Internet-ready PCs in the ZTL and ZFW TMUs. However, it is much more difficult to make operational use of the CIWS web site in the TMU, given that available PCs were (a) not located in close proximity to the TMA positions and (b) often being used for other operationally-critical tasks, limiting its availability for CIWS weather assessments.

Table 3-1. Site Selection Criteria for 2009 WX-TMA Integration Study*



Terminal	TMA Facility for Evaluation	Type Convective Weather	TMA Experience	CIWS Experience	ITWS/CIWS Test Site	Potential Delay Reduction Benefit	Additional Factors
ATL	ZTL	More Unorg	Medium	No	No	High	High Storm Frequency; CLT TMA
BOS	ZBW	More Unorg	High	Very High	1999-present	Medium High for ACM	Close Proximity; Work w/SME; EWR ACM
ORD	ZAU	All Types	Medium	Very High	2001-present	High-Very High	Target of Opportunity
DFW	ZFW	More Org	Very High	No	1994-2003 (ITWS)	Medium	Greater En Route Maneuverability

**The most significant factors for including these specific sites are highlighted in orange.*

Table 3-2. WX-TMA Site Survey and CIWS Training Status

Site	Access to Dedicated CIWS Display	CIWS Training
ZTL	NO – CIWS web displayed on large screen in TMU	YES – CIWS web
ZBW	YES – close to BOS TMA as of June 2009 (CIWS display purchased by TMA Office)	YES
ZAU	YES – close to TMA	YES
ZFW	NO – PC access for CIWS web	YES – CIWS web

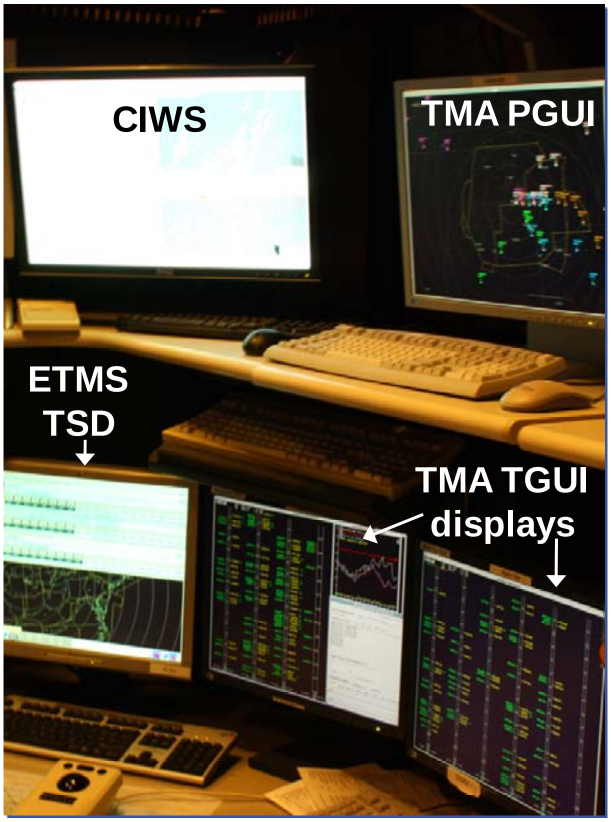


Figure 3-1. Location of CIWS and TMA displays at the TMU Arrival position in ZAU ARTCC.

3.2 INTERVIEWS WITH TMA SUBJECT MATTER EXPERTS

Subject Matter Experts (SME) from the National TMA Workgroup and select FAA facilities were interviewed to determine TMA fair-weather practices and to identify current TMA capabilities and limitations during weather impact events. Observations were made of fair weather metering operations and TMA usage to help clarify comments and descriptions provided by the SMEs during the interviews. The SMEs were asked to identify the challenges of metering traffic during convective weather, to prioritize TMA weather integration needs, and to discuss specific weather integration options for the TMA displays.

Structured interviews were conducted in Spring 2009 with the following TMA SMEs:

- Jay Conroy (ZBW), additional ZBW TMCs
- Danny Vincent (ZFW)
- Mark Thompson (ZTL), additional ZTL TMCs
- Keith Friedlein (ZAU), additional ZAU TMCs

3.2.1 Use of TMA in Fair Weather

All SMEs concurred with statements from recent FAA and industry reports that TMA metering operations often result in increased capacity and improved landing rates, reduced airborne holding, and overall more predictable, well-coordinated, and efficient air traffic management. TMA usage however can vary substantially given differences in relative airspace constraints, user experience, and preferences in metering tactics.

Frequency of TMA usage

Of the four sites in our study, TMA operations occur most frequently at ZTL, where Charlotte (CLT) arrivals are metered daily and Atlanta (ATL) traffic is metered on most days. The reductions in air traffic demand in the NAS have limited the need for metering operations elsewhere:

- ZFW rarely meters DFW arrivals (as demand in 2009 rarely exceeds DFW's abundant capacity – terminal capacity reductions caused for instance by high winds are needed to warrant TBFM), but does provide daily support for Houston Intercontinental (IAH) ACM;
- ZBW meters Boston (BOS) traffic only when terminal capacity is reduced below demand (e.g., during low ceiling and visibility conditions, during strong winds, or when runways are wet and Land and Hold Short Operations (LAHSO) are limited), but does provide daily support for Newark (EWR) ACM;
- ZAU had not routinely metered Chicago O'Hare (ORD) traffic since TMA site adaptation refinements were needed after the fifth ORD runway opened in November 2008. The TMA modification was implemented in mid-2009 and testing and limited metering has resumed. ZAU does provide daily support for Detroit (DTW) ACM.

TMA Technique

SME interview results in Table 3-3 indicate that different facilities prefer to use different approaches to TMA scheduling. Interviews at each site revealed two basic approaches to TMA metering – passive and aggressive. With passive metering, traffic managers configure TMA and then mostly let the TMA scheduling algorithms manage the TBFM operation. With this approach, traffic managers tend to move flights and adjust arrival slots only when the metering delay of individual flights is excessive or if STA assigned delays become negative. With aggressive metering, traffic managers configure TMA, but then continue to shuffle flights and compress gaps in an attempt to "push" TMA to optimize airport landing rates. In general, ZBW and ZAU conduct passive metering while ZTL aggressively manages TBFM operations, attempting to override TMA slot assignments for improved landing sequences. It is worth noting that relative demand differences at these airports, airport specific issues (e.g., the NY TRACON must handle EWR arrivals from three different ARTCCs and hence is the overall lead for EWR metering), and established traffic management procedures (e.g., even before TMA, ZTL has always sought to optimize ATL runway slot usage through aggressive traffic management [see Robinson et al. 2006 – Section 4]) may drive the specific TMA metering approach used operationally.

Table 3-3. **Most Frequently Used TMA Scheduling Actions***

	ZBW	ZFW	ZTL	ZAU
Add/delete meter fix blocked interval	+	++	+	N
Meter fix STA or Runway STA manually set for an aircraft by the TMC	++ (runway)	+	+	N
Request by TMC to reschedule one or more aircraft	++	+	+	++
Super stream class redefinition or separation distance change	+	+	+	+
Add/delete gate blocked interval	++	++	N	N
Find slot by TMC	+	+	N	N
Airport arrival rate change	N	++	N	N
Meter fix arrival rate change	N	+	N	N
Add meter fix sequence constraint	N	+	N	N
Hovering	+	N	N	N

** ++ = used most often; + = used; N = not typically used*

Freeze Horizons

SMEs were each asked about specific TMA features and preferred scheduling actions at each site. Site-adapted TMA freeze horizons (FH) varied at each facility – with the shortest FHs at ZBW (95–200 nm for Boston (BOS) metering) and the longest FHs at ZTL (220–320 nm for Atlanta (ATL) and Charlotte (CLT) metering). The EWR FH is 390 nm (for eastbound arrivals to the PENNS fix) and extends well into ZOB airspace (Figure 3-2). In general, shorter FHs may minimize delay but may also result in extra work for sector controllers due to last minute changes to a sequence or delay times. Conversely, longer FHs may better support sector controllers but at a potential cost of increased avoidable delay. Interestingly, ZBW prefers longer FHs for BOS metering (SME stated that 400 nmi would be "ideal"), allowing for a greater distance in en route airspace to delay aircraft. ZTL however prefers shorter FHs for ATL and CLT metering, which would allow them to manually resequence arrival flows in an attempt to maximize landing throughput without affecting the metering times managed by the air traffic controllers (since flights beyond the FH are not yet assigned metering times). In fact, ZTL has been actively working with ZDC to shorten the FH for the ATL and CLT northeast arrival fix. One TMC at ZTL suggested that Freeze Horizons be modified in conjunction with demand changes – the Freeze Horizon should extend further as volume increases. However, on this topic, the ZBW SME cautions that modifying the FH during active metering will alter controller expectations as to when and where TMA delay management is required for individual aircraft. This would increase controller workload and may decrease controller productivity. For this reason, the FH distances are not currently modified when TMA was in operational use.

3.2.2 Use of TMA in Convective Weather

The SMEs all described how, to a varying degree, convective weather disrupts metering operations and limits TMA benefits. They all agreed that without explicit, high-resolution weather depictions, forecast information, and even weather-aware slot sequencing and airspace availability support information integrated with TMA, TBFM operations during convective weather events will remain difficult and often unsustainable.

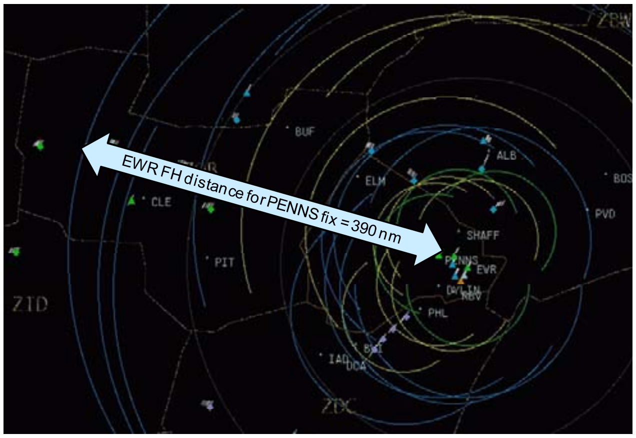


Figure 3-2. EWR TMA PGUI display showing the 390 nm FH distance for PENNS arrivals extends into western ZOB (just beyond Detroit [DTW] airport).

Figure 3-3 summarizes all comments from the SMEs in describing the impact of missing or incomplete TMA weather information on TBFM operations. With no weather concerns, TBFM operations facilitated via TMA work as anticipated and the desired benefits are often achieved (green path in Figure 3-3). The SMEs and TMCs interviewed explained repeatedly that the improved predictability and more intimate awareness of the ATM environment provided by TMA usage is what propels the more quantifiable TMA benefits (e.g., improved landing rates, reduced no-notice holding, etc.). Unfortunately, without explicit weather information available in TMA, predictability and ATM awareness can be significantly hampered during adverse weather, resulting in cascading TBFM impacts that either (at best) reduce metering efficiency or (at worst) force TBFM operations to be halted – both of which result in increased avoidable delay (red path in Figure 3-3).

Figure 3-3 also shows that it is not only convective weather that can significantly disrupt TMA operations. According to the interviewed SMEs, time-varying capacity constraints caused by low ceiling and visibility, strong winds, or wind shifts must also be properly planned for to achieve TMA benefits. Additional TMA weather needs are discussed in detail in Section 3.2.4.

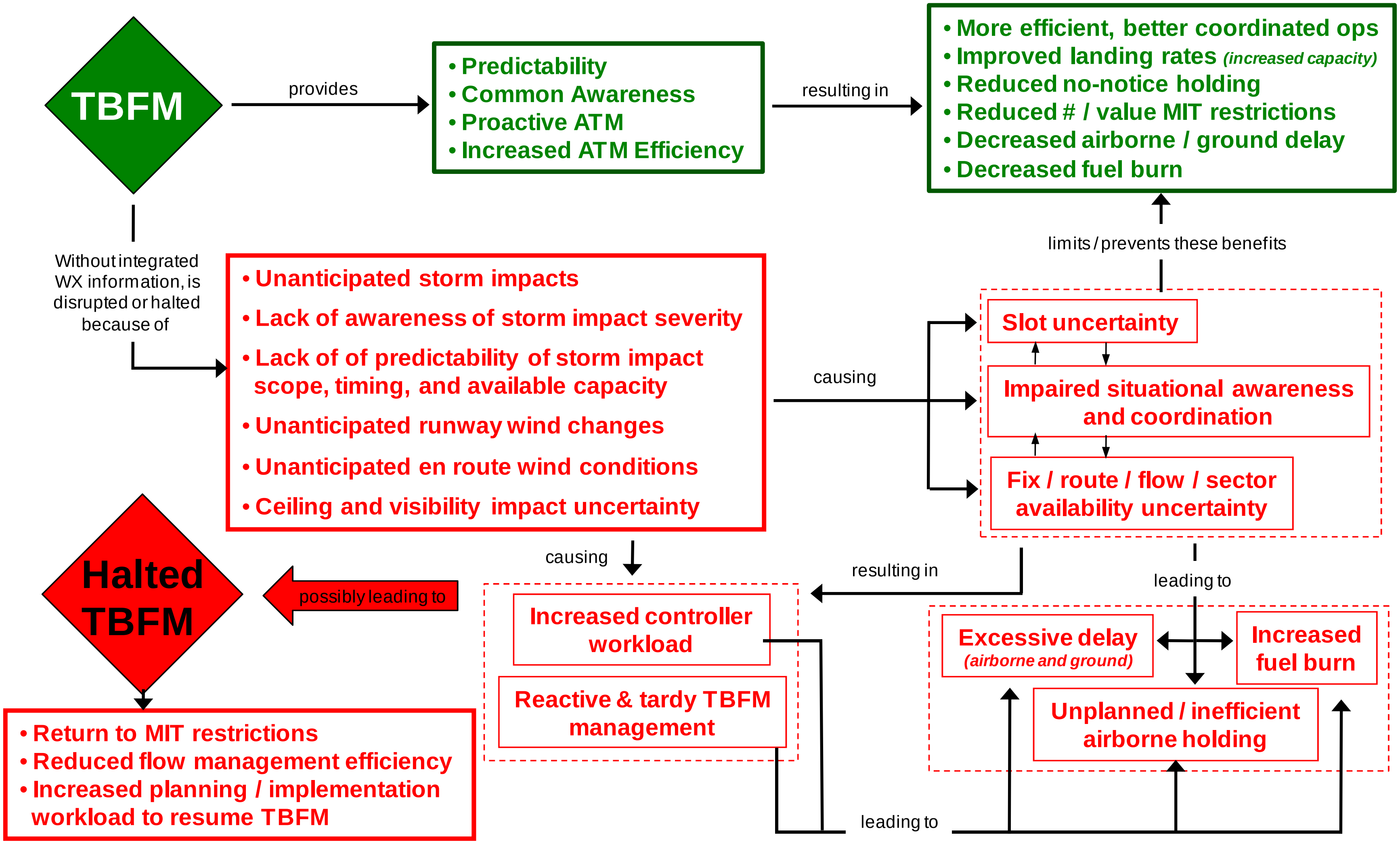


Figure 3-3. Summary of assessment by TMA SMEs of the impact of missing or incomplete TMA weather information on TBFM operations.

The TMA metering capabilities during convective weather varied across the four sites. At ZFW, when DFW metering was a routine occurrence, traffic managers with years of metering experience could continue to use TMA through the weather, and even meter out of holding stacks using TMA. In fact, the ZFW SME said that they prefer to use TMA to manage holding stacks because it allows them to provide more accurate estimates to pilots of how long holding will continue. This in turn can let pilots know they have enough fuel to still land (if they know the hold will soon end) and can prevent (and has prevented) diversions. Similarly, CLT metering at ZTL often continues during convective weather, until the terminal is directly impacted by storms or if impacts at the arrival fixes are prolonged and severe. TMA usage at ZTL for ATL during convective weather is halted more frequently than CLT, likely due to the increased en route arrival demand and the agreements with the sector controllers about metering when the TMA software was in the process of being updated. ZBW also will continue to meter BOS traffic during convective weather, but here too TMA metering is usually halted when the metering actions become too reactive and acceptable controller workloads can no longer be maintained.

At all the sites, SMEs and interviewed traffic managers stated that in general, there are specific scheduling actions and configuration parameters in TMA that can be used to manage TBFM during weather impact events. Moreover, it is their opinion that weather information integrated into TMA decision support would (a) allow facilities to continue to meter during significant weather or (b) increase the operational utility of TMA and metering efficiency when severe weather is ongoing.

How facilities use TMA when convective weather is present can depend on where the weather emerges relative to the terminal. If convective weather is present outside of the FH, TMA automatically adjusts its times when an aircraft deviates, and the impact on TMA is small. When thunderstorms are located within the FH and in en route airspace, the ZFW SME stated that they use Single Gate Free Flow[4] scheduling actions in TMA, with consideration to how much delay or deviations are experienced. If there is a high demand on a single meter fix, ZFW may apply temporary MIT restrictions to traffic flying to that fix. If the weather is at or near the fix, the ZBW SME stated that they would likely reroute the flow. If convective weather is within the TRACON airspace, ZBW and ZFW SMEs said that they usually suspend metering operations. The ZTL SME said that ZTL may change the TRACON buffer in TMA (the maximum per flight metering delay that can be passed into TRACON airspace) from 5–6 minutes to 2–3 minutes to allow more metered delay to be absorbed in Center airspace rather than in TRACON airspace.

3.2.3 Preferred CIWS Weather Information in TMA

During interviews, SMEs were asked to rank various CIWS weather products in terms of how useful they would be in supporting metering operations if added to the TMA PGUI display. The results are listed in Table 3-4. Based upon the overall feedback, the focus of near-term TMA PGUI weather integration will be to include CIWS Precipitation and Echo Tops – current weather and forecasts, storm motion and evolution, and lightning information on this display.

---

[4] Single Gate Free Flow (SGFF) is a TMA scheduling action where delays on one metered flow are mitigated or removed, allowing traffic in this flow to be favored for arrival to the meter fix or runway threshold. In this manner, traffic in the "favored" flow may avoid significant disruptions caused by adverse weather. To accommodate SGFF, additional delay is redistributed to the other "non-favored" metered flows.

