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Multi-Center Traffic Management Advisor: Operational Test Results

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Time-based metering is an efficient air traffic management alternative to the more common practice of distance-based metering (or "miles-in-trail spacing"). The efficiency benefit is most pronounced where air traffic flows merge, such as in terminal airspace, at en-route choke points, overhead merge points, or where severe-weather avoidance routes converge—the primary bottlenecks in today's system. To date, the practice of time-based metering in the United States has been confined to arrival airspace, and only in less-constrained regions, such as the West and South, in part due to limitations in the national airspace system infrastructure. Thus, time-based metering has not been available to redress the most critical bottlenecks in the national airspace system and, coincidently, those where time-based metering would be most advantageous.

This paper discusses a prototype time-based metering system designed to overcome limitations of the national airspace system to produce a more versatile and scalable time-based metering capability. Results of a live, operational field test are presented which validate that the prototype—the Multi-center Traffic Management Advisor—can extend time-based metering operations beyond the terminal area to improve traffic flow at critical bottlenecks en route and on departure. In the field test, which focused specifically on Philadelphia-bound traffic in four Air Route Traffic Control Centers, airborne delay and airborne holding were significantly less when Multi-center Traffic Management Advisor was in use relative to control periods. The results demonstrate that the Multi-center Traffic Management Advisor is effective in coordinating time-based metering programs among adjacent air traffic control facilities, even in the complex Northeast corridor of the United States. This is a necessary step toward addressing the most critical air traffic bottlenecks in the national airspace system. Potential for nationwide time-based metering and its implications for the next-generation air transportation system also are discussed.

I. Introduction

TIME-BASED METERING (referred to herein simply as "metering") is an efficient alternative to the more common practice of distance-based or "miles-in-trail" spacing.[1] Time-based metering moderates the use of a resource (e.g., airspace, a runway, a navigational fix) among competing aircraft by assigning each inbound aircraft a

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unique crossing time, or "slot," which is efficiently sequenced and spaced relative to the other traffic. On the other hand, miles-in-trail spacing stems demand by enforcing a predetermined minimum in-trail spacing restriction between successive aircraft on an airway. Whereas miles-in-trail spacing restrictions are fixed based on historical traffic demand patterns or ad-hoc projections, time-based metering allocates slots dynamically in proportion to the current demand profile.[1,2] The result is typically improved utilization of available capacity, reduced delay, improved predictability, and moderated controller workload.[3-6] When Los Angeles Center converted from miles-in-trail spacing to time-based metering in 2002, the Federal Aviation Administration (FAA) measured an 8% increase in arrival rates, a 12% reduction in airborne holding, and a 23% reduction in delay.[5] Comparable results have been measured at other sites.[5] The operational advantages of time-based metering have prompted the FAA to install time-based metering automation in all twenty Air Route Traffic Control Centers (ARTCCs, or "Centers") by September 2007.

While this significant step towards modernization is expected to bring relief to congested arrival operations at a number of additional airports, the current state of the art in time-based metering automation is not designed to handle the complexities of our most congested regions, such as the Northeast corridor, nor is it capable of metering for congestion en route.[7] Recognizing these limitations, the FAA and NASA initiated a collaborative research effort in 2000 to design, develop, and demonstrate the next-generation metering system. If successful, the prototype technology would be transferred to the FAA for deployment to the National Airspace System (NAS).[8] Teaming with the MITRE Center for Advanced Aviation Systems Development (CAASD) and the Computer Sciences Corporation (CSC), the research team developed a prototype system using a new, distributed systems approach to provide time-based metering services to complex and en-route airspace.[9]

The prototype system is called the Multi-center Traffic Management Advisor (McTMA), and it bears much in common with its ancestor, the FAA's current metering system, single-center TMA. Like its predecessor, McTMA is a decision-support tool designed to help traffic management personnel develop and execute time-based metering initiatives in order to efficiently manage potential overcapacity situations. Multi-center TMA is built upon a hardware and software baseline in common with single-center TMA, uses the same data sources and interfaces, and users interact with the same devices and displays. The primary display is illustrated in Figure 1.

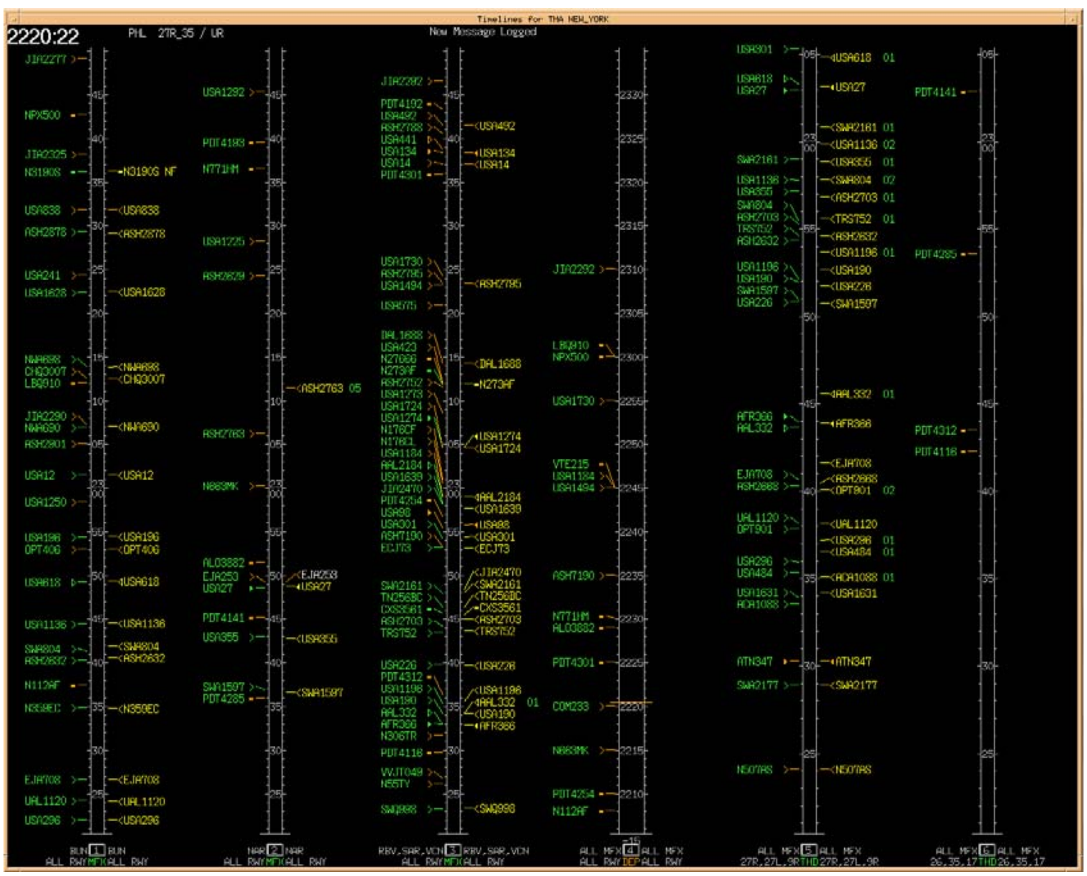

Figure 1. This Multi-center TMA timeline display is adapted for the arrival fixes and runways at PHL; the layout, format, and input devices are identical to existing NAS time-based metering displays.