Table 3-4. Ranking of Desired CIWS Products on TMA PGUI*

	ZBW	ZFW	ZTL	ZAU
Echo tops	1	4	1	2
Echo tops forecast	2	4	2	6
Lightning	7	1	1	(w/Precip, Tops)
Storm motion vectors	6	2	1	3
Growth & Decay	5	3	2	4
Precipitation/Echo Tops Forecast Contours	-	4	2	-
Precipitation Forecast animation	4	4	low	5
Precipitation	3	4	least	1

**1 = most desirable; ZTL ranked a collection of features as most (1) and second-most (2) desirable*

In discussing the usefulness of these various CIWS products in support of TMA operations, SMEs stated that:

- There is real benefit to integrating CIWS weather forecasts with TMA when weather is in the TRACON.
- CIWS Precipitation on the PGUI would provide significant situational awareness enhancements – may allow traffic managers to stay ahead of potential impacts.
- CIWS forecasts were desired because "when a cornerpost or a runway is affected, anything that is unpredictable is difficult to meter. When there are predictable circumstances, we can meter for anything regardless of the severity."
- In en route airspace, the CIWS Echo Tops Forecast is the most useful product for managing TMA impacts.
- CIWS Echo Tops information would be useful in determining when and for how long en route arrivals could remain in a metered flow by overflying the weather.
- Combining CIWS Forecasts with TMA would support the development and use of dynamic meter points (planned TMA enhancement).
- Knowledge about where storms are growing could support TMA pre-planning for impacts anticipated to become more severe.
- Lightning activity in a storm cell is often a good indicator for anticipated pilot deviations – having lightning information in TMA would increase situational awareness and predictability of the metering operation.

Some interviewed SMEs strongly believed that it is even more important to integrate information about weather impacts and constraints on the TMA TGUI and load graph displays. The SMEs stated that if a TMA user is highly experienced, he may not even use a PGUI display – needing only the TGUI to optimize arrival flows into an airport. During discussions, they noted that explicit (flight, fix, and flow-specific) statements of the location and duration of airspace impacts evident from the actual metered timelines may best support proactive, predictable TBFM operations. Preliminary PGUI, TGUI, and load graph storyboard concepts for WX-TMA integration are presented in Section 4.

3.2.4 Additional TMA Weather Needs

Interviewed SMEs identified other weather impacts besides thunderstorms that can also significantly disrupt and suspend TBFM operations:

1. Terminal Winds

SMEs stated that the uncertainties associated with surface winds at the airport are a significant concern. Currently, TMA receives updated wind data only once per hour and the TMA operators feel this is insufficient. Much of the TMA metering for arrivals is significantly impacted by the airport runway matrix settings, and these settings can vary significantly for changing wind conditions. Wind shifts at the airport may require a completely different runway configuration – and this change must be accounted for in TMA. If traffic managers can not anticipate these changing surface wind conditions in TMA, then avoidable delay increases, controller workload increases (as more aircraft may be required to hold close to the terminal), and arrival slot uncertainty increases – to the point where metering may need to be suspended. For improved terminal wind information in support of TBFM operations, the SMEs suggested that Gust Front and Terminal Wind products from the Integrated Terminal Weather System (ITWS) (Evans and Ducot, 1994; Cole and Wilson, 1994) may also be useful candidates for WX-TMA integration.

Providing ITWS Terminal Winds information in TMA may also provide assistance during strong wind or highly-sheared synoptic wind events that result in compression/expansion of aircraft spacing upon arrival approach in the terminal area. During these events, arrival capacity constraints may not be anticipated without explicit, high-resolution wind information. Moreover, TMA ETAs may become unstable as a result of anomalous winds, causing TMA delay times to be in error – this in turn can result in reduced capacity, increased management complexities, and increased controller workload. In these instances, TMA users may benefit from a display of Terminal Winds over various fixes in TMA to make proactive decisions for anticipated capacity reductions caused by wind compression upon approach. TMA users may find it even more useful if graphical information depicting regions of headwind/tailwind shear (Allan et al. 2004) – impacting specific meter flows, and specific flights within these flows – was integrated directly on the TMA TGUI.

2. Wind Estimates for TMA Trajectory Calculations

The TMA trajectory models utilize 13 km resolution gridded, 3-D wind data from the RUC model, which updates once per hour, to estimate and update aircraft positions. These trajectory calculations are used to estimate ETAs, and to identify available meter slots for STAs, for TMA traffic. However, SMEs believe that the resolution and update rate of the wind data used in TMA are not adequate, and errors in ETA calculations and metered delay assignments are a frequent problem. As a result, slot assignments may be incorrect and/or controllers may be working harder to slow down aircraft that actually do not require any delay. These problems are most frequent during conditions with strong winds and fast-moving weather.

The TMA SMEs believe that there is significant potential benefit to improving the wind data used in TMA trajectory calculations. Specifically, ingest of model wind data with higher horizontal and vertical spatial resolution may decrease errors in TMA trajectory calculations. In addition, augmenting model wind data with the higher update rate information from the ITWS Terminal Winds product may also increase the accuracy of TMA metering calculations.

3. Low Ceiling and Visibility

Field observations of TMA usage revealed that unanticipated capacity constraints caused by reduced ceilings and visibility at the airport can significantly disrupt and even suspend metering operations. On several occasions at ZTL this summer (for both ATL and CLT operations), a reduction in ceiling height or visibility at the airport to below a critical, operational threshold would result in a near-instantaneous 10-20% reduction in arrival capacity. Without anticipating and preparing for this capacity loss in TMA (through increased spacing, increased TRACON buffers, modified runway matrix settings, etc.), this significant change in available capacity caused a loss of available meter slots, unplanned airborne holding, unstable meter delay assignments, and increased controller workload.

SMEs and TMCs stated that improved, high-resolution ceiling and visibility (C&V) forecasts, available within the TMA suite of available weather decision support products, may allow traffic managers at coordinating TMA facilities to become better aware of potentially significant reductions in available capacity. This would allow TMA operators and coordinators to pre-plan and perhaps begin to "hedge" for severe C&V impacts, allowing metering operations to remain under control and to continue – which would likely minimize system-wide delays. Moreover, high-quality C&V forecasts may also allow traffic managers to plan for predicted improvements in C&V conditions by proactively easing TMA scheduling restrictions and utilizing extra meter slots expected to become available.

3.3 DATA ANALYSIS FOR BASELINE TMA USAGE DURING CONVECTIVE WEATHER

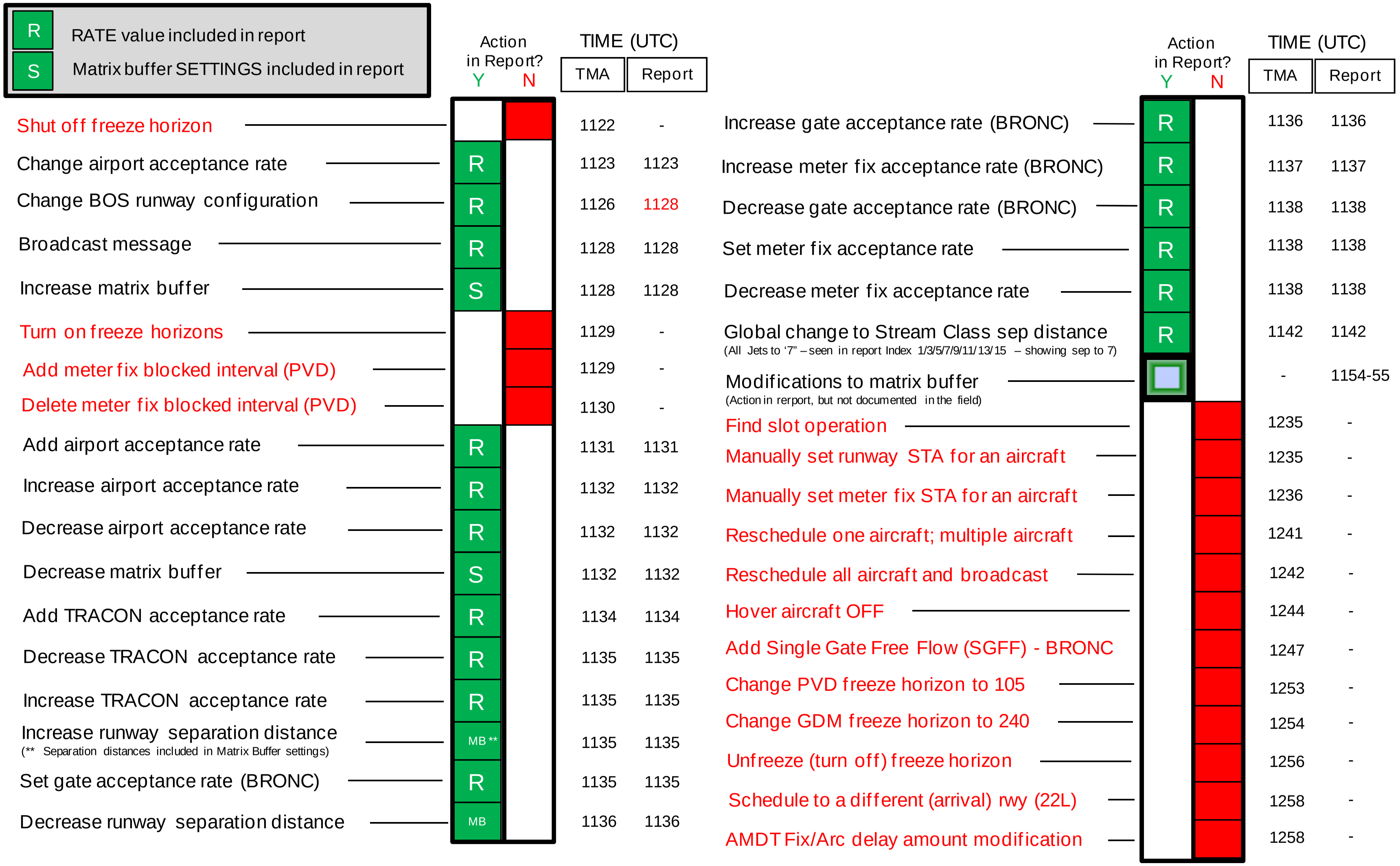
3.3.1 Data for Examining TMA Scheduling Actions

An effort was made to determine the baseline usage of TMA scheduling events during convective weather. Specifically, we sought to identify the frequency and variability of executed TMA scheduling events utilized to mitigate weather impacts at multiple TMA sites across many adverse weather days. Moreover, we planned to analyze CIWS weather and enhanced traffic management system (ETMS) flight track data to determine the effectiveness of managing metered traffic flows during severe weather events (e.g., was the arrival traffic flow reasonably efficient or were there flow characteristics indicative of inefficient traffic flow such as holding patterns and/or under-utilized arrival fix capacity when the storm impacted ended).

To accomplish this baseline analysis, reports listing TMA activities and specific actions were provided by the FAA and Flatirons Solution Inc. It was unclear what type of TMA scheduling data the Flatirons reports captured, so a small experiment was conducted at ZBW to manipulate various scheduling actions in TMA, particularly those the SMEs stated were used in convective weather. This experiment was conducted on 14 May 2009. For each event, the ZBW SME would input the event and then broadcast it. As the event was broadcasted, the time was noted by observers to compare with the time on the Flatirons report.

Figure 3-4 depicts the results from this experiment. The times of the report appeared to be mostly accurate compared to what time was noted upon broadcast of the event. Many TMA scheduling events were logged in the reports, including acceptance rate changes and matrix buffer changes. However, some of the critical, tactical TMA scheduling actions – those actions identified during the SME interviews as the most used TMA options during convective weather – such as adding/deleting blocked intervals, manually setting STAs, rescheduling all aircraft (rippling), and single gate free flow were not logged in the Flatirons reports.

Based on this analysis, the FAA worked with Flatirons to create daily TMA reports that record a more complete suite of executed scheduling actions. However, these expanded reports were not available to support the baseline TMA usage analysis for this phase of the study. Therefore, all examinations of TMA baseline practices and actions were based upon real-time observations at FAA facilities of TMA usage during weather.



R RATE value included in report

S Matrix buffer SETTINGS included in report

Action	Action in Report? Y	Action in Report? N	TIME (UTC) TMA	TIME (UTC) Report
Shut off freeze horizon		🟥	1122	-
Change airport acceptance rate	R		1123	1123
Change BOS runway configuration	R		1126	1128
Broadcast message	R		1128	1128
Increase matrix buffer	S		1128	1128
Turn on freeze horizons		🟥	1129	-
Add meter fix blocked interval (PVD)		🟥	1129	-
Delete meter fix blocked interval (PVD)		🟥	1130	-
Add airport acceptance rate	R		1131	1131
Increase airport acceptance rate	R		1132	1132
Decrease airport acceptance rate	R		1132	1132
Decrease matrix buffer	S		1132	1132
Add TRACON acceptance rate	R		1134	1134
Decrease TRACON acceptance rate	R		1135	1135
Increase TRACON acceptance rate	R		1135	1135
Increase runway separation distance (** Separation distances included in Matrix Buffer settings)	MB **		1135	1135
Set gate acceptance rate (BRONC)	R		1135	1135
Decrease runway separation distance	MB		1136	1136

Action	Action in Report? Y	Action in Report? N	TIME (UTC) TMA	TIME (UTC) Report
Increase gate acceptance rate (BRONC)	R		1136	1136
Increase meter fix acceptance rate (BRONC)	R		1137	1137
Decrease gate acceptance rate (BRONC)	R		1138	1138
Set meter fix acceptance rate	R		1138	1138
Decrease meter fix acceptance rate	R		1138	1138
Global change to Stream Class sep distance (All Jets to '7" – seen in report Index 1/3/5/7/9/11/13/15 – showing sep to 7)	R		1142	1142
Modifications to matrix buffer (Action in rerport, but not documented in the field)	🟦		-	1154-55
Find slot operation		🟥	1235	-
Manually set runway STA for an aircraft		🟥	1235	-
Manually set meter fix STA for an aircraft		🟥	1236	-
Reschedule one aircraft; multiple aircraft		🟥	1241	-
Reschedule all aircraft and broadcast		🟥	1242	-
Hover aircraft OFF		🟥	1244	-
Add Single Gate Free Flow (SGFF) - BRONC		🟥	1247	-
Change PVD freeze horizon to 105		🟥	1253	-
Change GDM freeze horizon to 240		🟥	1254	-
Unfreeze (turn off) freeze horizon		🟥	1256	-
Schedule to a different (arrival) rwy (22L)		🟥	1258	-
AMDT Fix/Arc delay amount modification		🟥	1258	-

Figure 3-4. Results from the FAA/Flatirons TMA report validation experiment.

3.3.2 Pre- vs. Post-TMA Airport Landing Rate Efficiency during Convective Weather

A data-driven analysis was conducted to examine differences in the fair-weather and convective weather landing rate efficiency at LaGuardia, New York (LGA) airport before and after TMA went into operational use on 22 July 2009. This analysis was conducted to determine if the reduced effectiveness of TMA metering during convective weather, with the current practices and weather decision support limitations identified by the SMEs, is evident in broad, FAA-sanctioned efficiency metrics.

In this analysis, Terminal Arrival Efficiency Rate[5] (TAER) statistics from the FAA Aviation System Performance Metrics (ASPM) database were used to assess the mean landing rate efficiency at LGA for select case days in 2009 before and after TMA became operational on 22 July. The selected case days (47 total) are listed in Table 3-5. Pre-TMA cases were chosen between 01 June and 17 July 2009. Post-TMA cases were chosen between 24 July and 31 August 2009 – all case days are weekdays. Selected days were identified as fair weather days or convective weather days. On fair weather days, no thunderstorms were located in the Northeast quadrant of the U.S., and there were no terminal weather issues at LGA (e.g., high winds or low ceilings and visibility). Convective weather case days were selected if thunderstorms were located in a region from just inside the N90 TRACON boundary to the ZNY ARTCC boundary (including immediate ZOB, ZBW, ZDC airspace bordering ZNY), but NOT directly impacting the LGA terminal. Time periods on selected case days when thunderstorms directly impacted LGA terminal, requiring a Ground Stop program, were not included in this TAER statistical evaluation. On fair weather days, the average daily TAER was computed for 1500–2300 UTC. On convective weather days, the average TAER was computed for the same period, unless thunderstorms impacted LGA before 2300 UTC. In those cases, TAER was computed until the start of the LGA impact.

Figure 3-5 shows the mean daily TAER at LGA airport on fair weather vs. en route convective weather days before and after TMA went into operational use. These results indicate the following:

1. The fair weather landing rate efficiency increased 2.5 % after TMA went into use at LGA. This is consistent with TMA capacity improvements cited at other TMA airports (FAA, 2009).
2. The TAER during en route convective weather days was 7–8% lower than the fair weather TAER for both pre and post-TMA days. The average “weather day” TAER remained below 90, even after TMA went into use at LGA.
3. The LGA TAER exceeded the FAA target goal for airport landing rate efficiency for FY-2010 (94) only on fair weather Post-TMA days. However, for all post-TMA case days, the reduced efficiency on en route convective weather days caused the daily mean post-TMA TAER (90.1) to drop well below the targeted goal.

---

[5] TAER = Actual Arrivals / Arrival Demand (not to exceed AAR); Wheels-on time is used to calculate quarter-hour arrival traffic. Arrival demand is based on the computed wheels-on time plus the filed en route time, with the end of demand occurring with the actual wheels-on time. The TAER cannot exceed 100. For complete information on the methodology for computing TAER, refer to: http://aspm.faa.gov/aspm/Customer Satisfaction/TAER SAER Updated Briefing.pdf.

Table 3-5. LGA 2009 Case Days for TAER Analysis

Pre-TMA Date	Fair Wx	En Route Wx	Post-TMA Date	Fair Wx	En Route Wx
01 Jun	▨		24 Jul		▨
02 Jun		▨	27 Jul		▨
03 Jun		▨	28 Jul		▨
08 Jun		▨	30 Jul	▨	
10 Jun		▨	03 Aug	▨	
15 Jun		▨	04 Aug	▨	
16 Jun	▨		07 Aug	▨	
19 Jun	▨		10 Aug		▨
22 Jun	▨		11 Aug		▨
23 Jun	▨		14 Aug	▨	
24 Jun	▨		17 Aug	▨	
25 Jun		▨	18 Aug		▨
26 Jun		▨	19 Aug		▨
29 Jun	▨		20 Aug		▨
30 Jun		▨	24 Aug	▨	
01 Jul		▨	25 Aug	▨	
03 Jul		▨	26 Aug	▨	
06 Jul	▨		27 Aug	▨	
07 Jul		▨	28 Aug		▨
08 Jul	▨		31 Aug	▨	
09 Jul	▨				
10 Jul	▨				
13 Jul	▨				
14 Jul	▨				
15 Jul	▨				
16 Jul		▨			
17 Jul		▨			

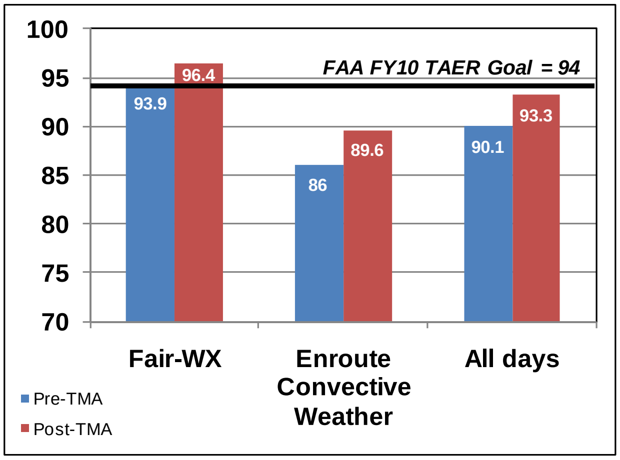


Figure 3-5. Daily mean TAER at LGA on fair weather and en route convective weather days before and after TMA went into operation on 22 July 2009.

Some improvement in the LGA TAER was evident on post-TMA en route convective weather days. However, this improvement may be partially attributed to improved WX-ATM management and increased pilot aggressiveness that often occurs as the summer storm season progresses (Robinson et al. 2010). The small sample size of this analysis may have also contributed to this result. TMA usage for LGA arrivals may have also contributed to improved landing rates on these weather days, but this contribution was likely minor. SME interviews, confirmed through ZNY/N90 field observations and a review of National Traffic Management Logs (NTML), revealed that NY metering operations were usually suspended soon after a Severe Weather Avoidance Program (SWAP) for convective weather was first declared.[6]

The fraction of total LGA arrival flights between 1500-2300 UTC delayed 15 min or greater on fair weather days decreased from 19% before TMA to 13% after TMA. However, on en route convective weather days, there was very little difference before and after TMA in the percentage of LGA arrival flights that were delayed: 32 % of LGA arrivals during the study period were delayed prior to operational deployment of TMA while 30% of arrivals were delayed after TMA was deployed. The similarity in statistics is not surprising, again because NY TMA operations (e.g., EWR and/or LGA) were usually suspended when convective weather developed within the metered airspace.

Excess arrival demand statistics were also computed from ASPM data for the LGA case days. For each analysis day, with and without convective weather, the mean daily excess arrival demand was derived from the difference between “wheels-on” LGA arrivals in each quarter hour period vs. the total arrivals plus the airborne flights that also had intended to land during that quarter hour period (“wheels-off” + filed en route time). The results in Figure 3-6 show that on fair weather days, the excess 15-min airborne arrival demand decreased significantly after TMA went into operation at LGA. The post-TMA

---

[6] Even after TMA metering (and in the case of LGA, ACM operations) were terminated, TMA was still used to assist with scheduling departures to LGA from airports within the Freeze Horizon that were still on the ground. Under these circumstances, controllers would not be receiving TMA flight lists and would not be managing delay assignments, but some improvement in post-TMA TAER during convective weather may have been derived from this TMA-assisted scheduling.

decrease in LGA airborne arrival demand surplus by 10 aircraft per hour during fair weather illustrates how TMA is useful in scheduling traffic to match available capacity, thus maximizing the use of available slots while minimizing airborne holding. However, on days when en route convective weather was present, there was only a marginal, post-TMA reduction in LGA airborne arrival demand surplus. Even after TMA became operational, there were typically several more airborne flights on en route convective weather days seeking to land each hour than could be accommodated given available LGA runway capacity. These results, in conjunction with SME interview results, suggest that without proper TMA scheduling and without proactive execution of TMA scheduling actions to accommodate en route weather constraints on metered flows, airborne holding and inefficient flow capacity management will continue to be an issue.

The results from this analysis verify comments and feedback from the TMA SMEs regarding the need for improved TMA usage during convective weather. Metrics and comparisons derived from data-driven analyses such as the one presented here can be used to objectively measure potential improvements in TMA metering operations after specific WX-TMA decision support capabilities are in use.

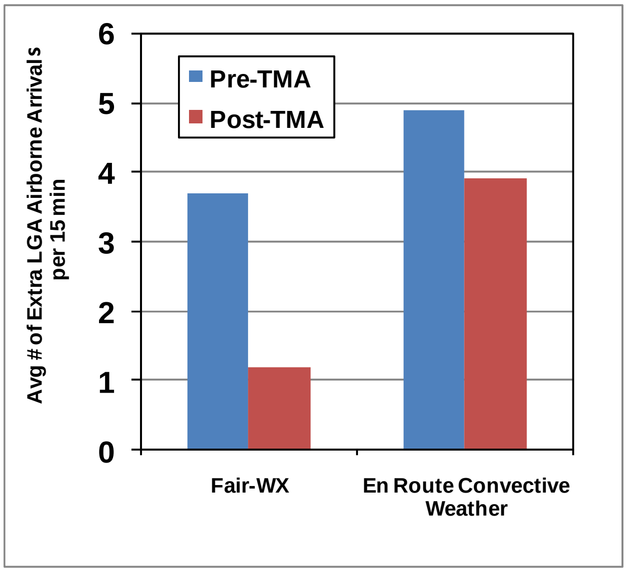


Figure 3-6. Mean daily excess LGA arrival demand on fair weather vs. en route convective weather days before and after TMA was in operational use.

3.4 OBSERVATIONS OF TMA USAGE DURING CONVECTIVE WEATHER

Real-time observations of TMA operations at FAA facilities were made on six convective weather days during summer 2009. Due to the frequency of TMA usage at ZTL for both CLT and ATL operations, a majority of field observations were conducted at ZTL. During these field observations, TMA actions, arrival management actions, weather constraints, and other relevant traffic management occurrences were noted to develop a deeper understanding of baseline TMA operations. In this section, an information processing model is presented to illustrate the information consolidation process observed. Key weather and TMA issues that were observed in the field will be discussed.

3.4.1 Weather and TMA Information Processing Model

A general TMC information processing model that illustrates the weather and TMA information issues observed in the current traffic management environment is shown in Figure 3-7. This model is derived from observations of TMCs at different facilities gathering weather and traffic information and using it to make scheduling decisions within the TMA tool. Subtleties of information sources available and the weather mitigation strategies may vary by facility, but in general, the TMCs followed the information processing path described.

Weather information in the ARTCC TMU can be gathered from various sources, depending on the systems available at a particular facility. Some common weather information sources include CIWS, ITWS, weather on the DSR display, the Weather and Radar Processor (WARP) briefing terminal, the Traffic Situation Display (TSD), and the En Route Information Display System (ERIDS). Each of these weather sources provides their own overlapping levels of information. The TMC searches for and seeks to comprehend the weather situation affecting (or may soon affect) their airspace, estimating the location, duration, and severity of weather impacts. Once the weather situation is comprehended, the TMC must interpret how the weather situation affects air traffic capacity now and into the future. In parallel, the TMC also must understand the current and pending traffic demand situation. The TMC perceives this information from TMA, DSR displays, the TSD, and other sources to develop a picture of the current and future demand situation for the resource of interest (e.g., route, fix, airport, runway, etc). Occasionally, other facility TMCs and/or Area Supervisors may also call the TMC with information that changes the TMCs understanding of the current weather or demand situation. Since the detailed traffic information provided by TMA is separate from the available weather information sources, an information integration step is required for the TMCs to understand how the weather is affecting or is expected to affect the metered traffic flows. This information is then used to develop a weather mitigation strategy in TMA.

These weather mitigation strategies are often learned in TMC training and validated through experience in using TMA. The timing of executing a weather mitigation strategy is important. The TMC seeks to wait as late as possible to ensure that the weather information he or she is basing the decision on will actually occur. However, the nature of the traffic management action benefits most from an early execution so that the parties (TMCs, controllers, other facilities, and airline customers) have an opportunity to plan for the new situation. Because many weather mitigation strategies in TMA can only be executed within a particular time window to be effective, the TMCs may have to update their weather and demand information several times (and integrate the information together again) before a strategy is finally decided upon and executed. Once the scheduling action is taken in TMA, the TMC often needs to coordinate additionally with the Area Supervisors or other facility TMCs to alert them of an adjustment of metering times. The TMC receives information about how this strategy finally affects the demand by revisiting the TMA TGUI once the action has been taken and the metering times have been updated.

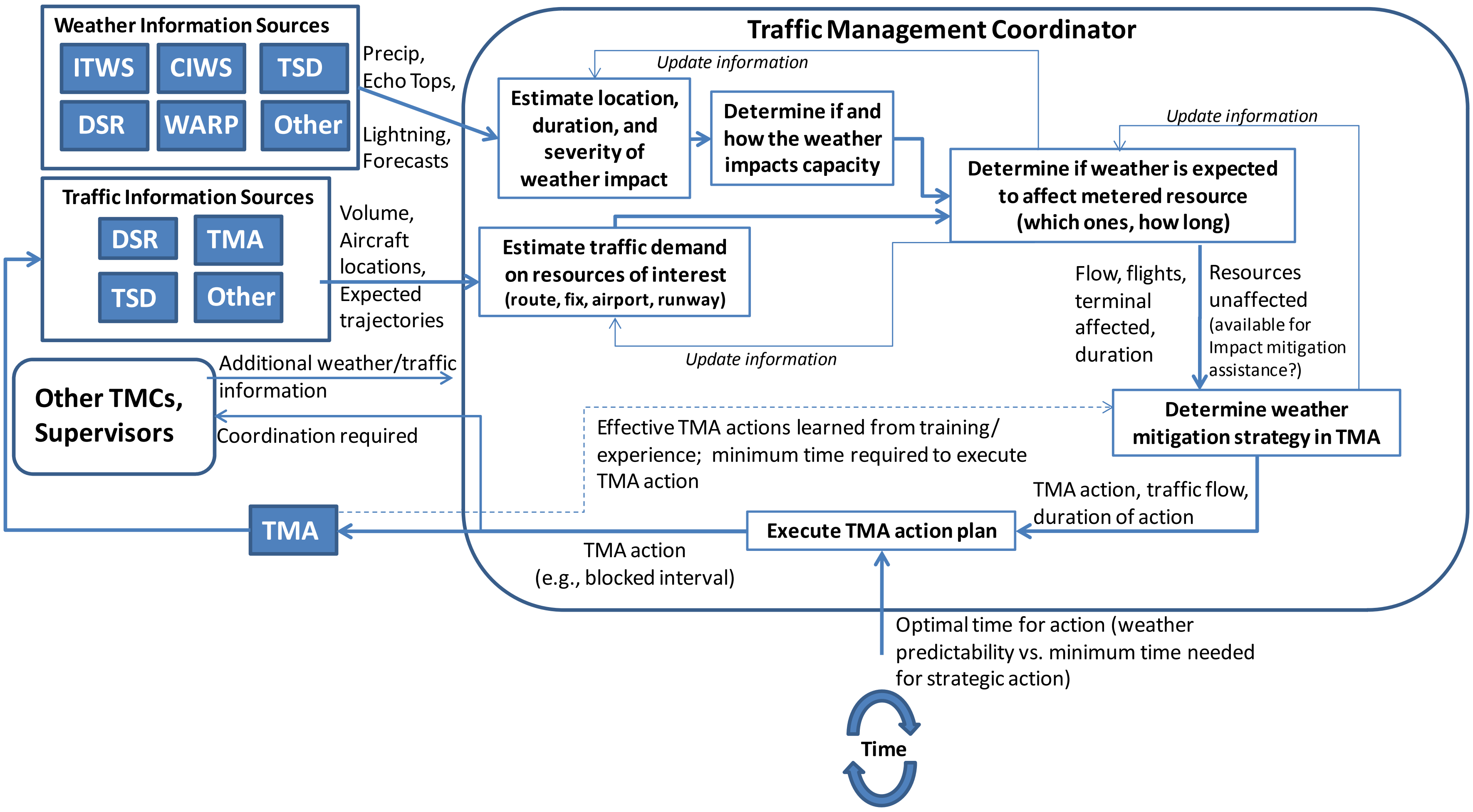


Figure 3-7. TMC information processing model for TMA usage during convective weather.

3.4.2 Observed WX-TMA Decision-Making and Coordination Issues

Within the framework of the information processing model described above, three issues observed as TMCs attempted to understand the impact of weather on metered traffic in TMA include:

1. Physical and cognitive difficulties of integrating the weather information with the TMA information,
2. Failure to acquire/receive weather impact information with sufficient time to execute a TMA mitigation strategy, and
3. Possible lack of awareness of a weather situation or its impact on metered traffic

One of the primary issues supported in the field observations, which was the impetus for this research study itself, was the difficulty associated with integrating weather information and TMA information. In the information processing model, this lack of integrated information is shown by two separated information perception paths until the weather and TMA information must be cognitively integrated by the TMC. As a result, during convective weather impact events, a significant amount of physical "neck-craning" was observed as TMCs referred back and forth between weather tools and TMA during their decision-making process. In ZTL, the reference generally occurred between two monitors (e.g., ITWS and TGUI or PGUI) at a single TMC workstation. At ZBW, the situation was more extreme, with the TMC, on several occasions, walking across the room from the TMA position to view the CIWS situation display and the TSD (to see traffic and weather in one common picture) – mentally cataloguing this collected weather information as they returned back to the TMA displays (see Section 5.1.1).

Additionally, there is cognitive work in integrating the information from two sources. Weather information is displayed spatially, while a majority of the TMA information used for strategic control purposes is displayed temporally. This requires some level of cognitive information axis transformation (Davison-Reynolds, 2006). It can be difficult for the TMCs to determine where the weather is now relative to the TGUI timeline and what specific flights and flows are affected. Complicating the issue is the need for traffic managers to project where the weather of significance will be in the future and what traffic will be impacted given this weather projection.

The TMA metering operation may not be too difficult to manage during weather if this complex information integration occurred infrequently during the operational decision-making process. However, as one may note from the information processing model, this information integration needs to occur regularly as new weather and traffic information is routinely reprocessed.

A second key issue with weather and TMA information involves how much advance warning a TMC has that weather will impacts metered traffic. As was discussed in the information processing model in Figure 3-7, there is an effective time window for implementing a weather impact mitigation strategy within TMA. Given the difficulties in accurately forecasting convective weather and the need for TMCs to integrate additional information in order to assess potential capacity constraints, often awareness of pending weather impacts is achieved too late for a TMA solution to be implemented. An example of this was observed at ZTL when CLT traffic, deviating around weather at the CTF (southeast) arrival fix, entered TRACON airspace and arrived at the runway with negative delays (landing in other arrival slots, effectively reducing the arrival capacity). The ZTL TMC working the CLT TMA position mentioned that if he had known 30 minutes ahead of time that the flights would reach the meter point with negative delays (because of weather deviations), he would have made proactive plans to ensure that the available arrival capacity was better utilized.

The third issue observed was an occasional complete lack of awareness of a weather impact on a metered flow. This could manifest in an adjacent facility TMC phoning the facility and completely shutting off a flow that was over-delivering to a weather-impacted sector. In an observation at ATL in July, ATL Tower called ZTL to tell them that arrival traffic will be held at all fixes due to windshear at the airport. Before this call, ZTL was unaware that this severe disruption to the ATL metering operation was about to occur. Another example of lack of awareness is responding to the area controllers who have discovered that they are unable to meet the metering times due to weather deviations, forcing TMCs to completely suspend the metering operation. Without weather information directly available on the TMA displays, it can be difficult for the TMCs to distinguish weather deviations from controlled vectoring invoked to manage assigned metered delays. Often, this call from the area would be the first indication to the TMC that the metering operation has been disrupted.

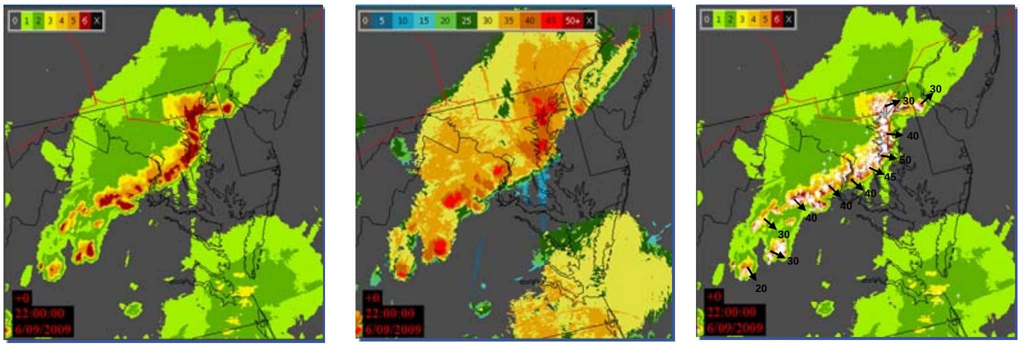
This page intentionally left blank.

4. INITIAL CONCEPTS FOR INTEGRATED WX-TMA DECISION SUPPORT

Presented here are the initial concepts for integrating CIWS products and CIWS-derived flow/flight impact assessments into TMA PGUI, TGUI, and load graph displays. These decision support concepts are based upon the feedback of the SMEs, the observed challenges and needs of WX-TMA integration identified during field evaluations, and examinations of the potential benefits of improved WX-TMA decision support. Examples of the potential applications of these WX-TMA concepts are provided in Section 5.

4.1 CIWS WEATHER ON TMA PGUI DISPLAY

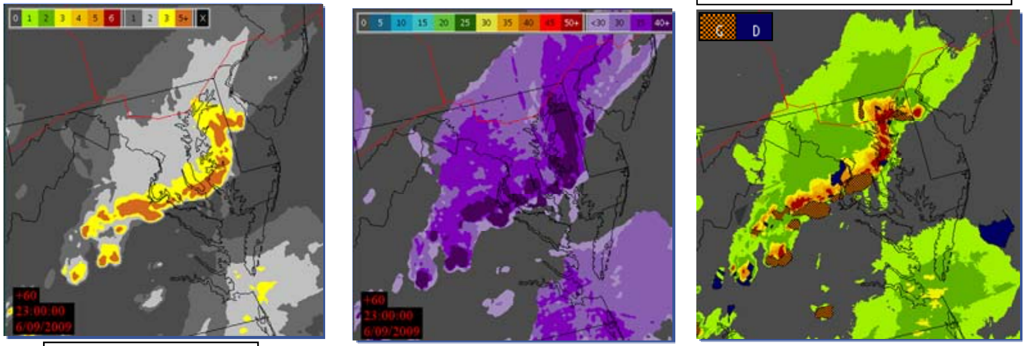
The primary CIWS weather products initially considered for implementation on the TMA PGUI display are shown in Figure 4-1. They include the Vertically Integrated Liquid (VIL) Precipitation and Echo Tops (current weather mosaic and 0–2 hour forecasts) and Cloud-to-Ground Lightning, Storm Motion Vectors, and Storm Growth and Decay Trends (shown alone, or atop the Precipitation or Echo Tops Mosaic).



VIL Precipitation

Echo Tops

Lightning, Storm Motion
(Overlays on Precipitation)



0 – 2 Hour Precip Forecast

0 – 2 Hour Echo Tops Forecast

Storm Growth & Decay Trends (Overlay on Precipitation)

Figure 4-1. CIWS weather products considered for implementation on the TMA PGUI display.