For all its similarities to the operational system, the Multi-center TMA design is considerably more versatile and more capable, owing to the replacement of single-center TMA's centralized architecture with a new distributed architecture. The distributed architecture enables the TMA at one Center to exchange data with the TMA at one or more adjacent Centers, as illustrated in Figure 2.[9] In so doing, the collective Multi-center TMA system—utilizing an innovative "distributed scheduling" algorithm—is designed to develop flexible, *collaborative* metering plans that respect the constraints in place throughout the region, producing a coordinated, efficient, and workable multi-facility metering operation for complex airspace such as the Northeast corridor.[7, 10-11] Idris, Evans, and Evans identify specific mechanisms by which McTMA's distributed architecture is expected to reduce delay, reduce fuel burn, increase throughput, and improve inter-facility collaboration.[12] Furthermore, McTMA's distributed architecture makes it more versatile than its predecessor, enabling it to meter en-route traffic through choke points, departure traffic for the overhead merge, and/or deviating traffic where Severe Weather Avoidance Plan (SWAP) routes converge.[13] The modular, distributed architecture provides the infrastructural basis to now consider operational concepts for nationwide, coast-to-coast time-based metering in the near future, reducing or eliminating our reliance on static miles-in-trail restrictions and bringing the "TMA effect" to operations anywhere in the NAS.[13]

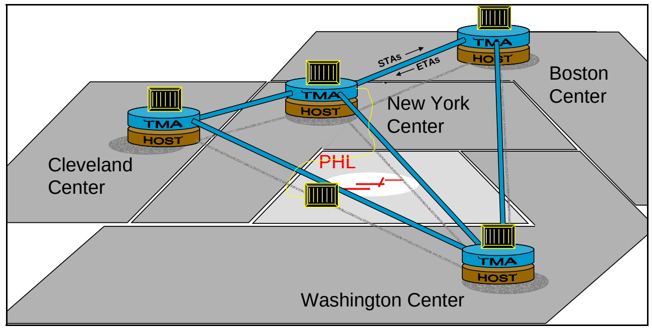

Figure 2. Multi-center TMA's distributed architecture enables adjacent TMAs to share Host data and metering data across a wide-area network. This enables metering programs to be coordinated and optimized across one or many facility boundaries.

Building on the results of prior evaluations[14], this paper discusses the conduct and results of the operational field test and demonstration of the Multi-center Traffic Management Advisor. Section II presents a brief technical primer on the key elements of McTMA distributed architecture. Section III introduces this field trial activity in the larger context of the overall two-year McTMA field test program. Section IV identifies the objectives and describes the procedure. Section V presents the results. Section VI discusses the significance of the results and avenues of future work. We close with our conclusions and a perspective on the role of time-based metering and TMA in the Next-Generation Air Transportation System.

II. McTMA Distributed Architecture: three key innovations

At the heart of the McTMA research are three key innovations: point-in-space metering, distributed scheduling, and TMAnet. These innovations differentiate McTMA as a modular, scalable architecture, as opposed to an enlarged TMA. They are described briefly here, as background for later discussion.

Point-in-space metering is the capability to apply time-based metering at any predefined fix, boundary, or gate. For traffic managers, point-in-space metering means that they can call up a TMA timeline for said fix or boundary, apply a crossing restriction in the form of an acceptance rate or a miles-in-trail restriction, and initiate time-based metering for traffic inbound to that point or boundary. Previously, this could only be done for arrival fixes or runway ends; point-in-space metering makes it possible for any point or gate in the NAS, irrespective of phase of flight. An important byproduct of point-in-space metering is that it delivers a "rolling freeze" capability. By placing meter points in series along a route upstream of congestion, an aircraft's slot at its upstream-most meter point can be locked in ("frozen") while it's provisional slot at downstream meter points is allowed to drift. As the aircraft passes each meter point, its slot at the next one is frozen. This continues in "rolling" fashion until the final meter point is reached. Although this mechanism sacrifices some optimality in the final metering solution, it produces a more workable, robust solution. It enables the overall metering system to shed residual scheduling error by "grounding" the schedule at each meter point like grounding an electric circuit sheds residual charge. The result is a far more robust sequencing method, which reduces controller workload and improves schedule compliance. The rolling freeze is critical to the notion of regional or coast-to-coast metering. The rolling freeze is discussed in more depth by Landry.[10,11]

Point-in-space metering (and the rolling freeze) is necessary but not sufficient for metering across complex and/or regional airspace; ***distributed scheduling*** also is required. Distributed scheduling is the protocol by which adjacent (arrival, departure, and/or en-route) metering programs are integrated to form a continuous, dynamic, time-based metering network. The distinction is that, by itself, point-in-space metering is blind to the evolving traffic situation downstream of the meter point. In that sense, it suffers from the same shortcoming as a miles-in-trail restriction. Armed only with point-in-space metering, traffic managers are forced to meter to a somewhat arbitrary static restriction. Distributed scheduling provides a dynamic "look-ahead" capability and a provisional slot-reservation system to continuously monitor and communicate back upstream the evolving demand/capacity situation at the point of congestion. As a result, competing traffic flows in disparate specialties, facilities, or regions of the country can be intelligently sequenced and spaced for their ultimate downstream merge. Distributed scheduling is the key to reducing dependence on miles-in-trail restrictions. Distributed scheduling is discussed in more depth by Landry.[10,11]

TMAnet is the data communications network for McTMA. Each Center's TMA system shares aircraft data and scheduling data with neighboring TMA systems via TMAnet. The network utilizes commercial, off-the-shelf data networking equipment (e.g., T1 lines and routers) and standard communications protocols (e.g., publish–subscribe) to enable TMA systems to exchange the information that makes collaborative metering possible. New TMA nodes are readily added or removed from the network by adding/removing their publication and subscription permissions.

All three of the McTMA innovations are critical to advancing the operational use of time-based metering beyond the present-day practice of arrival metering on a 200 nautical mile horizon.

III. Field Test Program Overview

The McTMA field test program consisted of twenty-eight separate events, or "field trials." These field trials were conducted between January 2003 and November 2004 to evaluate system performance and refine the operational concept as the prototype matured. The primary objective of the field test program was to satisfy the transition criteria for FAA/NASA Technology Readiness Level (TRL) 6, effectively establishing the technical case, the operational case, and the business case for transfer of the technology from NASA to the FAA for deployment.

On recommendation of the RTCA, Philadelphia International Airport (PHL), a busy Northeast corridor hub, was chosen as the focus airport for research, development, and demonstration of Multi-center TMA. The primary air traffic control (ATC) facilities surrounding Philadelphia and involved in the PHL arrival process—Boston Center (ZBW), Cleveland Center (ZOB), New York Center (ZNY), Washington Center (ZDC)—were selected as Multi-center TMA sites, and each was equipped with a McTMA prototype system. Repeater displays were installed at the Philadelphia Terminal Radar Approach Control (PHL TRACON) and the ATC System Command Center ("Command Center") to foster shared situation awareness and facilitate collaboration at the local and regional levels, respectively.

The approach capitalized on the partnership established for this program between FAA, NASA, MITRE CAASD, and CSC. NASA and CAASD personnel comprised the research team (which led the field activities), with members assigned to each McTMA facility. FAA Air Traffic personnel were involved as members of the McTMA System Design Team (the "cadre"). These subject matter experts were involved at every step of the field test program. They provided observations and feedback concerning functional requirements, system operation, training, and procedures. The cadre included management and union Traffic Management Coordinators (TMCs) as well as sector controllers. Human factors specialists observed operations and queried the users to assess system usability, suitability and acceptability. CSC provided system-support personnel on site during each field trial activity.