Collectively, these products were identified by the TMA SMEs to be most useful for supporting and improving metering operations during convective weather. Moreover, field observations and post-event review of TMA operations during convective weather reveal that the availability of each of these CIWS products on the PGUI (used together or individually on an "as needed" basis) would reduce TMC workload, promote higher-quality, proactive TMA scheduling decisions, and increase airspace usage efficiency (see Section 5).

Previous investigations of operational CIWS usage in the Great Lakes and Northeast corridors of the NAS have demonstrated that each of these CIWS products were utilized by traffic managers to (a) keep routes/flows open longer or reopen closed routes sooner and (b) make proactive rerouting decisions [Figure 4-2, from Robinson et al. (2006)]. The use of CIWS for "routes open longer (RO)" and "proactive reroute (PRR)" decisions is applicable to TMA decision-making.

In TMA, RO applications of CIWS PGUI products would correspond to:

- Determining when storms will not significantly impact metered flows
- Optimizing scheduling actions that maintain TBFM for impacted flows
- Identifying and returning an earlier return to TBFM

In TMA, PRR applications of CIWS PGUI products would correspond to:

- Proactively rerouting impacted arrivals to a different arrival fix
- Rerouting to balance and manage weather impacts and metered delay

Each of these applications would help to maintain the predictability and slot integrity of the TMA operation during convective weather. Recall from Section 3 that the SMEs consider this to be critical for metering operations to continue during off-nominal conditions.

CIWS Precipitation and Echo Tops Forecasts are considered key products for weather decision support in TMA. CIWS provides 0-2 hour animated forecasts as well as 30, 60, and 120 min forecast contours. Ideally both forms of CIWS forecast products should be considered for PGUI display, but supporting animation capabilities in TMA may require a new approach.

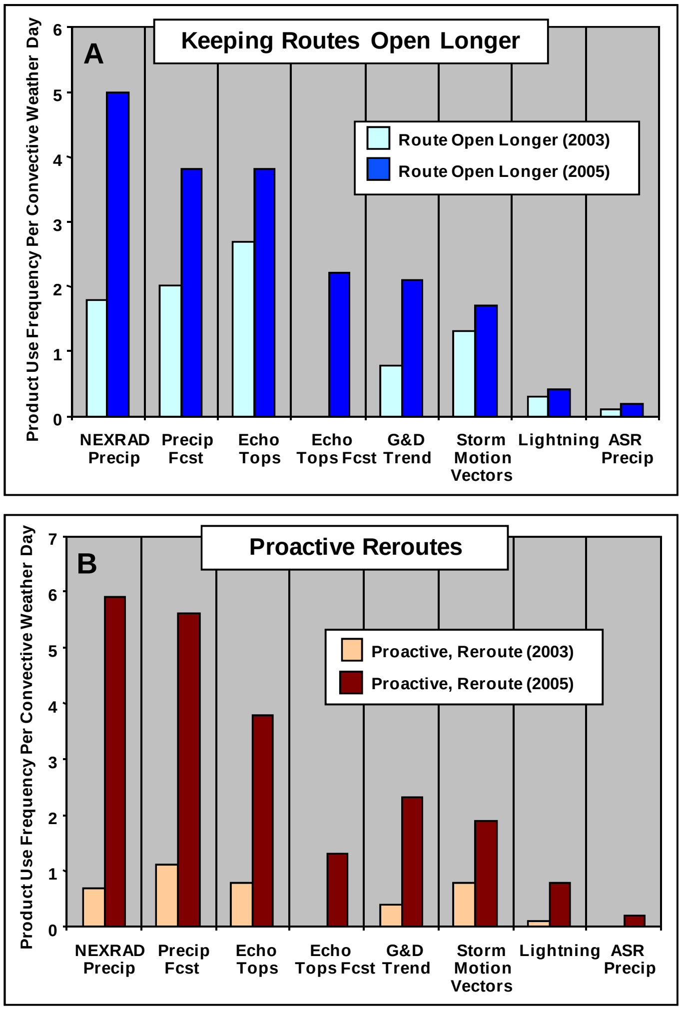


Figure 4-2. Frequency of use of various CIWS products for key decisions in convective weather: (A) Keeping Routes Open Longer (RO), and (B) Proactive Reroutes (PRR) (Robinson et al. 2006).

A concept to consider for integrating animated weather forecast information into TMA is the Future Traffic – Future Weather (FTFW) display concept currently under development to integrate CIWS with the Traffic Flow Management System (TFMS) (Taber et al. 2007) – see Figure 4-3. With this capability, TMA would not only be much more weather-aware, TMA "what-if" capabilities – a key enhancement desired by interviewed SMEs – would be significantly more robust.

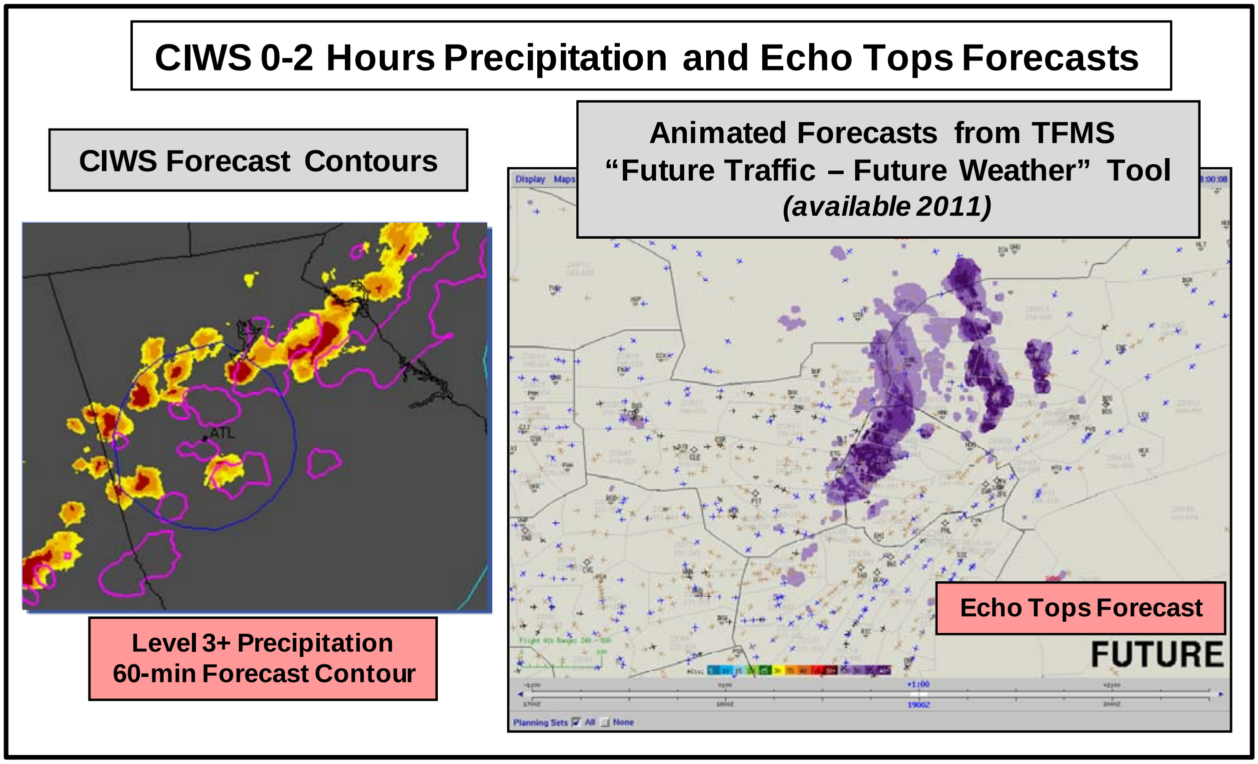


Figure 4-3. Options for integrating CIWS Precipitation and Echo Tops Forecast information into the TMA PGUI: CIWS forecast contours (left) and Future Traffic – Future Weather (FTFW) concept for integrating animated CIWS forecasts with predicted locations of aircraft (right).

4.2 WEATHER AVOIDANCE FIELD (WAF) PRODUCT ON TMA PGUI

In trajectory-based operations, it is necessary to identify flight trajectories through or around convective weather that pilots will find acceptable. Therefore, a critical task for successful TMA execution is for traffic managers to assimilate all pertinent weather information and ultimately identify the airspace regions that flights in time-metered flows will seek to avoid.

DeLaura and Evans (2006) have created a Convective Weather Avoidance Model (CWAM) which uses CIWS Precipitation and Echo Tops products to predict aircraft weather deviations. Using this model, one can calculate three dimensional weather avoidance fields (WAFs) that give the probability of pilot deviation due to convective weather at each pixel as a function of echo top height and precipitation intensity (Figure 4-4).

TMA SMEs also expressed interest in the CIWS-derived WAF product. A WAF product integrated onto the TMA PGUI effectively combines the salient information from both the precipitation and echo tops products and depicts airspace impacts in a manner that is of most concern to traffic managers servicing metering operations – as explicit predictions of potential traffic flow disruptions. Both the current WAF and the 0–2 hour WAF forecasts could be made available on the PGUI display. Conceivably, the complete three-dimensional WAF data could be used to develop a customized map of pilot deviation probability polygons that accounts for common altitudes and descent profiles along each TMA metered flow into an airport.[7]

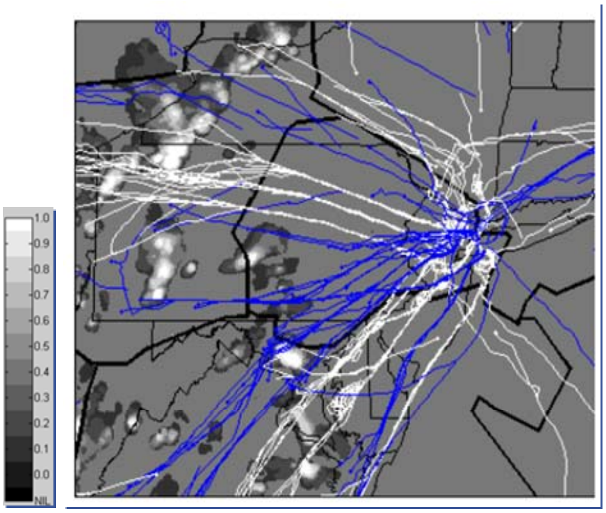


Figure 4-4. Convective Weather Avoidance Field (WAF) depicting weather hazards as the probability of pilot deviations. Metro NY departure (blue) and arrival (white) traffic is also shown to demonstrate the correlation of high WAFs (shown in brighter WAF levels) to traffic deviations and airspace avoidance.

4.3 WEATHER IMPACT GUIDANCE ON TMA TGUI AND LOAD GRAPH DISPLAYS

As discussed in Section 3, interviewed SMEs strongly supported weather impact guidance applied directly to the TMA TGUI and load graph displays. Field observations further substantiated the need for TGUI weather impact information for traffic managers to make better quality TMA scheduling decisions. Initial concepts that were favorably received included metered-flow and flight-specific blockage forecasts on the TGUI timelines. The concept and technology of the RAPT, which is deployed in NY to enhance departure flow management efficiency (e.g., Robinson et al. 2010; Robinson et al. 2009) could be adapted for TMA TGUI flow impact forecasts. RAPT utilizes CIWS-derived WAF forecasts and a model for airspace structure and flight trajectories to predict the duration and severity of flight-specific weather impacts along predetermined routes. With this same method, tactical weather impact forecasts on a metered flow or for specific flights scheduled in a metered flow could be generated for the TMA TGUI.

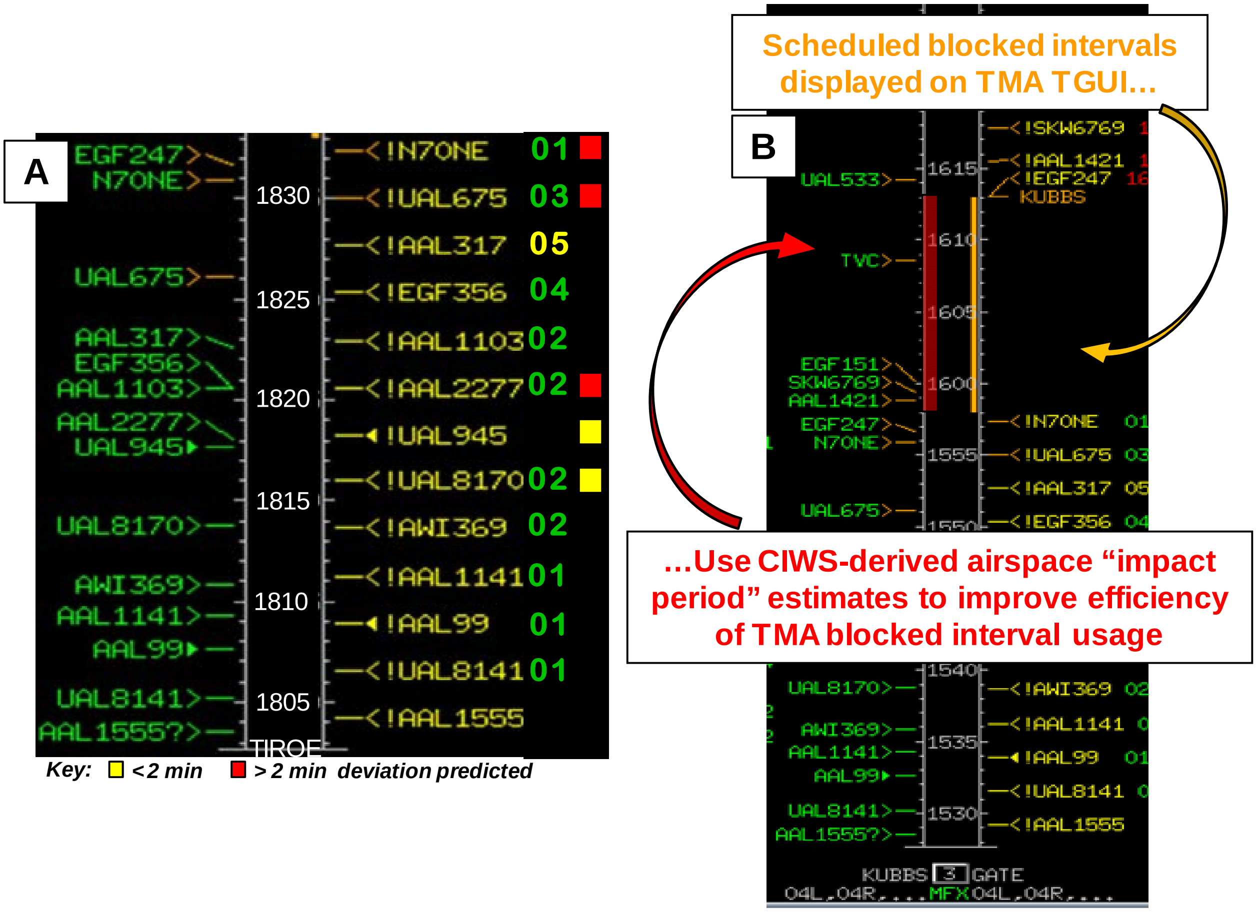
A TGUI display concept that includes weather impact guidance is shown in Figure 4-5. Flight-specific impact forecasts (Figure 4-5A), with perhaps some information of the severity of the impact (e.g., a yellow or red weather impact status to show whether flight disruptions are anticipated to minor or significant), may help traffic managers (a) make more surgical metering decisions and (b) identify the true

---

[7] In other words, along a metered flow inside the Freeze Horizon, an 80% probability threshold for pilot deviation around convective weather would occur at lower altitudes at the arrival fix, but at higher cruise altitudes out near the freeze horizon. The complete 3-D WAF field could be customized to account for this phase of flight variability along a metered flow.

scope of weather impacts on TBFM operations (possibly preventing “over-reactions” or conversely, facilitating more proactive TMA actions to maintain efficient metering). Examples of the potential operational applications of this TGUI guidance are provided in Section 5.

TGUI weather impact forecasts could also be displayed to more explicitly depict periods when a meter fix, gate, or runway is predicted to be impacted by weather (Figure 4-5B). Interviewed traffic managers have noted that they frequently rely on the use of scheduled blocked intervals in TMA in an attempt to manage TBFM during convective weather events (see Table 3). SMEs agree that applying scheduled blocked intervals based upon predicted weather impact periods (start time and duration) for a fix or gate will likely improve metering efficiency (and may even postpone or prevent TMA termination). Examples of the potential operational applications of TGUI flow/runway-impact forecasts are provided in Section 5.



Scheduled blocked intervals displayed on TMA TGUI…

…Use CIWS-derived airspace “impact period” estimates to improve efficiency of TMA blocked interval usage

Figure 4-5. Concepts for including CIWS-derived impact forecasts on the TMA TGUI, for both (A) individual flights scheduled in a metered flow and (B) anticipated impacts on a metered fix, gate, or runway.

Weather impact forecasts for a meter fix or at the runways can be also made available directly on the TMA load graph displays (Figure 4-6). With this concept, traffic management decisions made with the load graphs to anticipate and plan for spikes or reductions in meter demand could directly account for adverse weather impacts. This would likely result in more efficient ATM and TBFM planning. When presented with this concept, the TMA SMEs agreed that integrating weather decision support information into the TMA load graphs would reduce traffic management workload and would be used to improve TMA operations.

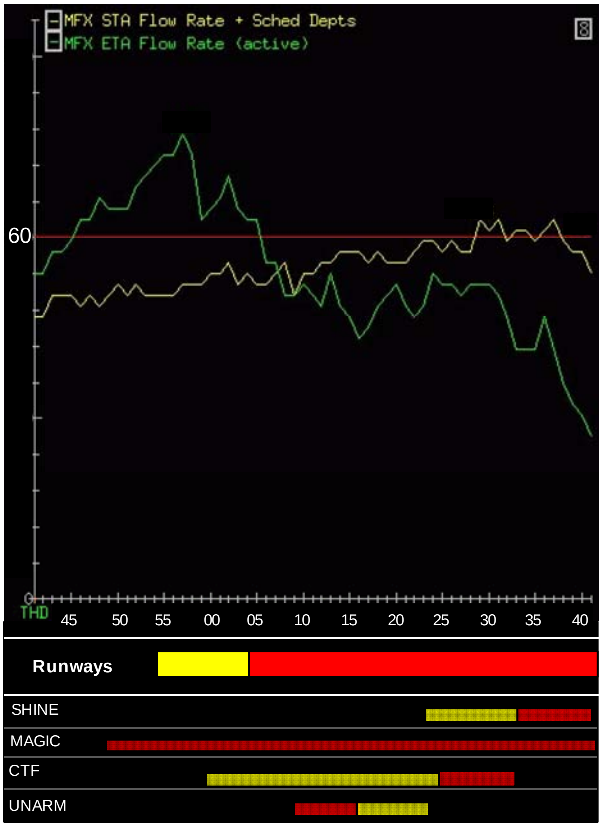


Figure 4-6. Concept for providing weather impact forecasts on the TMA load graphs. In this example, the impact forecast timelines show when minor and significant weather impacts will directly affect the Charlotte airport (CLT) runways and each of the primary CLT meter fixes.

Another primary feature of TMA is the En Route Departure Capability (EDC). EDC is used to meter internal ARTCC departures to a fix near the center boundary, often to ensure efficiency in meeting spacing restrictions. During convective weather, it is important to know when and to what degree a departure flow metered via EDC may be impacted (causing deviations) or blocked (requiring reroutes) in order to proactively mitigate avoidable delay. Since the RAPT prototype is already designed to probe departures flows and predict departure route availability, adapting RAPT capabilities to provide EDC blockage guidance is a straightforward concept to consider. Scheduled EDC departure traffic are shown on a separate TGUI timeline just like the timelines for metered arrival flows. Therefore, the flow and flight-specific weather decision support concepts for the TGUI shown in Figure 4-5 could also be used for TMA EDC management.

4.4 RESEARCH NEEDS FOR PROPOSED WEATHER-TMA INTEGRATION CONCEPTS

Research efforts to develop a pilot CWAM and WAF for convective weather need to be extended when applied to time-based metering operations. In terms of TMA operations, it is not enough to predict the likelihood of pilot deviations around adverse weather: to adequately manage slots in a metered flow and to proactively prepare for off-nominal trajectories, traffic managers must also know this anticipated weather-avoiding trajectory and the subsequent change in flight time to the meter threshold.

An example of how the CWAM database of identified weather deviations need to be re-analyzed to examine not only deviation likelihoods but the deviation characteristics is shown in Figure 4-7. This analysis demonstrates how one may begin to statistically model the relationships of WAF probabilities, WAF coverage, and WAF location in the context of the airspace structure and constraints to deviation distance and airborne delay compared to planned trajectories. This model could help determine airspace-specific distributions of deviation delays given certain WAF impact events (e.g., lines, air mass storms, embedded convection), which may be useful for traffic managers bounding TMA "slot-size" and defining stream class settings during off-nominal conditions. The use of delay distribution models in TMA decision support (e.g., to set slot size) will require human factors research to develop a concept of operations that takes into account the information and uncertainty implicit in a predicted statistical distribution of trajectory delays, and to identify the best ways to summarize and present this information to decision makers.

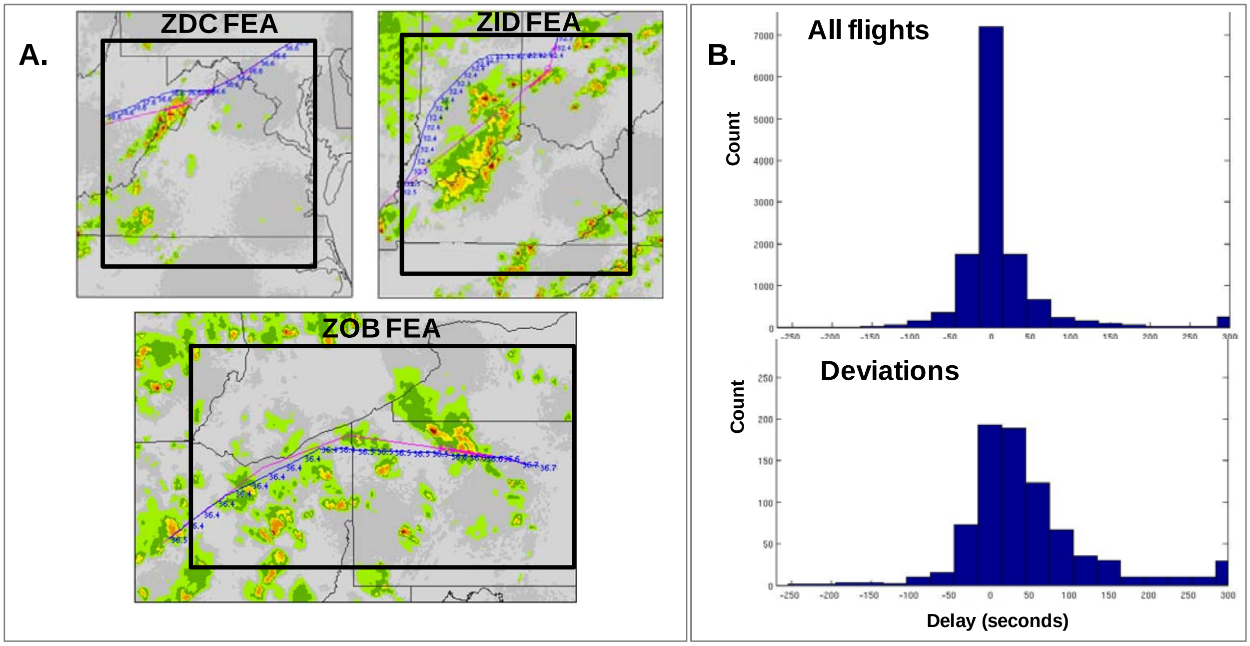


Figure 4-7. (A) Inspection of filed (pink) vs. flown (blue) flight trajectories in the Convective Weather Avoidance Model (CWAM) database as they traverse arbitrary Flow Evaluation Areas (FEAs) impacted by convective weather. (B) Delay distribution of 19,000 flights traversing these FEAs during 11 weather days in 2006–2008 resulting from differences in planned vs. actual flight trajectories when crossing the FEA.

The CWAM would also have to be expanded to support WX-TMA integrated decision support. Currently, WAFs have only been developed for en route, level flight traffic. To account for all phases of flights in a metered flow – from en route traffic beyond the TMA freeze horizon to traffic descending through a meter fix and arriving at the runway – the CWAM must also include climbing/descending and low-altitude traffic. Preliminary work has begun to develop CWAM for low-altitude and climb/descent phase traffic. Once these CWAMs are developed, a trajectory delay prediction problem similar to that in en route airspace must be addressed.

While decision support based on statistical models for trajectory delays may improve TMA efficiency in convective weather, the ultimate goal is to accurately predict the trajectory of each metered flight, accounting for pilot deviations to avoid convective weather. Unfortunately, significant uncertainty will remain in the prediction of pilot choices of weather-avoiding trajectories due to variations in pilot-perceived deviation 'cost functions' that are difficult to model. Pilots may have different tolerance for schedule delay (pilot A may be willing to accept a 50 mile deviation around weather, pilot B may prefer to accept the risk of weather penetration) and discomfort (pilot A will accept more bumpiness than pilot B). Pilots may also differ in their judgment about what they see out the cockpit window or on their airborne weather radar (Crowe et al., 2010). Attempts to model the many subjective variable that may affect pilot decision making may actually increase the uncertainty of trajectory predictions.

However, pilot behavior may become more predictable if WAF information and deviation delay forecasts could be provided in the cockpit for pilots to assess. Furthermore, decision support tools like the Aircraft Operations Planner (AOP: Ballin et al., 2004) could be enhanced to provide a selection of deconflicted weather-avoiding trajectory options to the cockpit, from which pilots could select and downlink their preferred choice. This would provide a highly reliable expression of pilot intent that should significantly increase the accuracy of trajectory prediction through regions of convective weather, with sufficient lead time to make the adjustments in metering times necessitated by the deviation. The electronic exchange and coordination of trajectory options could also result in significant reduction of pilot, controller, and coordination workload, if the human factors involved in coordinating and executing trajectory modifications and properly accounted for. The reduction in workload should translate directly into increased capacity.

This page intentionally left blank.

5. POTENTIAL BENEFITS OF INTEGRATED WX-TMA DECISION SUPPORT CONCEPTS

Observed events in 2009 when weather impacted TMA operations were analyzed to assess the potential applications and benefits of integrated WX-TMA decision support concepts proposed in the previous Section. Presented here are case examples where CIWS products or CIWS-derived weather impact guidance integrated into TMA PGUI, TGUI, and load graph displays may improve TMA operations during convective weather. The categories of WX-TMA usage illustrated in this Section pertain to (a) improved awareness, coordination, and productivity, and (b) improved execution of TMA metering actions.

5.1 IMPROVED TMA-WEATHER IMPACT AWARENESS, COORDINATION, AND PRODUCTIVITY

5.1.1 Isolated Traffic Deviations during EWR TMA Operation: 16 July 2009

Observations of EWR TMA Adjacent Center Metering tasks and responsibilities at ZBW Center were collected during a thunderstorm event on 16 July 2009. On this day, a small cluster of embedded thunderstorms impacted N90 and southern ZBW airspace during the morning hours. At 1415 UTC, two EWR arrivals deviate around isolated storms in ZBW airspace, near the N90 TRACON. The ZBW TMC using TMA to monitor EWR ACM was unaware of these deviations until N90 called and reported the issue (Figure 5-1). Without weather information in the TMA displays, the ZBW TMC was required to get up from his position and walk to two additional weather displays (CIWS and weather on TSD – the latter so weather could be viewed in the context of the EWR traffic), assess the weather impact and internalize the information gathered, and then return to the TMA PGUI and TGUI displays and translate the collected weather information into an estimated impact on the ACM operations to determine the proper impact mitigation action (if required at all). Also, without a common, objective forecast of the weather impacts in TMA, considerable extra effort was expended at both N90 and ZBW trying to determine how many more EWR arrivals will be affected by the storms. In fact, 15 minutes later (1430 UTC), N90 and ZBW – unsure from TMA of how many more EWR arrivals will deviate around weather – begin coordinating a reroute of EWR traffic from ZBW that was ultimately unneeded (See Figure 5-1). By 1445 UTC, more metered EWR traffic had passed through the convective weather region and remained on their route (no deviations), but the ZBW TMC was still visiting multiple displays to try and determine if the metered flow would be disrupted.

If CIWS weather products were available on the TMA PGUI, and flight-specific weather impact forecasts were available on the TGUI (Figure 5-2), the traffic managers at both N90 and ZBW would have quickly determined that:

- Two EWR arrivals via the SHAFF fix (from ZBW) may deviate at around 1415 UTC to avoid convection (TGUI – Figure 5-2A); both of these flights require two minutes of delay to meet their scheduled arrival time, so the minor deviations are not expected to generate negative delays;

- The next EWR SHAFF arrivals, 15 minutes after the two flights predicted to deviate, are not expected to be impacted by weather (i.e., the impact on EWR SHAFF traffic is minor and short-lived – TGUI, Figure 5-2A);
- The weather impacting flights in the EWR SHAFF flow are isolated, moving away from the fix and the Standard Terminal Arrival Route (STAR), and predicted to be completely clear of the route within 30 minutes (PGUI – Figure 5-2B).

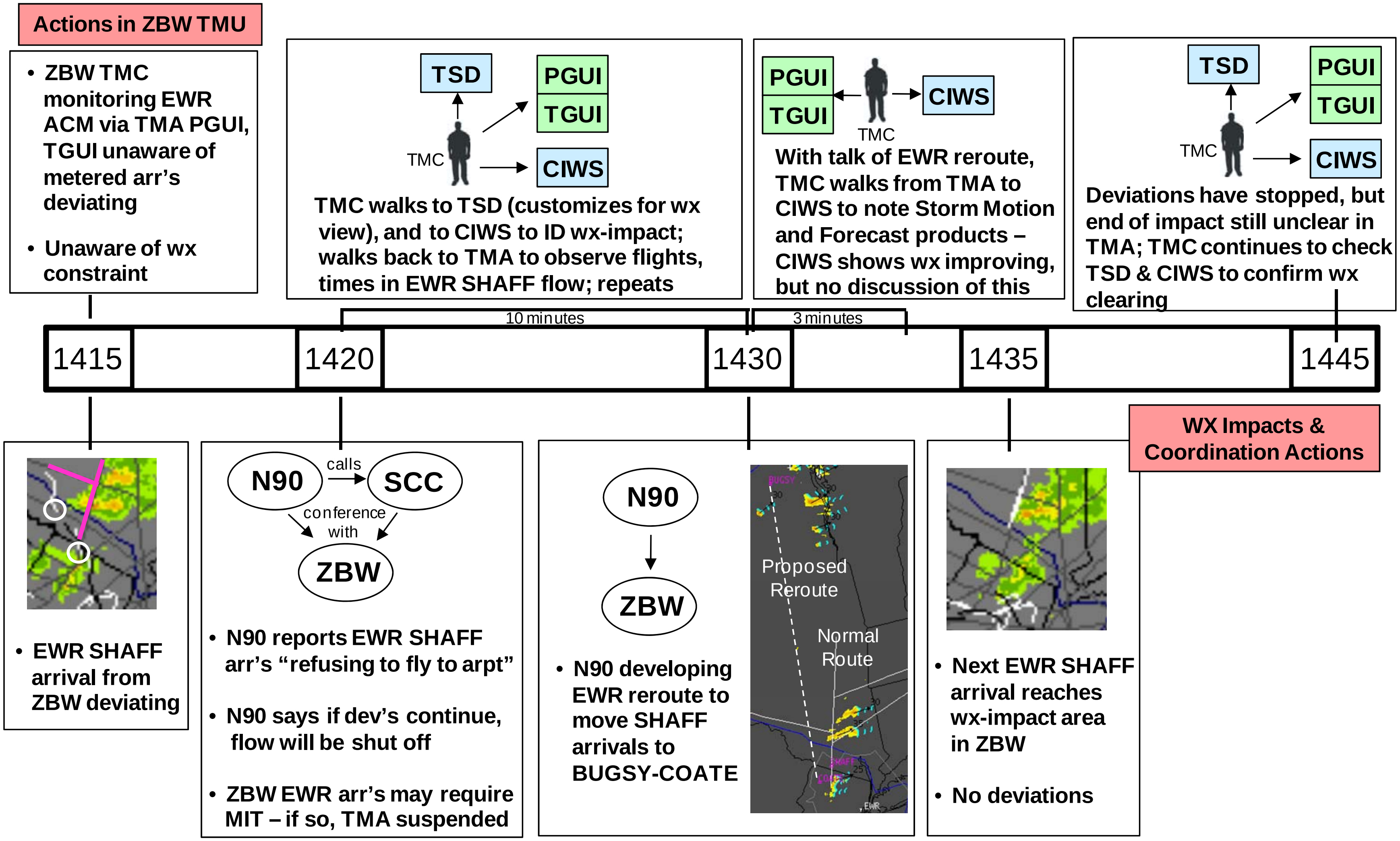
With objective information on the timing and severity of TMA weather impacts directly accessible from the TMA displays, the coordinating facilities (both N90 and ZBW) would have been aware of potential disruptions BEFORE they occurred. ACM coordination would have been streamlined, allowing traffic managers to attend to additional tasks (i.e., increased productivity – see Figure 5-2C, compared to Figure 5-1). Moreover, by assessing weather impacts on metered traffic using only the TMA displays, the need for the TMC to stop monitoring TMA (at a time of off-nominal metering operations, when intensive monitoring is more required) and walk to multiple weather displays to try and determine the scope of the weather impact would be eliminated. Finally, the integrated WX-TMA information would have allowed traffic managers to more quickly determine the proper impact mitigation actions needed (in this case, none), thus avoiding the development, coordination, and potential execution of unnecessary reroutes or restrictions.

5.1.2 TRACON – ARTCC TMA Coordination for Storm Impacts: 16 Sep 2009

Observations of ATL and CLT metering operations were conducted at ZTL during a thunderstorm event on 16 Sep 2009. At 1825 UTC, metered ATL arrival traffic via the northwest ERLIN and HERKO flows were encountering isolated convective cells in the A80 TRACON and skirting a larger storm complex in ZTL airspace (Figures 5-3A, B). At this time, A80 TRACON called ZTL to inform the Center of arrivals deviating (slightly) around an isolated cell in TRACON airspace (See Figure 5-3A). Dual STARs (HERKO and ERLIN) were in use at this time but because of the traffic deviations around the storm located on the ERLIN STAR, the A80 traffic manager wants to use only the HERKO STAR to serve metered ATL arrivals from the northwest. At this request, ZTL was forced to monitor both these flows and assess the feasibility of adequately metering (with manageable delay) all northwest ATL arrivals using only the HERKO STAR. As a result, ZTL TMU productivity was reduced and workload increased as TMCs gathered weather information from multiple sources and tried to estimate capacity impacts and TMA capabilities for the metered HERKO arrival flow (recall TMA information-processing diagram in Figure 3-7).

ZTL was concerned with the routing request from A80 because, from the standpoint of en route weather impacts, the southernmost HERKO arrival flow was the more significant concern when compared to the northernmost ERLIN flow, where ZTL storm impacts were minimal (see Figure 5-3B). In this case, had CIWS Storm Motion and Forecast products been available on the TMA PGUI, traffic managers at both facilities would have had common awareness of the various weather impacts by viewing only their TMA displays. With this integrated decision support information, it would likely have been easier for these coordinating facilities to determine that:

- The isolated storm cell causing small deviations in the TRACON was moving quickly off and away from the metered ERLIN arrival route (Figure 5-3C) - meaning impacts on arrivals should be short-lived;
- If one of the dual-STARs did need to be halted to accommodate TRACON deviations, the HERKO route should close before the ERLIN route since (a) the impact on the ERLIN route would soon end and (b) en route weather impacts in the near-term were anticipated to be more severe on the HERKO route (Figure 5-3D).



- ZBW TMC monitoring EWR ACM via TMA PGUI, TGUI unaware of metered arr's deviating
- Unaware of wx constraint

TMC walks to TSD (customizes for wx view), and to CIWS to ID wx-impact; walks back to TMA to observe flights, times in EWR SHAFF flow; repeats

With talk of EWR reroute, TMC walks from TMA to CIWS to note Storm Motion and Forecast products – CIWS shows wx improving, but no discussion of this

Deviations have stopped, but end of impact still unclear in TMA; TMC continues to check TSD & CIWS to confirm wx clearing

- EWR SHAFF arrival from ZBW deviating

- N90 reports EWR SHAFF arr's "refusing to fly to arpt"
- N90 says if dev's continue, flow will be shut off
- ZBW EWR arr's may require MIT – if so, TMA suspended

- N90 developing EWR reroute to move SHAFF arrivals to BUGSY-COATE

- Next EWR SHAFF arrival reaches wx-impact area in ZBW
- No deviations

Figure 5-1. Timeline of weather impacts and intrafacility coordination actions (bottom) and ZBW TMU actions and workload (top) in managing unanticipated EWR traffic deviations during the TMA metering operation on 16 July 2009. Times are UTC.