The size and complexity of the distributed McTMA system—not to mention the logistical complexity of a system having assets and operators in six facilities and five states—necessitated a deliberate, incremental approach to field testing. The approach involved a two-year series of field activities, advancing in stages. The program began with **system installation and checkout.** An extensive set of system checkout activities was performed to verify the local installation at each facility, as well as the TMA-to-TMA networking infrastructure between facilities. System installation and checkout was followed by **familiarization and development**. This began with informal classroom instruction for the cadre, then advanced to **back-room shadowing**, where system assessments began to take place. The "back room" was an area in each facility, away from the operational areas, where cadre personnel and research team members could operate the prototype in a one-way mode. This meant there was no output to the NAS, and live data was used without affecting air traffic operations directly (e.g., without altering Host computer data) or indirectly (e.g., without distracting an on-duty controller). Familiarization also included trips to existing TMA Centers (Houston, Los Angeles, or Miami) and simulation exercises in the ATC laboratory at the NASA Ames Research Center. As the system and operational concept matured, evaluations transitioned from back-room shadowing to **shadowing in the Traffic Management Unit (TMU)**. In the TMU, McTMA outputs could be cross-checked against other systems, and procedures for intra-facility local metering as well as inter-facility collaborative metering could be refined in the context of live operations. Once all of these activities had demonstrated full compliance with the FAA "quality gate" standards, then the field test program culminated with **operational**

demonstrations, the focus of the remainder of this paper. Table 1 provides a summary list of all field trial activities conducted as part of the overall McTMA field test program.

Table 1. McTMA field trials

#	2003-2004	Boston Center	Cleveland Center	NY Center	Wash. Center	Philly Tracon	ATC SCC	Notes
1	Jan. 6-10		⊙	⊙				
2	Jan. 13-17		⊙	⊙				
3	Jan. 27-31	⊙			⊙			
4	Feb. 3-7	⊙			⊙			
5	Mar. 3-7	⊙	⊙	⊙	⊙			
6	Mar. 10-14	⊙	⊙	⊙	⊙	⊙		
7	May 12-16	⊙	⊙	⊙	⊙	⊙	⊙	
8	May 19-22	⊙	⊙	⊙	⊙	⊙	⊙	
9	Jan. 6-9	⊙	◉	⊙	⊙	⊙	⊙	
10	Jan. 27						⊙	
11	Feb. 4				⊙		⊙	
12	Feb. 10				⊙		⊙	
13	Feb. 12			⊙				
14	Feb. 24-26	✓	✓	✓	✓	✓	✓	Trip to ZHU/ZMA
15	Mar. 2-4	⊙	◉	⊙	⊙	⊙	⊙	
16	Mar. 22	⊙	◉	⊙	⊙	⊙	⊙	
17	Mar. 30	⊙	◉	⊙	⊙	⊙	⊙	
18	Apr. 7		◉					
19	Apr. 20-22	✓	✓	✓	✓	✓	✓	HITL sim @ Ames
20	May 20			⊙		⊙	⊙	
21	June 9	⊙	◉	⊙	⊙	⊙	⊙	
22	June 16-18	◉	◉	◉	◉	⊙	⊙	
23	June 21-23	◉	◉	◉	◉	⊙	⊙	
24	July 15	◉	◉	◉	◉	⊙	⊙	
25	Sep. 15	◉	◉	◉	◉	⊙	⊙	
26	Oct. 5-8	◉	◉	◉	◉	⊙	⊙	
27	Nov. 15-16	◉	◉	◉	◉	⊙	⊙	
28	Nov. 17-18	●	●	●	●	⊙	⊙	Operational trials
⊙ back-room shadowing		◉ TMU shadowing			● operational evaluation		✓ other	
ZHU: Houston Center		ZMA: Miami Center			HITL sim: Human-in-the-loop simulation			

IV. Operational Field Trials

The field test program for the Multi-center Traffic Management Advisor culminated with an operational demonstration and evaluation of collaborative, multi-center operation of McTMA in the traffic management units. The objectives of the operational field trials were:

(1) *technical*: to demonstrate McTMA's ability to extend the metering horizon across facility boundaries and well beyond the traditional (<200 nm) metering range;

(2) *operational*: to demonstrate collaborative, inter-facility metering operations in the TMU; and

(3) *business*: to validate benefit mechanisms and outcomes hypothesized by Idris, Evans, and Evans.[12]

In the process, accomplishing the objectives above would serve to validate the McTMA distributed architecture as a scalable platform to support future evaluations of time-based metering operations on a regional or national scale.

A. Approach

Three approaches were considered for the operational evaluation of McTMA: (1) a multi-center airborne metering demonstration, where sector radar controllers in the four McTMA Centers would issue vectors to real aircraft on arrival to PHL to comply with McTMA metering advisories; (2) a multi-center airborne metering simulation, where sector controllers in the four McTMA Centers would issue vectors to simulated aircraft on arrival to PHL to comply with McTMA metering advisories in a simulation activity at the FAA William J. Hughes Technical Center; and (3) a multi-center departure metering demonstration with no sector controllers involved, where TMCs at the four McTMA Centers would issue wheels-up departure clearances to real aircraft departing for PHL from their internal airports in compliance with McTMA departure metering advisories.

Since all three approaches would probe the necessary McTMA functions (i.e., point-in-space metering, distributed scheduling, and TMAnet) in exactly the same way, we elected to adopt the most conservative approach: the departure metering evaluation (option 3). Departure metering operations required the participation of approximately one-fourth as many FAA operations personnel, dramatically reducing the logistical risk associated with the activity. Furthermore, because departure metering permits aircraft to proceed open-loop (with respect to TMA) while airborne, this approach was expected to produce more conservative significance measures than airborne metering operations or simulations. In the final analysis, the departure-metering approach produced a successful demonstration and important, statistically significant results, as discussed in Section V.

B. Procedure

A two-day, on-site, multi-facility, collaborative operational demonstration and evaluation of McTMA was conducted. For an eight-hour period on each of two consecutive days, cadre TMCs used McTMA departure-time advisories to release their internal departures bound for Philadelphia. There was no metering of airborne aircraft. The following paragraphs detail the experimental procedure.

1. Locations

The evaluation was conducted at FAA air traffic control facilities throughout the Northeast corridor. Participating facilities included: Boston Center, Cleveland Center, New York Center, Washington Center, Philadelphia TRACON, and the Command Center. ARTCC cadre personnel operated McTMA from their respective TMUs, while the PHL and Command Center cadres used McTMA from their respective back rooms, since the test procedure did not require them to be on their operational floor.

2. Participants

The demonstration/evaluation team was composed of individuals from NASA, FAA, MITRE CAASD, and CSC. Participants included management and union representatives from the traffic management units at Boston, Cleveland, New York, and Washington Centers, Philadelphia TRACON, and the Command Center. Subject matter experts from single-center TMA sites were on hand at each ARTCC and at PHL to share their expertise and perspectives. One research team member and one on-site support staff member (CSC) were on hand at each ARTCC and at PHL to conduct the field trial activities; one research team member and no on-site support staff were on hand at the Command Center. CSC engineers monitored the activity from the McTMA laboratory in Egg Harbor, New Jersey. Representatives of the FAA Program Office also witnessed the field trial activities at various locations.

3. Schedule

The field trial procedure called for collaborative use of the McTMA system for departure metering to PHL during the following periods:

- November 17, 2004: 0600–1400 EST
- November 18, 2004: 0600–1400 EST

These test periods were chosen to encompass the morning rush (9am), the noon rush, and most of the 2pm rush. Although the test periods ended at 2pm (in the middle of the 2pm rush), most of the departures arriving PHL during the 2pm rush departed prior to the 2pm conclusion of the test period. Therefore, most of the aircraft of interest were departed based on a McTMA advisory, even though they landed after the test period had concluded.