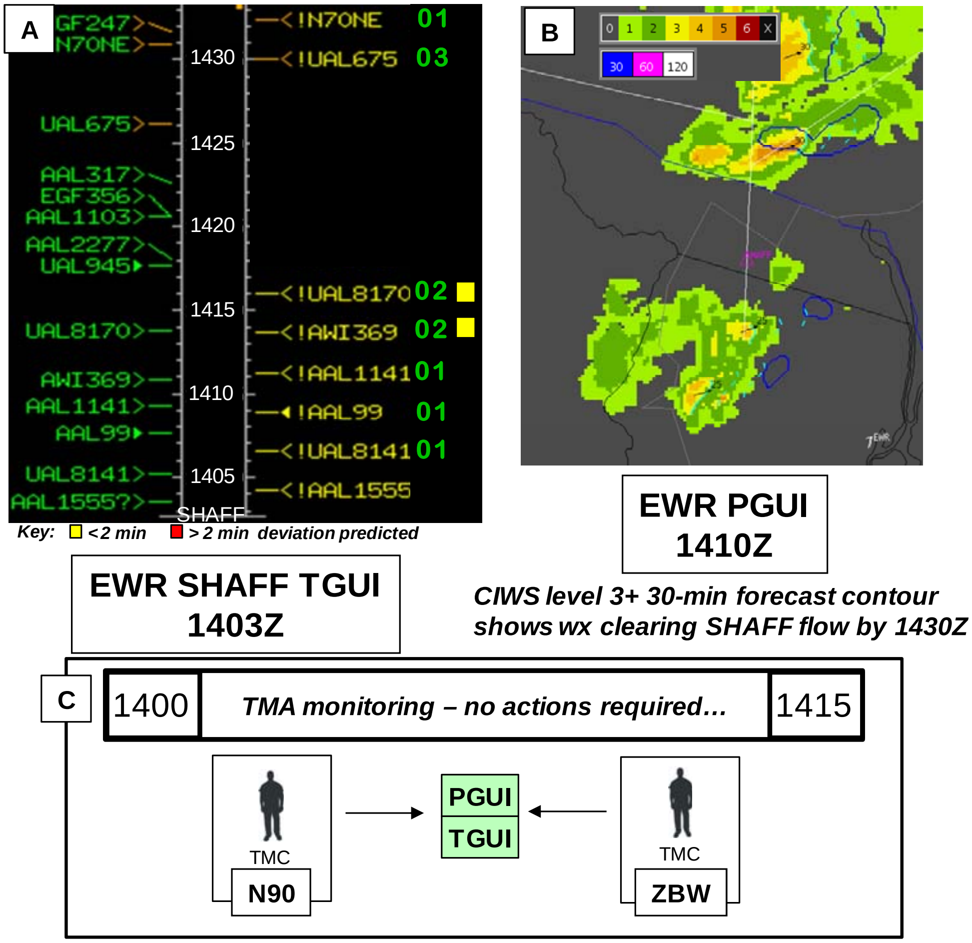


Figure 5-2. Weather impact guidance, as it may have appeared in TMA, during 16 July 2009 EWR ACM event. (A) Flight-specific weather impact guidance on TGUI (yellow squares), (B) CIWS Precipitation, Storm Motion vectors and 30 minute Precipitation Forecast contours on PGUI, and (C) reduced intrafacility coordination and workload (compared to Figure 5-1) achieved through integrated WX-TMA decision support.

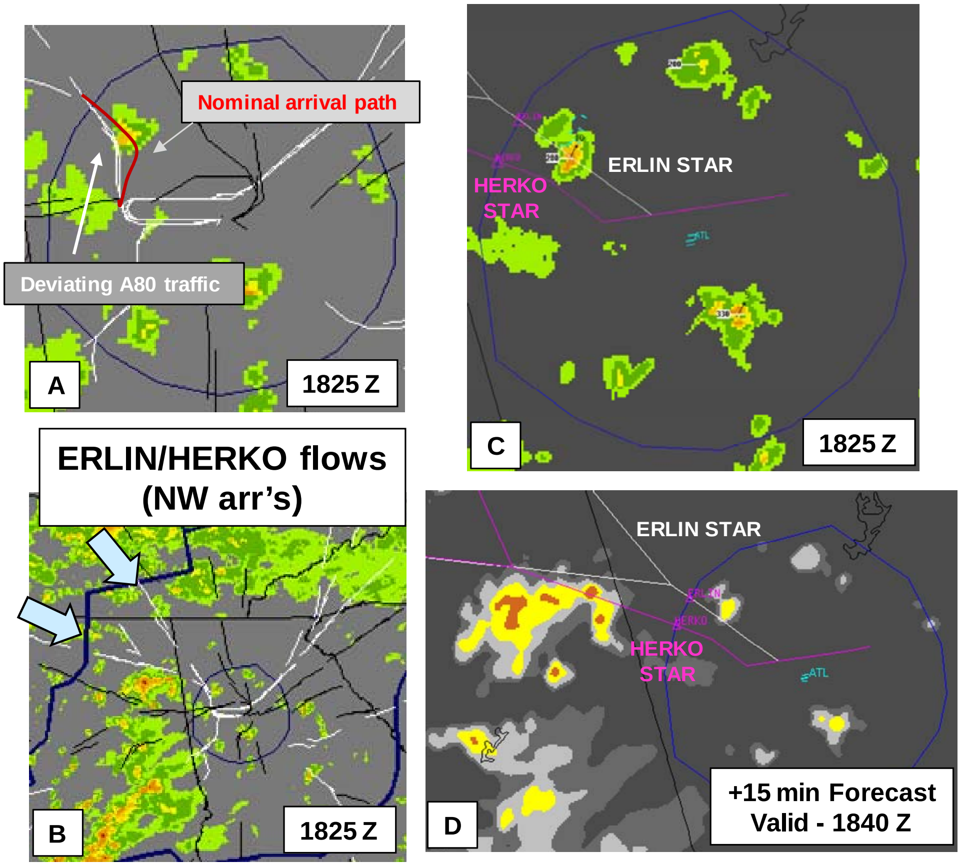


Figure 5-3. (A) Small, isolated precipitation cell causing minor deviations of ATL arrival traffic in the A80 TRACON on 16 July 2009. (B) Two routes (ERLIN and HERKO) serving ATL arrival traffic from the northwest and being metered in TMA during this weather event. (C) CIWS Precipitation, Storm Motion, and Echo Tops products and (D) CIWS Precipitation Forecast as they may appear on the TMA PGUI. This integrated WX-TMA information would have shown that the impact on metered traffic in the TRACON would be minor and short-lived, while storm impacts on the metered HERKO flow in en route airspace were anticipated to be significant in the near-term.

5.2 IMPROVED EXECUTION OF TMA METERING ACTIONS

5.2.1 Proactive TMA Scheduling Actions to Manage Weather Impacts: 27 Aug 2009

TMA was used to meter ATL arrival traffic on 27 Aug 2009. During this metering operation, a cluster of moderate to strong thunderstorms developed along the northwest A80 TRACON boundary, near the ERLIN arrival fix, around 1430 UTC. Metered traffic in the ERLIN flow began to deviate around 1500 UTC. These deviations continued as the convection remained quasi-stationary over the next 1.5 hours. The persistent deviations eventually eroded the arrival slot integrity of the metered northwest arrival flow, as frozen STAs fell behind continuously updating ETAs (that assumed a non-deviating flight trajectory), and TMA delay times became negative. At 1645 UTC, the ZTL TMC modified the TMA stream class spacing for arrival traffic in the ERLIN flow (increasing it from 8 miles to 10 miles) to account for the ongoing deviations. With this scheduling action, traffic managers increased the spacing between metered arrival slots to account for deviations.

Unfortunately, the implemented TMA scheduling action was late and mistimed as

1. the ERLIN deviations had already been occurring for greater than 1.5 hours (Figure 5-4 B, C) and
2. conditions were actually improving by 1645Z, the time when the ERLIN arrival spacing was increased (Figure 5-4D).

With CIWS weather products provided on the TMA PGUI, it would have been clear that deviations in the ERLIN arrival flow were weather avoidance actions and not controlled maneuvers for managing TMA delay assignments. Moreover, traffic managers could have viewed the CIWS Storm Growth and Decay product on the PGUI to recognize as early as 1445 UTC that storms near the ERLIN fix were intensifying (Figure 5-4 A-D, bottom panel). TMA managers could also have examined CIWS precipitation forecasts at 1500 UTC (Figure 5-4E), or forecasts of Echo Tops or WAFs (not shown), to note the intensifying storms near the ERLIN fix were predicted to move very little over the next hour, thus continuing to impact the metered arrival flow.

Using this weather information, combined with flight and flow specific weather impact forecasts in the TMA TGUI and load graphs (not shown), ZTL traffic managers could have implemented TMA scheduling actions (e.g., increased spacing, Single Gate Free Flow, etc.) when deviations in the metered flow first began at 1500 UTC (see Figure 5-4B). This proactive decision would have helped to maintain arrival slot integrity (e.g., fewer/smaller negative TMA delays) and to decrease controller workload.

In addition, use of integrated WX-TMA decision support during this weather event would have likely increased arrival capacity. Without convective weather information in TMA, spacing of ERLIN arrival traffic was increased at 1645 UTC – the time when weather impacts on this flow were *ending*. This TMA restriction was not removed until metering was cancelled at 1925 UTC (because of windshear advisories at ATL terminal that required a first-tier Ground Stop). Using PGUI weather, or TGUI/load graph weather impact forecasts, traffic managers could have planned to *ease* ERLIN restrictions by 1645 UTC (see Figure 5-4D), thus increasing the available arrival slots in the metered northwest flow.

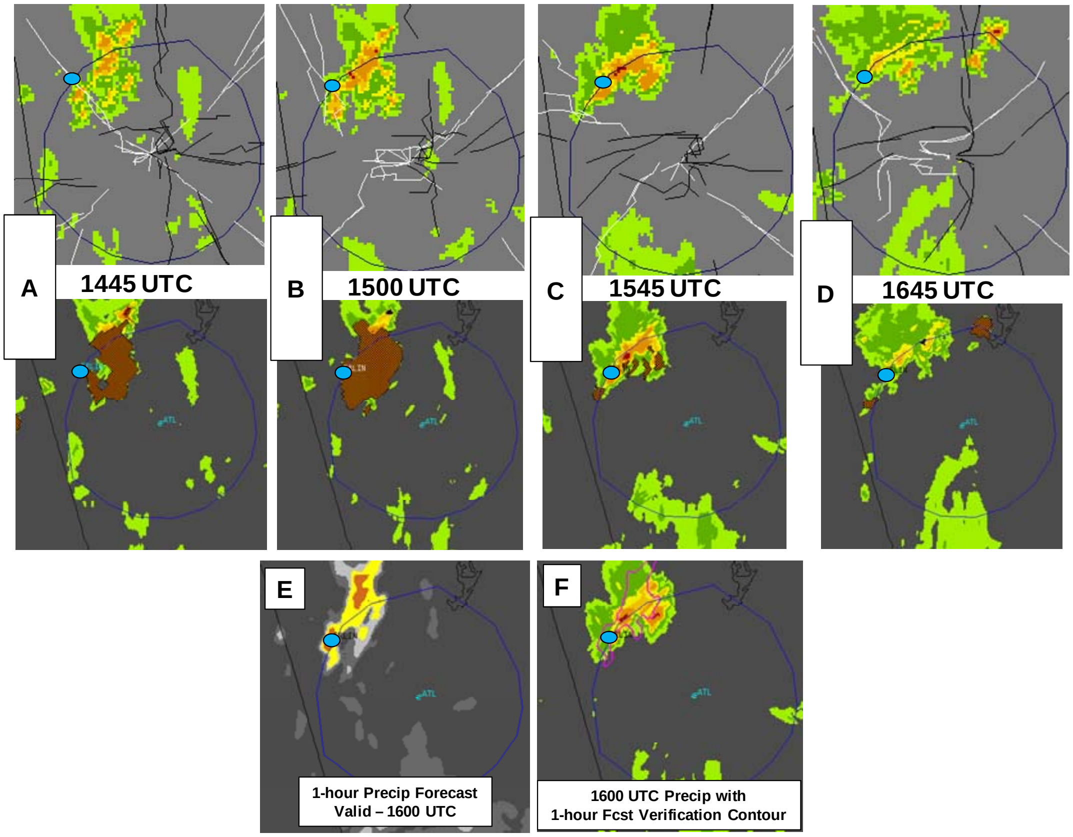


Figure 5-4. CIWS weather depictions and forecasts, with ATL arrival (white) and departure (black) traffic on 27 August 2009. The blue circle in each panel is the ERLIN arrival fix. CIWS Precipitation (top) and Storm Growth and Decay Trends (bottom – hatched orange areas show growth, dark blue areas show decay) at (A) 1445 UTC, (B) 1500 UTC, (C) 1545 UTC, and (D) 1645 UTC. The 1-hour CIWS Precipitation Forecast issued at 1500 UTC (E) showed that storms were predicted to remain on and near the ERLIN fix through 1600 UTC. The CIWS 1-hour Forecast Verification contour valid at 1600 UTC, compared against actual weather at that time (F), shows the CIWS forecast to be accurate.

5.2.2 Improved Execution of TMA "Blocked Interval" Actions: 28 Aug 2009

Observations of ATL and CLT metering operations were conducted at ZTL during a thunderstorm event on 28 Aug 2009. Between 2000-2300 UTC, numerous storm cells move through the CLT TRACON, affecting the TMA metering operation. In two instances, starting at 2017 UTC and again at 2059 UTC, a level 5-6 thunderstorm directly impacted the CLT terminal, requiring traffic management initiatives (TMIs) and TMA scheduling actions. In both cases, the ZTL TMC managing CLT TMA implemented a "runway blocked interval" for a period when the impacted runway in question was expected to be unavailable for landing traffic.

The TMA "blocked interval" scheduling action sets a user-selected time period when aircraft may not be scheduled to cross the meter fix or land on a runway. This action distributes TMA delay assignments to airborne traffic planning to land on the affected runway (or cross the affected meter fix) during the user-selected impact period. Setting a blocked runway interval in TMA is an effective way to accommodate significant meter point constraints during time-based metering operations. However, given that this scheduling action can result in significant reductions in runway usage and increased airborne delay (and fuel burn and controller workload), it is important that TMA blocked intervals be used as efficiently as possible. TMA blocked intervals are most efficient when

1. Implemented proactively – to mitigate deviations and arrival slot uncertainty; to allow more aircraft to incur TMA delays at higher altitudes, thus burning less fuel (and perhaps accommodated beyond the Freeze Horizon, before meter times are "locked")

2. Implemented with accurate start and stop times – to ensure that capacity is reduced no more than necessary and to mitigate direct weather impacts on the metered traffic

The lack of integrated convective weather decision support in TMA made it difficult for traffic managers to efficiently execute CLT blocked runway interval scheduling actions during the 28 Aug terminal impact event. The sequence of events during the 2100 UTC CLT terminal impact was as follows:

- **2059 UTC:** Level 5-6 storm cell moves over CLT; Only single-runway now in use as runway-23 is forced to close at this time (Figure 5-5A);
  - ZTL TMC monitors weather on ITWS display near TMA – no action taken in TMA until A80 TRACON calls to report runway-23 closure.
  - MAJIC (northeast) arrival flow go into holding; TMC tells Area to expect holding for 10 minutes (actual holding was 20 minutes)
  - ZTL TMC tells ZJX to "ignore [TMA] times" in CTF (southeast) arrival flow and instead to deliver with 30 MIT restriction (this transition to MIT restriction temporarily suspends CLT metering)

- **2109 UTC:** ZLT TMC sets runway blocked interval in TMA (for runway-23) from 2110-2145 UTC (Figure 5-5B)
  - Runway-23 not blocked for first 10 minutes of impact period (causing incorrect TMA times and underutilized runway capacity)
  - Runway-23 was directly impacted by storms until 2208Z (causing incorrect TMA times after 2145 UTC)

Without integrated WX-TMA decision support during this impact event, the runway blocked interval was not set proactively (implemented only after storms closed the runway and aircraft went into holding) and the blocked interval start and stop times were inaccurate. As a result, more arriving aircraft held less efficiently at lower altitudes near the TRACON boundary (which also increased controller workload) and landing capacity was not optimized, which contributed to increased avoidable delay. In addition, the inefficient use of the TMA blocked interval also increased arrival slot uncertainty, which contributed to the temporary suspension of the metering operation.

Had CIWS weather products and derived impact guidance been directly available in the TMA PGUI, TGUI, and load graph displays (Figure 5-6), traffic managers at all coordinating facilities (e.g., ZTL, CLT TRACON, ZJX, ZDC) may have used these data, in conjunction with the high-resolution TMA traffic information, to execute a proactive, well-timed runway-blocked interval scheduling action. Use of this integrated WX-TMA information likely would have decreased workload, increased use of the available capacity, and reduced avoidable delay.

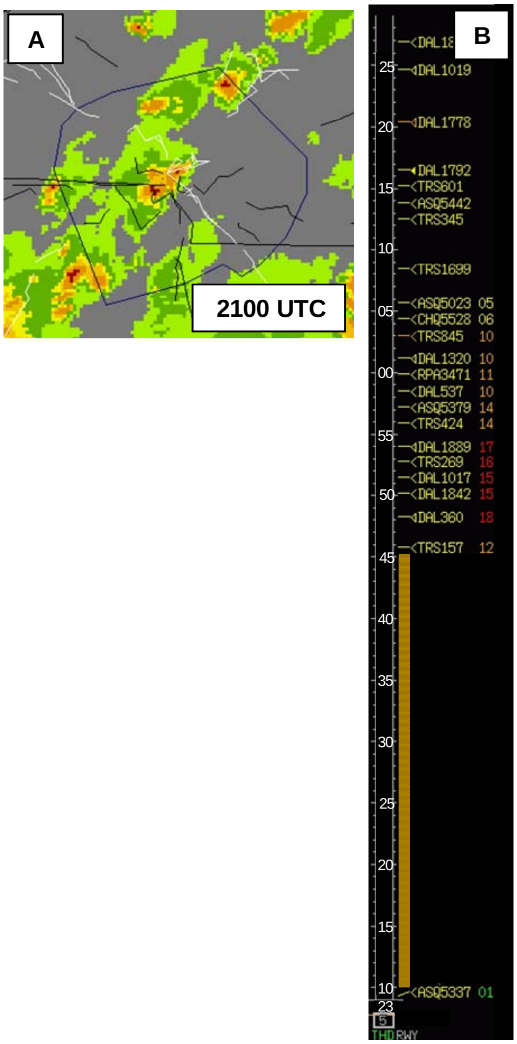


Figure 5-5. (A) CIWS precipitation, with CLT arriving (white) and departing (black) traffic at 2100 UTC on 28 August 2009. (B) Representation of TMA TGUI for CLT runway-23 at 2109 UTC. The orange rectangle in the TGUI shows the executed runway-blocked interval from 2110–2145 UTC. Note that no aircraft are scheduled to land during the blocked interval period.

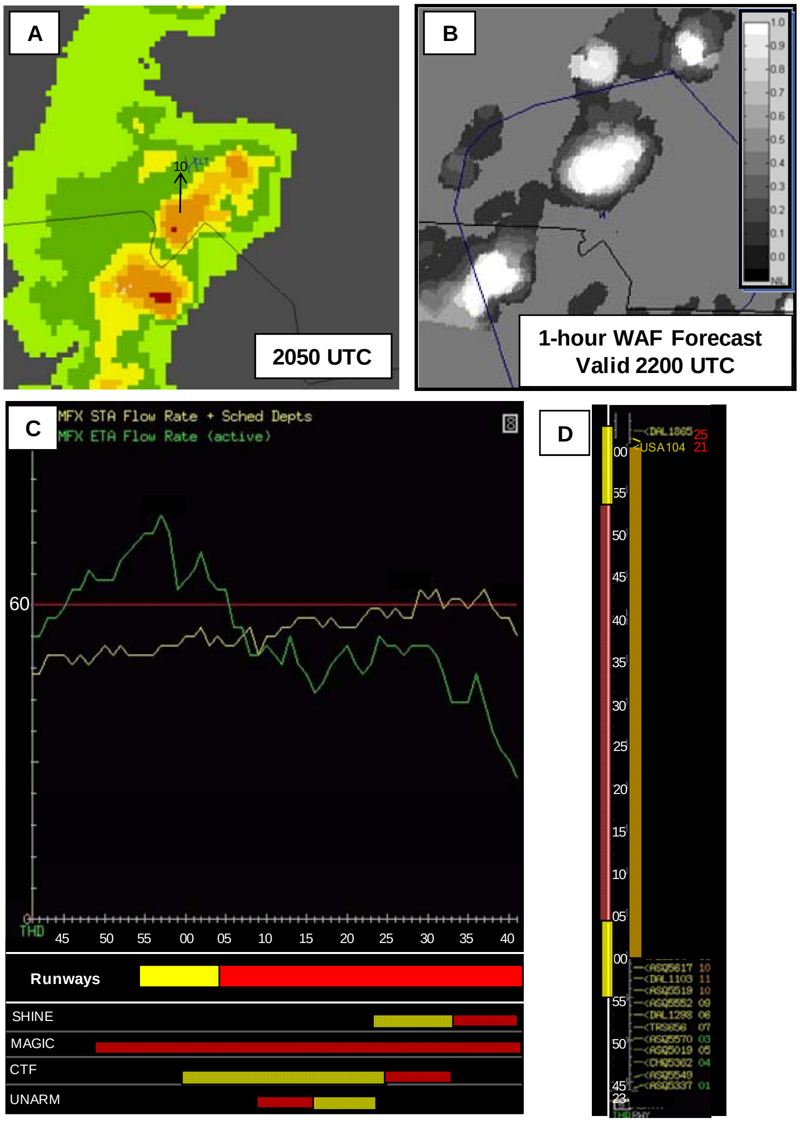


Figure 5-6. Convective weather decision support, as it may have appeared in TMA displays, during the storm impact event at CLT on 28 August 2009. (A) CIWS Precipitation and Storm Motion Vectors on the PGUI (at 2050 UTC) may have allowed traffic managers to more proactively prepare for the pending terminal weather impact. (B) A CIWS-derived, one-hour WAF forecast (shown in contours of pilot deviation probabilities) available on the PGUI, issued at 2100 UTC, may have allowed traffic managers to implement better exit strategies for TMA scheduling actions (as the WAF shows the most significant weather clearing the terminal after 2200 UTC). (C) Weather impact forecast timelines for the CLT runways and primary arrival fixes, available on the TMA load graph, may have provided a quick assessment of timing and severity of terminal impact. (D) Moderate (yellow) to significant (red) weather impact forecasts (left-side) on the TMA TGUI for runway-23 could have been used to implement a more proactive, more accurate (in terms of start and stop times) CLT runway-blocked interval (represented in TGUI by orange rectangle).

5.2.3 Improved TBFM Efficiency during Multi-Hour Weather Impact Event: 07 July 2009

On 07 July 2009, FAA/Flatiron reports on TMA show that ZBW metered BOS arrivals from 1334–2220 UTC. During this period, the runway configuration was modified four times, and flights were rescheduled in each instance. The TMA report also suggests that arrival separation for all BOS TMA stream classes was changed to 6.0 nmi at 1526 UTC (it is unclear from the report if this was an increase or decrease, but the former is assumed given ongoing storm impacts in ZBW at this time). This change in stream class separation coincides with the first observed deviation in the BOS eastbound arrival flow to the GDM meter fix (Figure 5-7). No other specific TMA actions were either performed or were discernable in the TMA report.

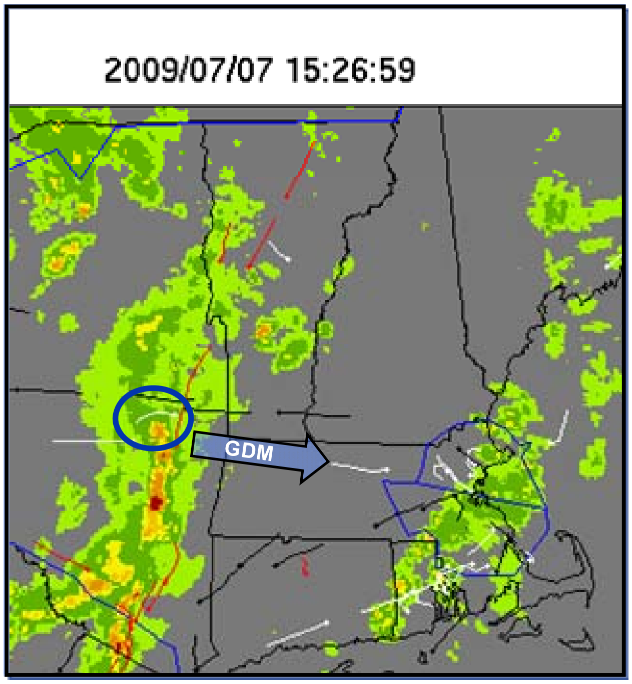


Figure 5-7. BOS arrivals (white) and departures (black) and EWR arrivals (red) with CIWS VIL precipitation at 1526 UTC on 07 July 2009. The first observed deviation in the eastbound BOS GDM arrival flow occurred at this time (circled).

During this event, several clusters of thunderstorms and an organized line of convection impacted ZBW airspace. Thunderstorms were present in ZBW from approximately 1500–0600 UTC (08 July). The primary BOS arrival flows from the west and south, as well as the terminal itself, were impacted extensively on this day.

CIWS weather products and flight tracks of metered BOS arrival traffic on 07 July were examined together to assess the metered flows during the convective weather event. Focusing on the specific CIWS products and CIWS-derived flow/flight impact guidance proposed for near-term WX-TMA integration concepts, a “what-if” exercise was conducted to identify potential opportunities for enhanced BOS TBFM efficiency during this prolonged weather impact event.

A summary of the potential applications and benefits of CIWS convective weather decision support in TMA PGUI, TGUI, and load graph displays is presented in Table 5-1. During the severe weather event, integrated WX-TMA displays may have allowed ZBW traffic managers to

- Proactively reroute metered traffic to an alternative fix (Figure 5-8)
- Reopen a closed route (meter flow) sooner, allowing more arrival traffic to fly shorter routes (Figure 5-9)
- Reduced holding and airborne delay (Figure 5-10)
- Reduce or avoid BOS Ground Stop restrictions (Figure 5-11)

Table 5-1. Opportunities and Potential Benefits if WX-TMA Integration Concepts Were Applied to BOS TMA Metering on 07 July 2009

Time (UTC)	TMA Missed Opportunity	WX-TMA Potential Benefit	Applicable WX-TMA Integration Concept
1700 (Fig. 5-8)	GDM arrivals forced through line and held east of storms (by choice) – to ensure traffic gets past wx before worsening; Creates increased controller workload and airborne holding in difficult area (near advancing wx and near deviating BOS PVD arrival flow) CIWS demonstrates potential opportunity to proactively route GDM traffic through northern portion of line towards SCUPP fix	Reduced airborne holding, decreased workload and complexity, safer operations (no holding near wx, near deviating arrivals), and improved TBFM integrity and predictability	PGUI: Precip with Growth & Decay Trends, Precip/Etops forecasts, WAF TGUI: SCUPP flow impact forecast Load graph: GDM/SCUPP fix impact forecast
2015 (Fig. 5-9)	Proactively and surgically reroute SCUPP arrivals back to GDM with less flight distance and fuel burn; Allow easier transition to GDM arrival flow with less controller effort	9 BOS arrivals reroute earlier and with less vectoring, saving ~40 nmi flying distance per aircraft; Total potential airborne flight distance saved = 360 nmi	PGUI: Echo Tops and Forecasts, WAFs TGUI: GDM flow impact forecast Load graph: GDM fix impact forecast
2255 (Fig. 5-10)	GDM arrivals "bunching", with minor holding, as deviations disrupt metered spacing; Because of this, GDM arrivals rerouted onto longer SCUPP route (2330 UTC) CIWS products show opportunity to proactively plan for deviations by increasing stream class spacing or matrix buffer to accommodate local and transient GDM constraint – allowing traffic to remain on preferred route (storms weakened by 2350)	Able to use the direct GDM arrival route for 2 extra hours (2300-0130) Avg flight distance between ZBW GDM vs. SCUPP arrival = 65 nmi 27 BOS arrivals may have continued to arrive via GDM Total flight distance saved: 1755 nmi	PGUI: Echo Tops, Echo Tops Forecast, Growth & Decay Trends, WAFs TGUI: GDM flow (and flight-specific) weather impact forecast Load graph: GDM fix impact forecast
0000 (Fig. 5-11)	BOS ground stop in place until 0030 UTC for ZBW, ZNY, ZDC, ZOB airports; WX-TMA shows opportunity to release ZNY airports from ground stop 30 min early and schedule BOS arrivals into available slots as weather and congestion clear PVD flow	Early Ground Stop termination would have allowed 3 NY to BOS to depart 30 min early and 2 NY to BOS flights to depart 15 min early; Total delay savings: 2 hours (not including surface queuing delay savings at metro NY airports	PGUI: Echo Tops, Echo Tops Forecast, Lightning, WAFs TGUI: PVD flow blockage forecast Load graph: PVD/BOS fix impact forecast

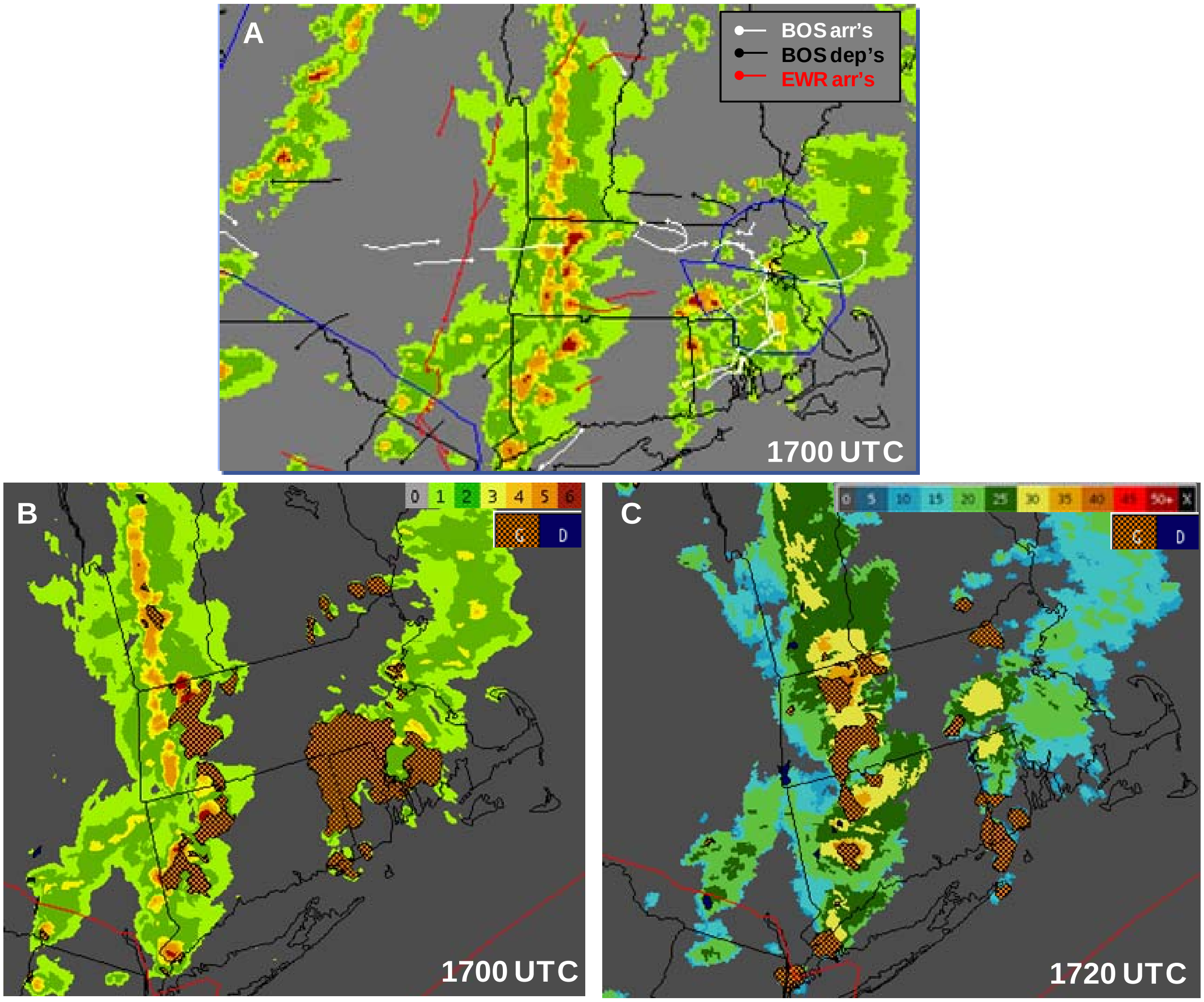


Figure 5-8. (A) BOS and EWR traffic (with CIWS precipitation) in ZBW airspace at 1700 UTC on 07 July 2009. CIWS Growth and Decay Trends (B, C), Echo Tops (C), and Forecasts, Lightning, and WAFs (not shown) illustrate that northern portion of the squall line along the NY border is less severe, with lower echo tops. With this information available in TMA, traffic managers could have proactively rerouted select GDM (eastbound) BOS arrivals further north to the SCUPP fix.

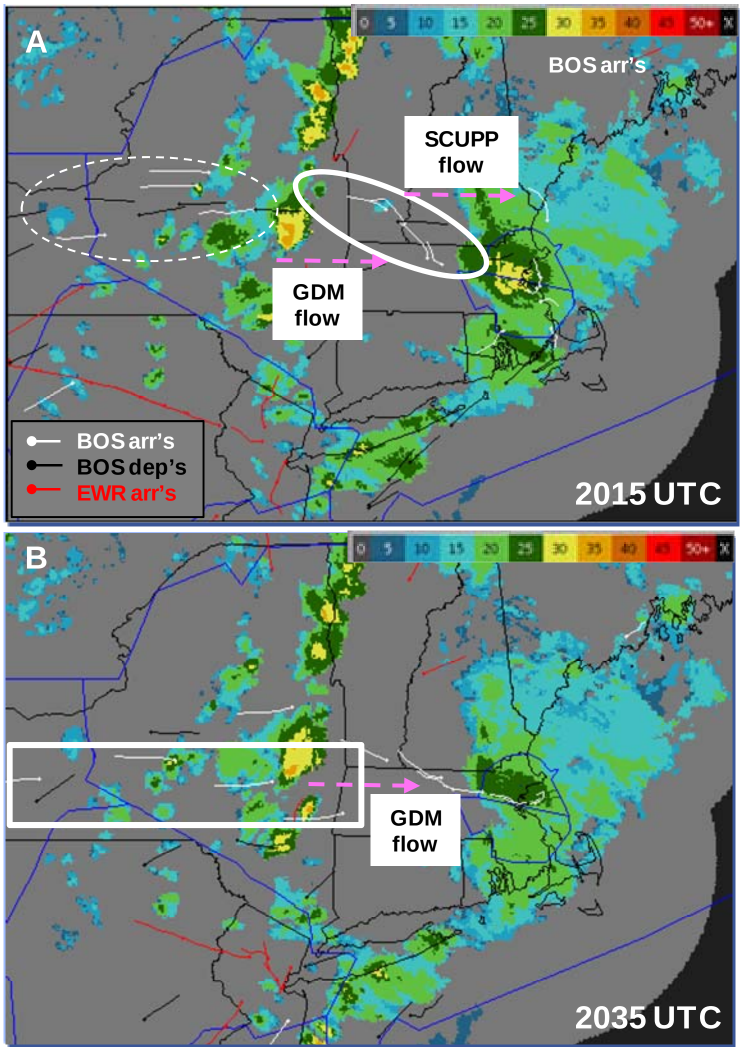


Figure 5-9. BOS arrival traffic (white) with CIWS Echo Tops at (A) 2015 UTC and (B) 2035 UTC. In (A), metered SCUPP traffic is rerouted back to the GDM flow (as the GDM arrival route was reopened at this time). CIWS products and derived flow (and flight-specific) blockage forecasts in TMA may have supported an earlier return to the GDM flow (as it appears at 2035 UTC – see boxed region in (B)). This may have avoided the longer route flown by 9 BOS arrivals rerouted from the SCUPP to the GDM flow after flying east of the broken line of thunderstorms.