The exact time periods during which McTMA was used to control departure times were from 0615 to 0830 and from 1015 to 1345 (all EST) on both days. Note that, since McTMA was only being used to control wheels-up times, only flights that *departed* during the time periods above were controlled by McTMA. So, when assessing PHL *arrival* metrics, the relevant arrival time periods lag the test periods: 0730–0930 and 1130–1445.

4. NAS conditions

Conditions remained favorable at PHL and across the Northeast throughout the day on both the 17th and 18th. At PHL, light winds prevailed, generally from the west. Visual flight rules were in effect all day, each day. PHL was configured in its highest-capacity runway configuration for the duration of the two-day demonstration. The runway configuration remained unchanged: arrivals on runways 26, 27R, and 35; departures on runways 27L and 35. No ground-delay programs or ground-stop initiatives were imposed on PHL arrivals, and all air routes inbound to PHL across the four Centers remained open.

5. *Affected aircraft population*

Over the two days, a total of 136 flights from 22 airports across the four Centers were departed on the basis of a McTMA departure advisory. Departure airports not under jurisdiction of the McTMA facilities were not eligible for McTMA departure metering (e.g., flights from the west coast were not subject to departure metering). Similarly, all flights originating from New York TRACON (N90) or Potomac TRACON (PCT) were exempt from McTMA departure metering, because those facilities handle departures to PHL internally.

6. *Test procedure*

The procedure for each Center was the same. At the start of the test period, each cadre TMC configured his local McTMA system to reflect the restrictions in force in the NAS. For example, the Cleveland Center TMC entered into McTMA the miles-in-trail restriction that New York Center had passed back to Cleveland at their boundary. This enabled McTMA to account for the constraint when computing its advisories. Each TMU then put its internal airports on notice to call for release ("approval request," or APREQ) of any departing flight to Philadelphia. Note that "call-for-release" operations for Philadelphia-bound departures are standard procedure in Boston Center and Cleveland Center during arrival rush periods. New York Center and Washington Center do not usually control their internal departures to PHL; those flights are permitted to depart when ready.

During the test, when an eligible flight was ready to depart for PHL, the control tower would call the TMU and provide the "ready time" for the flight—the estimated time at which the flight would be ready for takeoff (usually two to four minutes from the time of the call). The cadre TMC would enter the requested ready time into McTMA. McTMA would return an advised departure (wheels-up) time that factored in the projected capacity at the merge point and all downstream metering points up to and including the runway threshold. The algorithm behind this advisory is covered by Landry.[10-11] If one or more meter points was projected to be over capacity at the time that the departing flight was projected to reach it, then the advised departure time would include enough ground delay such that the approved departure time was not expected to result in an overcapacity situation downstream. The TMC was free to override the McTMA advisory and issue a different release time. In either case, the release time was relayed back to the pilot via the control tower, and the flight departed as closely to the approved time as possible. Researchers kept a "TMA APREQ Log" to capture the ready time, the McTMA-advised time, the approved departure-release time, and the actual time of departure.

V. Results

Results of the evaluation are based on data from the TMA APREQ logs from each facility (see above), data from the FAA's Aviation System Performance Metrics (ASPM) database, and the observations of the research team. Quantitative metrics include counts of airborne holding circuits, 15-minute averages of airborne delay and arrival delay, and occurrence counts of ground delays. Subjective metrics include the length of the final approach segment, amount of vectoring inside the TRACON, perceived changes in restrictions, and human factors observations.

The evaluation showed significantly better performance in operations when McTMA was in use. During several periods at PHL when airborne holding is routinely encountered, no such holding was observed when McTMA was in use. Compared with appropriate control periods, airborne delay was significantly less with no apparent penalty in gate arrival delay. Traffic inside the TRACON appeared better organized, with less vectoring and shorter final approach segments. One in-trail restriction appeared to have been reduced versus normal, and subjective feedback from the cadre was favorable. The demonstration validated the three key McTMA innovations which enable time-based metering to be applied more generally to departures, arrivals, and en route traffic within and beyond the Northeast corridor. The sections that follow present the data collected during the two-day field trial period.

A. Evaluation periods and control periods

In order to draw comparisons of NAS performance with and without McTMA, we define a set of evaluation periods and control periods. McTMA was actively in use for departure metering between the hours of 0600 and 1400 EST. We will refer to this as the "demonstration period." Allowing for flight time en route, those flights which departed near the end of the demonstration period (i.e., near 1400) did not land at PHL until sometime prior to 1500. Therefore, we will refer to the period from 0600 to 1500 as the "evaluation period."

An analysis of Philadelphia operations data from ASPM archives identified six control periods having very similar weather and arrival demand characteristics to the two evaluation periods. The weather and the arrival demand at PHL were very comparable between the morning evaluation period and the evening control period on the two field trial days. In addition, nearly identical conditions prevailed on Wednesday and Thursday of the week prior. Each of the eight resulting nine-hour comparison periods (two evaluation periods and six control periods) experienced a total operational demand—arrivals plus departures—of 742 ± 10 aircraft. Analysis of 15-minute operation counts showed very similar demand patterns on the four days, with slightly smaller demand in the evening periods than in the daytime periods on all days except November 10th. The runway configuration was identical throughout all eight comparison periods. We summarize the periods for comparison in Figure 3. These control and evaluation periods are referred to in the results sections that follow. Throughout, results from the control periods are annotated with orange markings, and results from the evaluation period are annotated with blue markings.

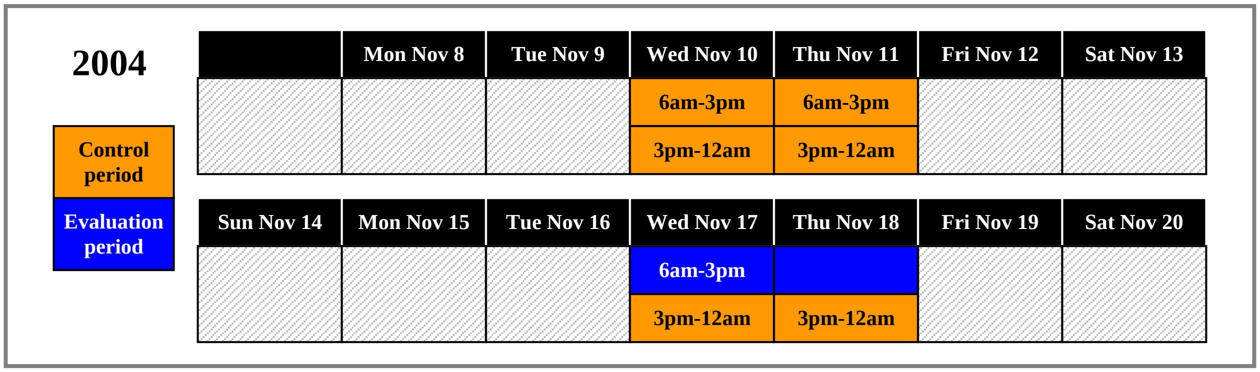

Figure 3. Results from the two operational-evaluation periods (blue) are compared against operational data from six control periods (orange).

B. Reduced delay

We performed an analysis of Philadelphia data using ASPM archives of airport throughput and delay. Figure 4 compares ASPM average airborne delay data for the two nine-hour McTMA evaluation periods and the six control periods. Airborne delay is defined as the difference between an aircraft's actual time in the air and the estimated time of flight reported in its flight plan at takeoff. One of the principal goals of the McTMA time-based metering tool is to reduce airborne delay.