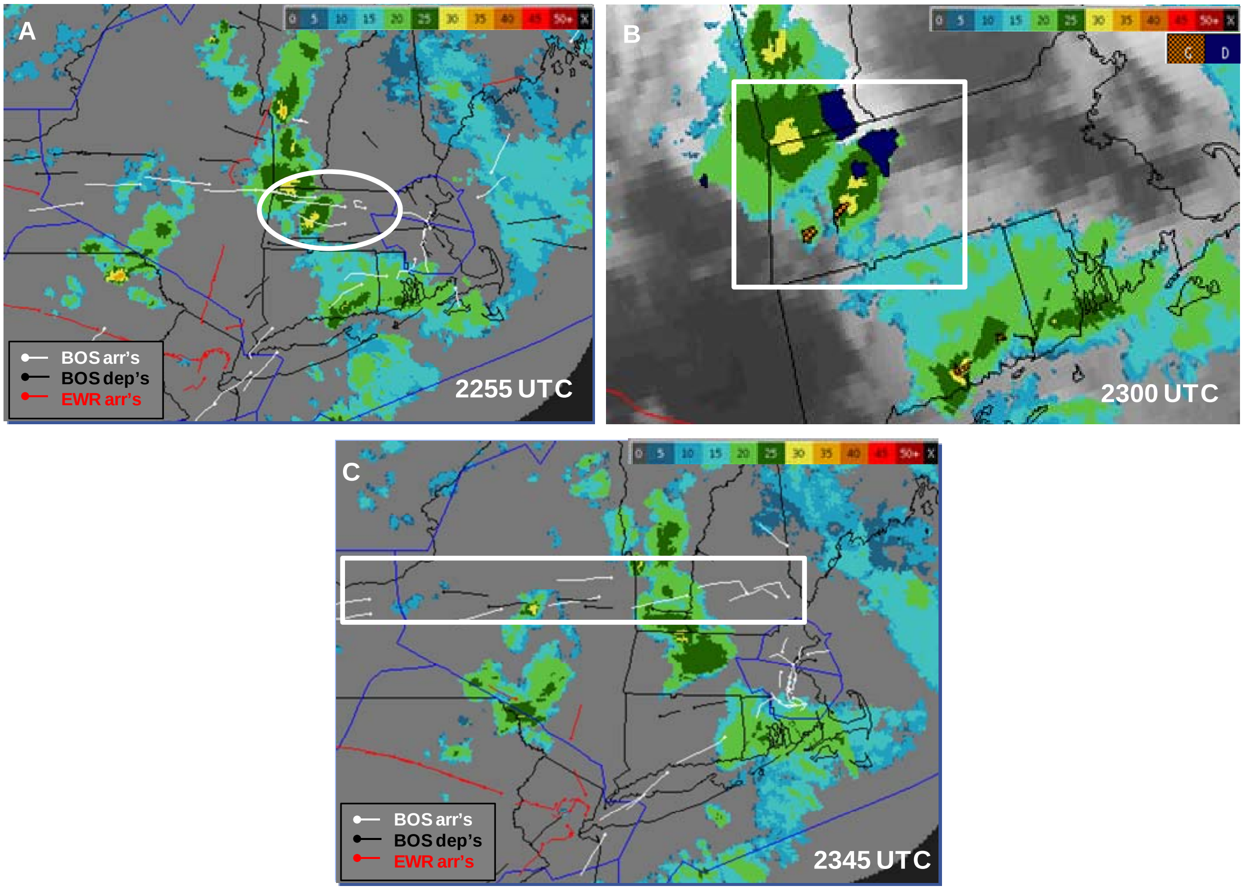


Figure 5-10. BOS arrival traffic on GDM flow at 2255 UTC on 07 July 2009 (A – circled) seen "bunching," with airborne holding, as aircraft deviate slightly around convection. TMA was halted at 2220 UTC, and GDM arrival spacing was no longer managed with TBFM (likely contributing to heavy delivery through weather region). CIWS Echo Tops and Growth and Decay Trends at 2300 UTC (Fig. B) show that storm tops only reached 30 kft, and weather showed more decay than growth – suggesting storm impacts on GDM flow were local and transient. With this information integrated into TMA, and if TBFM operations had continued, a prolonged reroute onto the longer SCUPP route (see boxed region at 2345 UTC in Fig. C) may have been avoided.

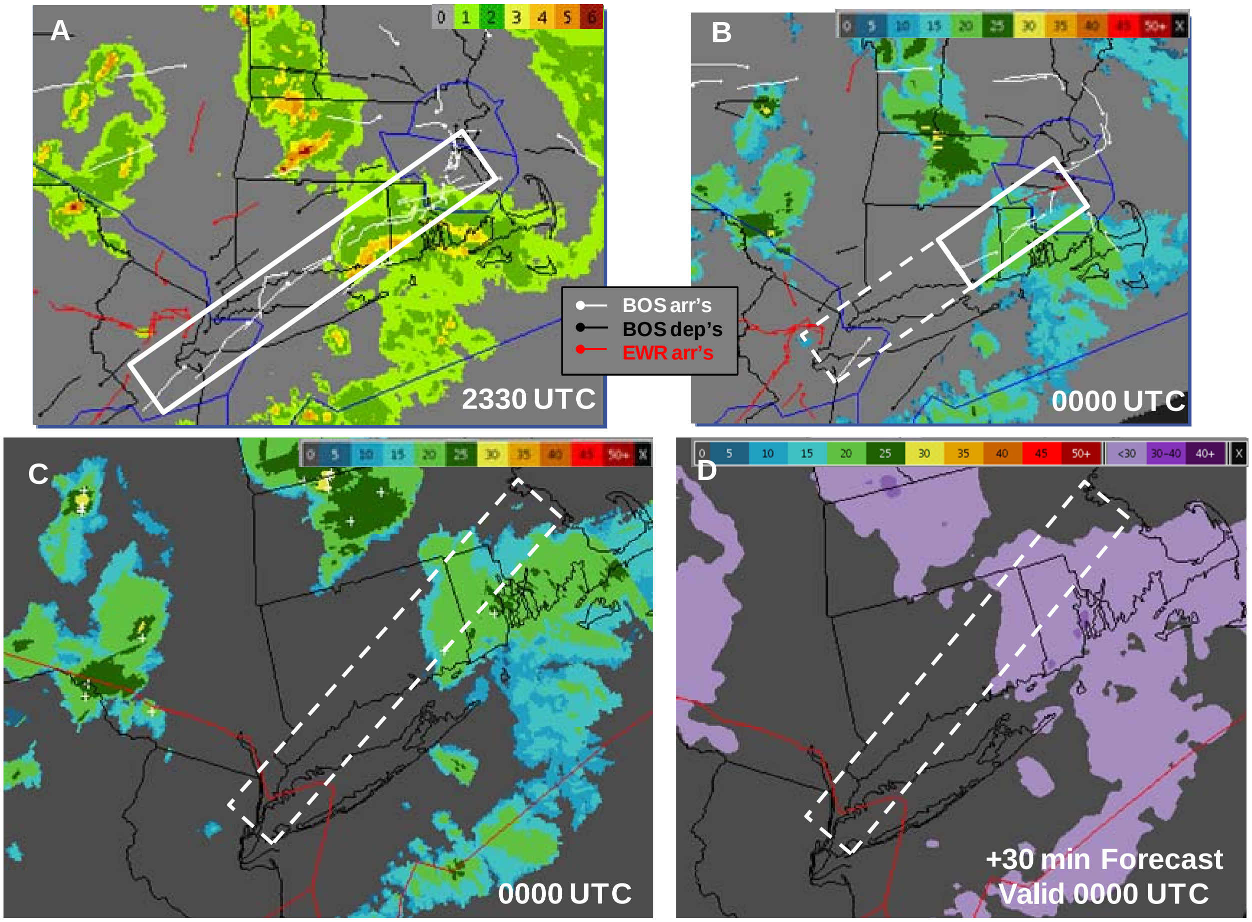


Figure 5-11. (A) Volume of BOS arrivals (white) in PVD flow was heavy at 2330 UTC on 07 July 2009 (boxed region). Aircraft within this flow were deviating – and a BOS Ground Stop was implemented at this time (until 0030 UTC). By 0000 UTC, however, PVD traffic was not deviating and flow demand was low (Fig. B) and weather impacts were minimal – CIWS Echo Tops and Lightning (Fig. C) show low topped storms and few lightning strikes (marked by '+'). The CIWS Echo Tops Forecast at 2330 UTC – valid at 0000 UTC – shows impacts on the PVD would be negligible. Integrated WX-TMA PGUI and TGUI/load graph guidance likely would have shown that the Ground Stop could have been avoided for at least NY airports – and that TMA slots were available in the PVD flow for these flights.

6. CONCLUSIONS

Time-based flow metering of traffic in capacity-constrained airspace regions is considered to be a cornerstone element of the NextGen operational concept. TMA is the principal operational TBFM system is use today. TMA use is coordinated through multiple FAA facilities (and between controllers and traffic managers at individual facilities) to optimize the flow of aircraft through several control points (e.g., outer metering arc, arrival fixes, final approach fixes, and runway thresholds) so as to maximize airspace capacity without compromising safety.

In general, the task with TMA is to merge streams of traffic and control aircraft (through assigned meter delays) so that they arrive at the runway (or runways) with minimal spacing and with the highest possible landing rate. This is done while satisfying not only the runway constraints but also other constraints in the system (e.g., arrival fixes and outer meter arcs). It should be recognized that this is a difficult problem since not only are there multiple streams of flights to blend, but the arriving aircraft have different performance characteristics (i.e., fly at different speeds, at different altitudes, and with different descent rates). The TMA scheduler takes account of all of these factors when computing scheduling solutions.

During fair-weather condition, it has been shown that TMA usage has increased capacity, reduced aircraft fuel burn, and decreased delay. Increased capacity usage of constrained resources (and delay savings achieved) with TMA are most significant when traffic demand nears or exceeds the available capacity. Demand often exceeds capacity when adverse weather such as thunderstorms (in en route or terminal airspace) or low ceilings and visibility at the airport restrict the number of available arrival slots. It is during these weather situations where TMA metered operations can provide the most potential benefit in terms of mitigating airborne delay and facilitating a more predictable air traffic management environment.

Unfortunately, the operational challenges in using TMA during adverse weather often become too great and the benefits of metering are often limited or lost entirely. Often, TMA metering operations are halted during convective weather events, as aircraft deviations in a metered flow are not anticipated or adequately planned for, resulting in erroneous, unpredictable, and/or unmanageable TMA slot allocations. Operational traffic managers and TMA SME have stated that the lack of weather information in TMA significantly limits the capabilities to make proactive decisions that would mitigate weather impacts on metered traffic flow.

Lincoln Laboratory conducted structured interviews with TMA SMEs and observed TMA usage during convective weather events in an effort to identify near-term TMA and CIWS weather integration capabilities that would provide enhanced decisions support for weather-impacted metering operations. Our observations and analysis of fair-weather TMA usage have confirmed previous studies that found that TMA increased airport capacity and improved air traffic management efficiency. We also quantified the degradation, in metrics such as the TAER and excess airborne arrival demand, in TMA benefits when convective weather is present. Field observations of TMA usage demonstrated that the lack of weather decision support in TMA made it difficult for traffic managers to make proactive, efficient metering decisions to utilize of available airspace capacity when convective weather was present.

Results from this exploratory study revealed several options for weather – TMA decision support integration and improved traffic metering decision-making:

- CIWS Precipitation, Echo Tops depictions and 0-2 hour forecasts, Storm Motion Vectors, Growth and Decay Trends, and Lightning products available on TMA PGUI display
- CIWS-derived forecasts of Convective WAF, defined in terms of probabilities of pilot deviations, available on the TMA PGUI display
- Individual flight and flow-specific weather impact forecasts, derived from CIWS forecasts and WAFs, available on the TMA TGUI display
- Runway and meter fix impact forecast timelines, derived from CIWS forecasts, available on the TMA load graph displays

Investigations of the potential operational benefits of these proposed WX-TMA decision support capabilities suggest that the cognitive workload associated with integrating information would be significantly reduced. This in turn would increase the opportunities for proactive TMA decision-making and increased efficiency of the metering operation. Overall, WX-TMA displays would improve situational awareness of potential weather impacts, improve coordination and planning for these potential impacts, and increase traffic manager and controller productivity.

The proposed WX-TMA decision support guidance is anticipated to improved the execution of TMA scheduling initiatives when convective weather impacts meter points or affects metered flows, requiring action in TMA to mitigate slot misallocation or to manage off-nominal meter delay assignments. Flight and flow impact forecasts on the TMA TGUI and load graph displays would support more proactive and better-timed scheduling initiatives. In turn, this would allow manageable metering conditions to persist (thus avoiding TMA suspension) and would optimize capacity and decrease avoidable delay at times when air traffic capacity constraints can be most significant.

Though much of the weather impact forecast guidance recommended for WX-TMA integration is based upon CIWS product usage plus the route blockage algorithms successfully implemented for the RAPT, additional research and development would be required to adapt these previous approaches for TBFM applications. Specifically, for TBFM operations during convective weather, it is not enough to know the likelihood of pilot deviations for WAFs from which route, flow, and fix impacts are defined: it is also important to know the anticipated weather-avoiding trajectory (and subsequent change in flight time to meter threshold) for aircraft predicted to deviate to avoid convection. Actual deviations represent some combination of pilot desire plus ATC actions to accommodate pilot needs (e.g., if a pilot requests a deviation, an air traffic controller will suggest where that pilot should deviate). More research is needed to model the dominant factors that contribute to minor versus significant deviation distances (beyond just the explicit weather characteristics).

Effort is also required to extend the largely, en route, level-flight convective weather avoidance research to account for weather impacts – and the model for weather blockage – for climbing and descending trajectories and for impacts within terminal airspace and at TRACON meter fixes. Coupling this research with investigations using high-resolution trajectory models will support the development of TMA flow and flight-specific weather impact forecasts that would be displayed on TGUI and load graph displays.

GLOSSARY

ACM	Adjacent Center Metering
AOP	Aircraft Operations Planner
ARTCC	Air Route Traffic Control Center
ASPM	Aviation System Performance Metrics
ATC	Air Traffic Control
ATM	Air Traffic Management
BOS	Boston Logan International Airport
C&V	Ceiling and Visibility
CIWS	Corridor Integrated Weather System
CLT	Charlotte Douglas International Airport
CWAM	Convective Weather Avoidance Model
DFW	Dallas/Fort Worth International Airport
DSR	Display System Replacement
DTW	Detroit Metropolitan Wayne County Airport
EDC	En Route Departure Capability
ERIDS	En Route Information Display System
ETA	Estimated Time of Arrival
ETMS	Enhanced Traffic Management System
EWR	Newark Liberty International Airport
FH	Freeze horizon
FTFW	Future Traffic – Future Weather
IAH	Houston George Bush Intercontinental Airport
ITWS	Integrated Terminal Weather System
LGA	LaGuardia Airport
LAHSO	Land and hold short operation
MIT	Miles-In-Trail
NAS	National Airspace System
NextGen	Next Generation Air Transportation System
NTML	National Traffic Management Log
OEP	Operational Evolution Partnership
ORD	Chicago O’Hare International Airport
PGUI	Planview Graphical User Interface
PRR	Proactive reroute
RAPT	Route Availability Planning Tool
RO	Routes open longer
RUC	Rapid Update Cycle
SCM	Single Center Metering
SME	Subject matter experts
STA	Scheduled Times of Arrival
STAR	Standard Terminal Arrival Route
SWAP	Severe Weather Avoidance Program
TAER	Terminal Arrival Efficiency Rate
TBFM	Time-based flow metering
TFMS	Traffic Flow Management System

TGUI	Timeline Graphical User Interface
TMA	Traffic Management Advisor
TMC	Traffic management coordinator
TMI	Traffic management initiative
TMU	Traffic Management Unit
TRACON	Terminal Radar Control
TSD	Traffic Situation Display
VIL	Vertically Integrated Liquid
WAF	Weather avoidance field
WARP	Weather and Radar Processor
WX	Weather
ZAU	Chicago ARTCC
ZBW	Boston ARTCC
ZDC	Washington D.C. ARTCC
ZFW	Fort Worth ARTCC
ZID	Indianapolis ARTCC
ZNY	New York ARTCC
ZOB	Cleveland ARTCC
ZTL	Atlanta ARTCC

REFERENCES

Allan, S., R. DeLaura, B. Martin, D. Clark, and C. Gross, 2004: Advanced Terminal Weather Products Demonstration in New York, *11th Conference on Aviation, Range, and Aerospace Meteorology*, AMS, Hyannis, MA.

Ballin, M., V. Sharma, R. Vivona, E. Johnson, and E. Ramiscal, 2002: A Flight Deck Decision Support Tool for Autonomous Airborne Operations, *American Institute of Aeronautics and Astronautics*, AIAA-2002-4554.

Cole, R. and F. Wilson, 1994: The Integrated Terminal Weather System Terminal Winds Product, *MIT Lincoln Laboratory Journal*, Volume 7, Number 2.

Crowe, B., R. DeLaura, and M. Matthews, 2010: Use of Aircraft-Based Data to Evaluate Factors in Pilot Decision Making in En Route Airspace, *14th Conference on Aviation, Range, and Aerospace Meteorology*, AMS, Atlanta, GA.

Davison Reynolds, H., 2006: Modeling the Air Traffic Controller's Cognitive Projection Process, MIT International Center for Air Transportation Technical Report, MIT ICAT 2006-1.

DeLaura, R., M. Robinson, R. Todd, and K. MacKenzie, 2008: Evaluation of Weather Impact Models in Departure Management Decision Support: Operational Performance of the Route Availability Planning Tool (RAPT) Prototype, *13th Conference on Aviation, Range, and Aerospace Meteorology*, AMS, New Orleans, LA.

DeLaura, R. and J. Evans, 2006: An Exploratory Study of Modeling Enroute Pilot Convective Storm Flight Deviation Behavior, *12th Conference on Aviation, Range, and Aerospace Meteorology*, AMS, Atlanta, GA.

Evans, J. and E. Ducot, 2006: Corridor Integrated Weather System, *MIT Lincoln Laboratory Journal*, Volume 16, Number 1.

Evans. J and E. Ducot, 1994: The Integrated Terminal Weather System (ITWS), *MIT Lincoln Laboratory Journal*, Volume 7, Number 2.

FAA, 2009: Traffic Flow Management in the National Airspace System, http://www.fly.faa.gov/Products/Training/Traffic_Management_for_Pilots/TFM_in_the_NAS_Booklet_ca10.pdf.

Robinson, M. and R. DeLaura, 2010: Observed Benefits of the New York Route Availability Planning Tool (RAPT) during the 2009 Convective Weather Season, Project Report, ATC-368, MIT Lincoln Laboratory, Lexington, MA.

Robinson, M., R. DeLaura, and N. Underhill, 2009: The Route Availability Planning Tool (RAPT): Evaluation of Departure Management Decision Support during the 2008 Convective Weather Season, 8th USA/Europe ATM 2009 R&D Seminar, Napa, CA.

Robinson, M., J. Evans, and T. Hancock, 2006: Assessment of Air Traffic Control Productivity Enhancements from the Corridor Integrated Weather System (CIWS), Project Report ATC-325, MIT Lincoln Laboratory, Lexington, MA.

Stobie, J. and R. Gillen, 2008: Integrating Convective Weather Forecasts With the Traffic Management Advisor (TMA), *13th Conference on Aviation, Range, and Aerospace Meteorology*, AMS, New Orleans, LA.

Taber, N., L. Klinker, G. Jacobs, 2007: A Tool for Visualizing Future Traffic Flow Complexity, *26th Digital Avionics Systems Conference*, Dallas, TX.

Volpe, 2008: Post Implementation Review and Benefits Analysis of Traffic Management Advisor / Adjacent Center Metering, EWR Airport Arrivals, Revision A1. Produced for FAA.