The results indicate significantly reduced average airborne delay (relative to all control periods) during the McTMA evaluation periods. Airborne delay averages during the two McTMA evaluation periods were 5.90 and 6.51 minutes per aircraft, respectively. Airborne delay averages in the control periods ranged from 7.34 to 11.31 minutes per aircraft.

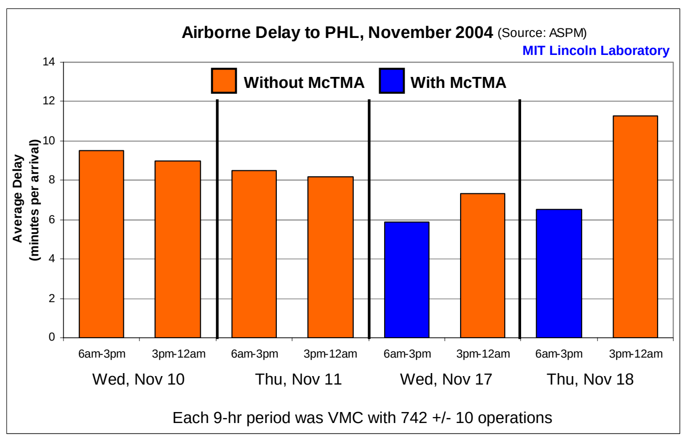

Figure 4. Airborne delay was significantly lower when McTMA was in use.

While a reduction in airborne delay is a positive result, it comes at the expense of increased ground delay on departure in compliance with McTMA departure metering. Aircraft operators would be quick to question whether the benefit of reduced delay en route is not exceeded by the penalty in delay on departure. The ASPM gate arrival delay metric addresses this question. Unlike airborne delay, gate arrival delay includes departure and arrival taxi delay components. ASPM reports two gate arrival delay metrics, one based on flight plans and the other based on schedules. The flight-plan based gate arrival delay is similar to airborne delay in that it is reckoned relative to a flight plan estimate. We use the other gate arrival delay metric, which is defined as the difference between the actual gate arrival time and the final gate arrival time published in a schedule for passenger use. Schedule-based gate arrival delay is more meaningful from a passenger viewpoint, and is generally the larger of the two gate arrival delay variants. However, airline schedule padding can make either gate arrival delay metric smaller than airborne delay.

The gate arrival delay results are shown in Figure 5. Gate arrival delay averages during the two McTMA evaluation periods were 5.31 and 7.17 minutes per aircraft, respectively. Average gate arrival delay was larger during the evaluation period on Thursday the 18th than during the corresponding control period on Thursday the 11th, which experienced an average gate arrival delay of 5.68 minutes per aircraft. However, the average gate arrival delay was smaller during the evaluation period on the 17th than during any of the other six control periods. (The five remaining control periods experienced gate arrival delay ranging from 7.96 to 12.86 minutes per aircraft.) The average gate arrival delay of 7.17 minutes per aircraft during the trial period on the 18th was significantly smaller than the 12.86 minutes per aircraft averaged during the afternoon control period of the same day.

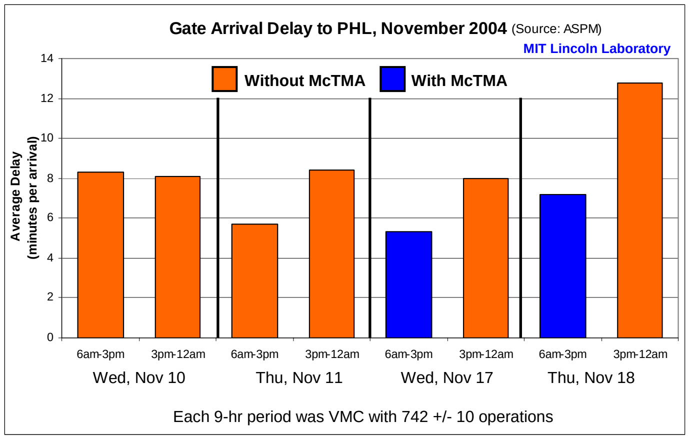

Figure 5. Gate arrival delay was not adversely affected by McTMA departure metering.

The charts above suggest not only that McTMA effectively moved the delay from the air to the ground, but that the additional penalty in ground delay advised by McTMA was compensated for by the reduction in flight time en route. This result suggests that aircraft operators would benefit from reduced fuel costs and increased predictability. There is also a corollary benefit to the public of reduced noise and emissions associated with airborne delay on arrival.

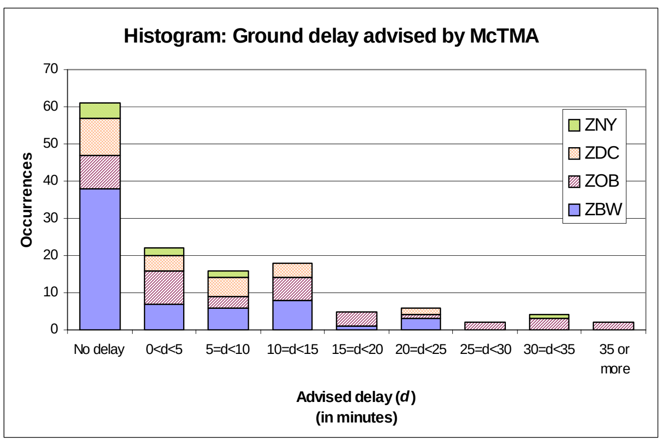

Figure 6. McTMA-advised ground delays: 86% were "not reportable" (<15 min).

Departure delay comparisons between the evaluation period and the control period were not possible due to the unavailability of departure delay data for the control period. However, departure delay data for the evaluation period suggest that any increase in ground delay owed to departure metering is small. Figure 6 is a histogram of the ground delay advised by McTMA. TMCs used McTMA advisories in determining the departure times of 136 flights over the two demonstration periods. Of those, 63 were by Boston Center, 39 by Cleveland Center, 25 by Washington Center, and 9 by New York Center. Note that all 136 departure advisories were for aircraft projected to arrive at PHL during an arrival rush period, where some amount of delay is customary. As shown in the figure, 45% of the flights received no ground delay. Another 16% received a delay of less than 5 minutes. Only 14% of advised ground delays were reportable (15 minutes or more). While this percentage is not insignificant, according to the McTMA cadre subject-matter experts, it is nevertheless comparable to arrival rush periods at Philadelphia without McTMA departure metering.

Six flights received a departure metering delay of 30 minutes or more. Such delays are not uncommon in these facilities for flights expected to arrive at the end of an arrival rush. Furthermore, one cadre TMC observed that "the flights that we're holding for departure metering now are the ones we usually wind up seeing spinning over the arrival fixes at Philly." The data for airborne holding are discussed presently.

C. Reduced airborne holding

Airborne holding is routine during arrival-rush operations at PHL. A primary objective of the McTMA research is to demonstrate how the use of McTMA will reduce facilities' dependence on miles-in-trail restrictions, which are less efficient than time-based metering.

Figure 7 illustrates how the amount of airborne holding at the PHL arrival fixes differed during the McTMA evaluation periods as compared with the control periods from the week prior. The upper chart in Figure 7 compares the evaluation period on Wednesday, November 17 to the applicable control period on Wednesday, November 10; the lower chart in Figure 7 compares the evaluation period on Thursday, November 18 to the applicable control period on Thursday, November 11. The number of airborne holding circuits at the arrival fixes was 90% less during each McTMA departure metering period.

This outcome had corollary benefits upstream and downstream of the arrival fixes. In the tightly packed Northeast corridor, when one facility resorts to airborne holding for an arrival stream, the upstream adjacent facilities typically have little choice but to do the same in their airspace. Such "ripple effects" have considerable impact on the efficiency of the operations in each affected airspace. However, during the McTMA evaluation periods, upstream sectors were able to avoid having to hold aircraft because the downstream sectors rarely resorted to airborne holding, and when they did, it was brief. Downstream, the arrival flows in the TRACON were more orderly, predictable, and efficient, easing workload for controllers and pilots, and expediting the path to touchdown. These are discussed in more detail in the next section.

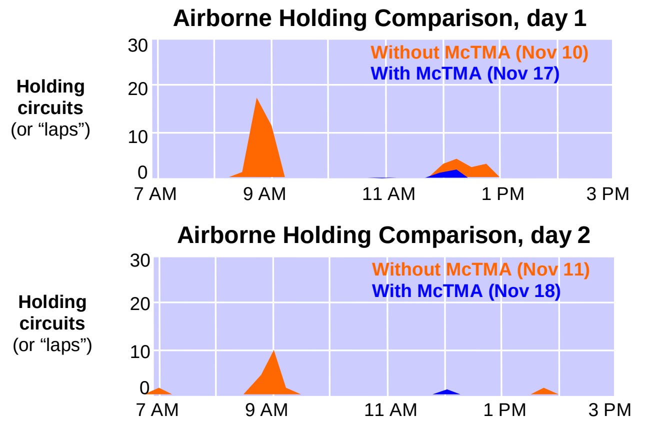

Figure 7. In each evaluation period, airborne holding was reduced during the McTMA evaluation period as compared to the control period one week prior.

D. Reduced vectoring

Figure 8 and Figure 9 illustrate how arrival flows inside the TRACON improved with the use of McTMA. Figure 8 depicts the routes flown by PHL arrivals as of 8:50am EST on November 11, a control period. Observe that there was airborne holding at all of the arrival fixes, and heavy vectoring in the northern part of the TRACON. The final approach segment for runway 27R was extended to the TRACON boundary, 25 miles to the east. Extending the final segment is a common technique used by controllers to help them deal with congestion in the terminal area. It provides extra time and space for them to ensure good sequences and proper separation in the arrival stream.

Compare Figure 8 to Figure 9, which depicts the routes flown by PHL arrivals at the same time of day a week later, during the second McTMA evaluation period. Observe that there was no airborne holding at any of the arrival fixes, and that vectoring in the TRACON was benign. The final approach segment for runway 27R was significantly shorter than in the control period, and the flow was steady and uneventful.

The results demonstrate how a more organized, more predictable, better sequenced flow into the arrival fixes enables TRACON controllers to better manage the terminal area traffic and more fully utilize available runway capacity. By avoiding airborne holding and heavy vectoring, controllers are able to establish better final approach sequences and spacing to maintain the right amount of pressure on the runways.

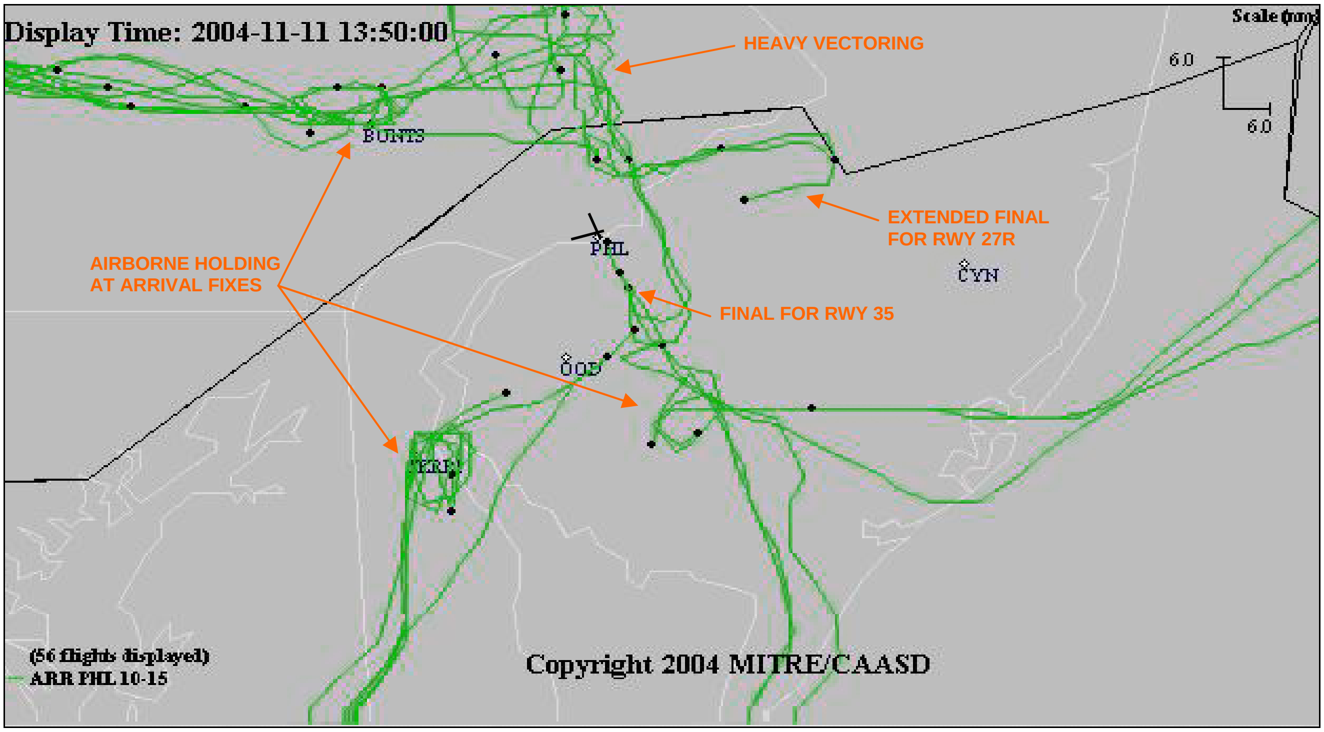

Figure 8. McTMA not in use: airborne holding occurred at all four arrival fixes; there was heavy vectoring in the northern part of the TRACON; and the final approach segment was extended to the TRACON boundary.

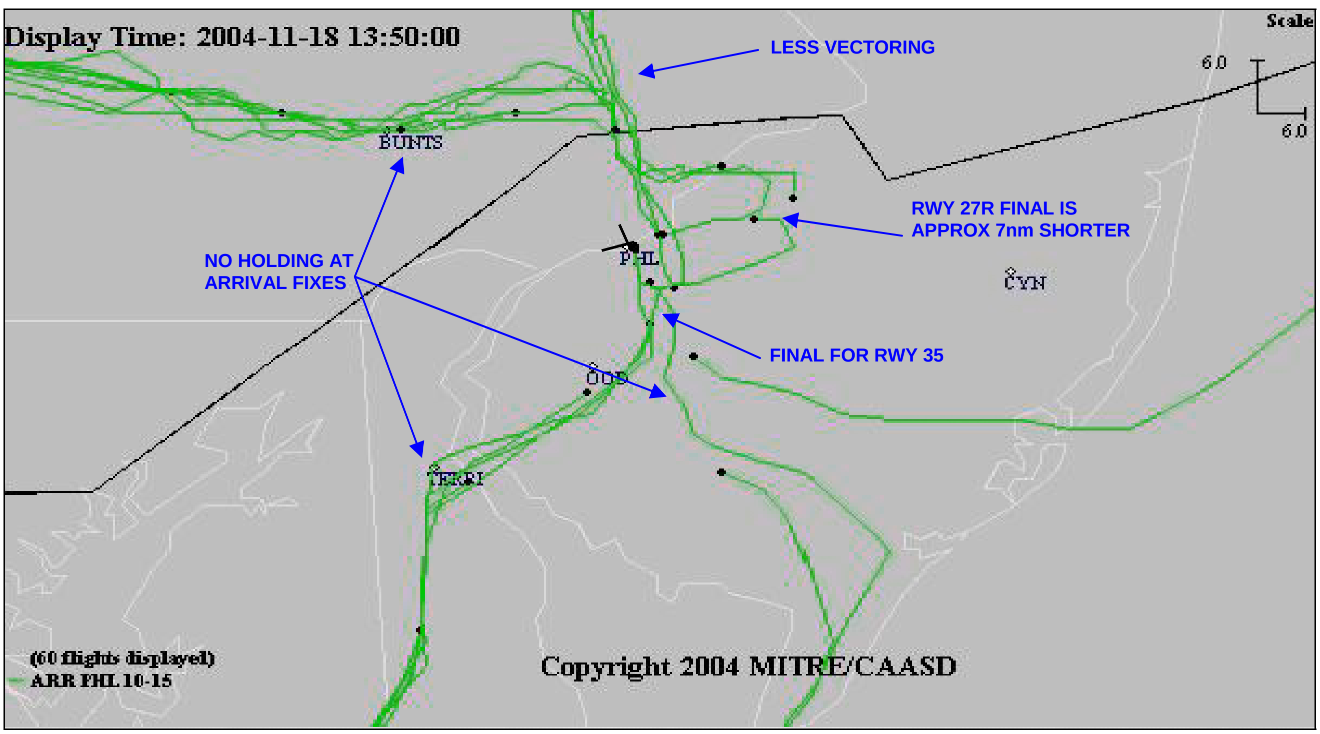

Figure 9. McTMA in use: no airborne holding occurred at any arrival fix; there was only minor vectoring in the TRACON; and the final approach segment was significantly shorter.

E. Shorter final approach segments

As mentioned above, when congestion becomes a factor inside the TRACON, a common first step taken by controllers is to extend the final approach segment. By extending the final approach segment, a controller provides himself a wider margin of time and space in which to make decisions and issue clearances to safely sequence arrival traffic for landing. This time and space comes at the expense of efficiency. Accordingly, the length of the final approach segment is often a good initial indication of arrival flow complexity; the longer the final, the higher the complexity. Delay, fuel burn, frequency congestion, and controller workload increase.

Figure 10 illustrates how the length of the final approach segments was reduced when McTMA was in use. Figure 10 (left) presents a consolidated view of all arrival trajectories landing between 8am and 9am EST on Nov. 11, during one of the control periods when McTMA was not in use; Figure 10 (right) presents data for the same time period one week later, during one of the evaluation periods when McTMA was in use. Note the extent of the final approach segments in each figure. When McTMA was in use, the length of the final was reduced significantly as compared to the period without McTMA.

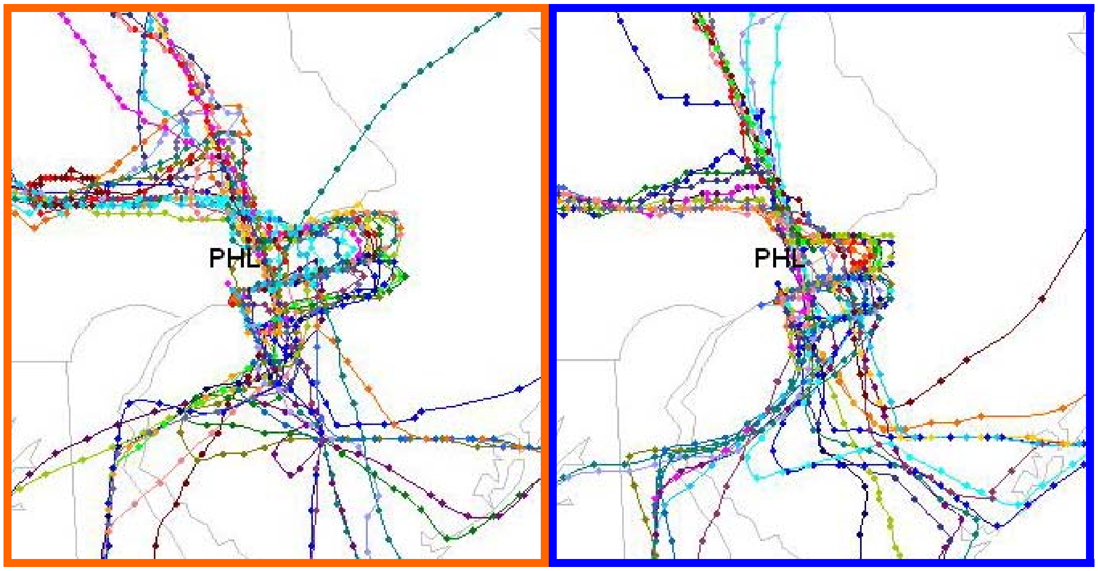

Figure 10. At left, approach control routings when McTMA was not in use (Nov 11, 1300-1400Z). At right, approach control routings when McTMA was in use (Nov 18, 1300-1400Z). Note fewer vectors and shorter final approach segment when McTMA was in use.

F. Reduced restrictions

The field trials produced anecdotal evidence supporting a key hypothesis of the research: that time-based metering operations reduce dependence on miles-in-trail (MIT) restrictions. Historically, PHL tends to issue a common set of MIT restrictions for each runway configuration to its upstream facilities, New York Center (ZNY) and Washington Center (ZDC). In turn, these facilities pass back restrictions to their upstream adjacent Centers.

Typically, ZNY inherits a 10-MIT restriction over the BUNTS arrival fix to PHL (see Figure 11). In order to meet this restriction, ZNY passes back a 20-MIT restriction per stream on the two flows it receives from Cleveland Center (ZOB): the primary flow over COFAX from the west, and the tributary flow from Toronto, Rochester, and Buffalo over Phillipsburg (PSB) from the northwest. These two 20-MIT flows merge together to form a 10-MIT stream crossing BUNTS.

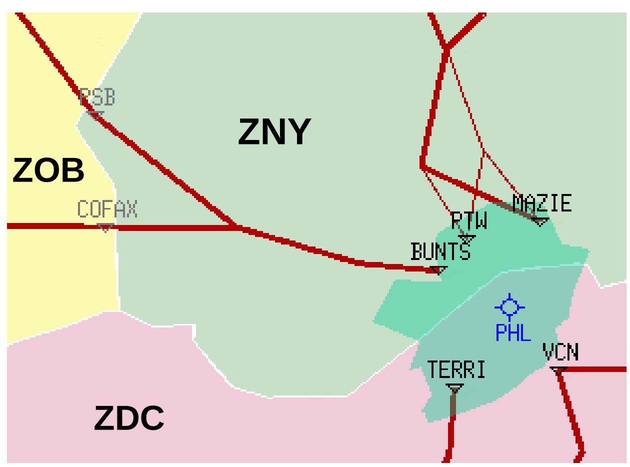

Figure 11. Arrival flows from Cleveland Center (ZOB) merge in New York Center (ZNY) before crossing the BUNTS arrival fix.

Wednesday, November 17 (i.e., the first McTMA evaluation period) began according to the typical scenario. PHL imposed a 10-MIT restriction at BUNTS, and ZNY therefore passed back a 20-MIT restriction on each of the two flows from ZOB. As the arrival rush began to build, the ZNY TMC determined via the McTMA timelines that the restriction was excessive and causing excess delay in Cleveland Center. After coordinating internally with Area A in New York Center (the area that accepts the handoffs from ZOB) and externally with Cleveland Center, the ZNY TMC reduced the restriction to 15 MIT. This was not scripted in the test procedure, nor had it been discussed or suggested at any time prior. It was a dividend of a new level of situation awareness provided by McTMA and a proactive traffic manager.

The decision to reduce the restriction produced no known adverse effects. New York Center managed the incoming flow smoothly, and Cleveland Center naturally viewed the reduced restriction favorably. Departure metering delays were reduced as a result.

VI. Discussion

These results suggest that the McTMA demonstration was successful. McTMA departure metering caused no problems that were apparent in the FAA's ASPM data, the shadowing logs, nor the anecdotal comments of cadre members gathered in the debrief sessions. The McTMA trials coincided with periods of average airborne delay at the Philadelphia airport that were significantly lower than the average airborne delay in each of six non-McTMA control periods that experienced nearly identical weather and demand conditions. This low airborne delay was accompanied by no significant penalty in average gate arrival delay during the McTMA evaluation periods. An independent study of the McTMA evaluation conducted by the FAA has corroborated these results.[15] Airborne holding was reduced 90% as compared to the control period, and traffic flow in the arrival airspace was more predictable, orderly, and efficient during the McTMA evaluation period. Although one cannot conclude that McTMA *caused* the observed improvements in operations, the results are nevertheless encouraging. It is especially noteworthy that such favorable results were observed merely with departure metering and no airborne metering. Airborne metering will close the McTMA control loop and therefore is expected to produce even more significant results.

McTMA's departure advisories were generally more conservative than the clearances that TMCs reported they would have issued without McTMA. That is, McTMA advised as much or more ground delay. This was not unexpected, because the McTMA scheduler considers additional restrictions beyond those with which the TMCs must ordinarily comply. Whereas TMCs usually consider only their internal restrictions, McTMA also considers the effect of the proposed departure on congestion downstream in other facilities and at the runway. The McTMA advisories were generally well-founded, based on the distributed scheduling logic, and the cadre TMCs recognized this when given the opportunity to study a specific departure event. The hypothesis that consideration of these downstream constraints in the form of a modest departure delay will avoid the need for airborne holding downstream and result in more efficient traffic flows to the runway without a penalty in gate arrival delay was corroborated by the observed data.

Based on cadre reports from each facility, workload to operate McTMA at Cleveland Center was relatively high (as compared to the other facilities) due to (a) the lack of Host radar surveillance data from Indianapolis Center (ZID) and (b) aircraft departing for PHL from internal airports not yet adapted in McTMA. ZID is adjacent to the west of ZOB, and during rush periods, it delivers a high-density stream of traffic to ZOB along J-152. Cleveland TMCs need surveillance of the incoming traffic while still in ZID airspace. Only then are they able to identify gaps in the incoming stream early enough to release their internal ZOB departures to hit the gaps. Because the McTMA system was not installed at ZID, McTMA did not have the benefit of surveillance on the incoming flow from ZID. The acceptance rate for McTMA departure advisories was lower at ZOB—and the workload higher—for this reason.

The other contributor to workload at ZOB was the significant number of small airports not eligible for departure metering because they were unknown to McTMA. A small amount of adaptation is required for an origin airport to be eligible for departure metering, and this adaptation was not in place for airports such as Erie (ERI), Grand Rapids (GRR), and Pontiac (PTK). Philadelphia departures from these airports represented unplanned competition for slots that McTMA potentially had already earmarked for metered traffic.

Neither of the above issues are shortcomings of the McTMA algorithms. Rather, they are installation requirements for an operational McTMA system discovered as part of the research. By entering an artificially high MIT restriction into McTMA for the ZOB/ZNY boundary, the cadre found that they could produce enough slack in the McTMA schedule such that ZOB could accommodate the unmetered "pop-up" departures and contend with the limited surveillance of traffic inbound from ZID. This was a useful temporary workaround. However, both a data feed from Indianapolis Center and adaptation of additional internal airports for departure metering would be required before McTMA departure metering could be adopted at Cleveland Center.

In Section F, we introduced anecdotal evidence suggesting the New York TMC's trust in McTMA information resulted in a reduction of two in-trail restrictions on Cleveland Center. However, one example to the contrary was also observed, wherein the PHL cadre did not appear to have enough confidence in the automation to alter their normal ("historically validated") restrictions based solely on McTMA information. In that case, McTMA indicated that the typical PHL arrival-fix restrictions were counter-productive, causing unnecessary delay. When asked whether they would consider removing or adjusting the restrictions, the PHL cadre said they would maintain the historically validated restrictions.

Recall that the PHL cadre was participating from their back room, not from the TMU. The back room did not have up-to-the-minute information about what restrictions were actually in place. In this case, the PHL TMU had, in fact, already removed the restrictions in question. In other words, the McTMA information had been correct—the restrictions weren't necessary. It was a useful (if accidental) test to probe the cadre's trust in McTMA. There is clearly some distance to go in this regard, but it served as a learning opportunity and hopefully helped build the cadre's trust in some small way.

The FAA is not planning to demonstrate airborne metering of PHL arrivals. It is instead making a case to integrate the three key Multi-center TMA innovations into the existing TMA system, producing one unified "best of" TMA tool for use on any traffic stream in the NAS. The FAA recognizes that the case for doing this does not hinge on an airborne metering demonstration to PHL. The operational test covered in this report validates the ability of McTMA to share data across Center boundaries (i.e., TMAnet), to meter to points and boundaries upstream of the TRACON (i.e., point-in-space metering), and to link TMA schedulers together to produce reliable, efficient metering plans across much larger metering horizons (i.e., distributed scheduling). These same capabilities are necessary and sufficient to extend time-based metering operations beyond the terminal area to improve traffic flow at critical bottlenecks on a regional and national scale.

The FAA is currently working toward a September 2007 deadline to have single-center TMA installed in all 20 ARTCCs. That system is expected to incorporate the point-in-space metering capability from McTMA. Distributed scheduling and the TMAnet are tentatively slated for integration thereafter.

VII. Conclusion

Among the first steps in the United States' Joint Planning and Development Office's (JPDO) plans for the Next-Generation Air Transportation System (NGATS) is to develop and deploy a nationwide time-based metering capability.[16] More than simple arrival metering, JPDO plans require a versatile, nationwide, coast-to-coast time-based metering capability, providing an efficient alternative to today's miles-in-trail restrictions and ground stops.

The McTMA research has produced and demonstrated a time-based metering tool more versatile and capable than any before it. It has doubled the metering horizon and extended metering operations into the en-route and departure domains. It has done so by developing a modular, scalable architecture with which any Center can meter any number of its traffic flows bound to any internal or external destination. This offers the FAA an efficient alternative to miles-in-trail spacing for any/all of its constituent Centers. Recognizing the operational and economic advantages, the FAA is now formally initiating transfer of the three key McTMA technologies from NASA to become part of the next-generation TMA: a single, common, national TMA baseline ready to meet the first increment of NGATS operational improvements.

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