A TIME-BASED APPROACH TO METERING ARRIVAL TRAFFIC TO PHILADELPHIA

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ABSTRACT

Time-based metering via the Traffic Management Advisor (TMA) has significantly improved arrival operations at capacity-constrained airports in the western U.S. such as Dallas-Ft. Worth International Airport. Arrival flow management in the northeast corridor is in critical need of improvement to reduce the routine occurrence of airborne holding and in-trail spacing restrictions. However, the implementation and acceptance of time-based metering for a major airport in the tightly-constrained northeast corridor presents challenges beyond those encountered in other regions of the country. Research is underway at NASA Ames Research Center to identify these challenges, comprehend the underlying system dynamics, and develop requirements for a second-generation TMA system—the Multi-Center Traffic Management Advisor—intended to improve arrival operations at major airports in the northeast corridor. Philadelphia International Airport has been selected as the initial development and test site. Several research activities, including site visits and simulations, have identified four primary technical challenges of metering in this airspace: (1) an infrastructure that is inadequate for multi-facility coordination, (2) limited ability to absorb delay, (3) uncertain departure times of short-haul PHL arrivals, and (4) workload implications of converting from a miles-in-trail operation to a time-based metering operation. System requirements addressing these technical challenges are discussed.

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INTRODUCTION

Review of Time-Based Metering Tools

Time-based spacing (or "metering") of arrival flows is not a new concept in air traffic management. NASA's Traffic Management Advisor (TMA) is the third generation of time-based metering tools, following the En Route Metering (ERM) program (1970's-80's) and the Arrival Sequencing Program (ASP) (1980's-present). Each of these tools was developed and deployed at Air Route Traffic Control Centers (ARTCCs, or "Centers") in the western United States (e.g., Fort Worth Center, Minneapolis Center) to improve the flow of arrival traffic to Terminal Radar Approach Control (Tracon) airspace at a major airport (e.g., Dallas–Ft. Worth, Minneapolis–St. Paul). While TMA's predecessors showed promise of realizing the operational efficiencies which motivated their development,[1] neither program was successfully transferred to operate in New York Center or Washington Center airspace, two facilities where congestion and delays are most acute.

TMA Demonstrates Benefits

TMA is part of the Center–Tracon Automation System (CTAS), a suite of air traffic management tools developed at NASA Ames Research Center.[2] TMA uses flight plan, track, weather, and controller input data to compute an efficient, time-based metering schedule for arrivals to an adapted Tracon and airport. The schedule maintains pressure on the terminal area without exceeding the capacity of the Tracon or airport. Schedule information is displayed in the Traffic Management Unit (TMU), and advisories are displayed at the appropriate sectors to inform the controllers of how much delay each aircraft needs to take (or "absorb") in order to conform to the scheduled times.

Like ERM and ASP, TMA is a single-Center concept. TMA was designed to help Traffic Management Coordinators (TMCs) and air traffic controllers generate and implement an efficient arrival plan for capacity-constrained airports *where the entire arrival flow process is managed and controlled by a single*

Center. As such, it is referred to as the *Single-Center* Traffic Management Advisor (TMA–SC). While the ERM and ASP software programs are resident within the Host Computer System (Host), TMA–SC runs on dedicated, commercial off-the-shelf (COTS) computer hardware, which is interfaced to the Host at that ARTCC. This architecture overcomes the limited processing power available in the Host. TMA's superior computational resources make possible the use of far more sophisticated trajectory modeling and scheduling algorithms relative to those implemented for ERM or ASP. As a result, TMA–SC has increased throughput and reduced workload relative to ASP at its initial deployment site, Fort Worth Center (ZFW)[3]. Based on the demonstrated results, the FAA is deploying TMA–SC to six other ARTCCs throughout the U.S. as part of its Free Flight Phase 1 program: Los Angeles, Oakland, Denver, Minneapolis, Atlanta, and Miami.

Multi-Center Approach for Northeast Corridor

Unlike the sites where ASP and TMA–SC are now being used,[§] the arrival flow process at most major airports in the northeast corridor involves airspace and personnel at more than one Center. If time-based arrival metering is to succeed in the northeast corridor, managers and controllers at all facilities having a role in arrival operations to the destination airport need to be involved and coordinate themselves to a common metering plan. An alternative to the single-Center approach is called for, because single-Center architectures are constrained by the absence of connectivity between Host computers in the National Airspace System (NAS) infrastructure. In short, a multi-Center approach is needed.

Multi-Center Traffic Management Advisor

Research is underway at NASA Ames Research Center to design and develop a successor TMA system—the *Multi-Center* Traffic Management Advisor (TMA–MC)—that will meet the unique requirements of complex arrival airspace associated with the northeast corridor. TMA–MC adopts a new, multi-facility architecture comprised of a network of ARTCC-based TMA systems which exchange data. This architecture makes it possible for personnel at all of the relevant facilities to collaboratively plan, negotiate, and implement a coordinated, efficient and workable arrival plan for the adapted airport.

Philadelphia International Airport (PHL), a busy northeast corridor hub airport, has been chosen for

initial development of TMA–MC. Accordingly, the facilities involved in the PHL arrival process—Boston Center (ZBW), Cleveland Center (ZOB), New York Center (ZNY), Washington Center (ZDC) and the Philadelphia Terminal Radar Approach Control (PHL Tracon)—have been selected as TMA–MC development sites. Visits to these and other northeast corridor facilities, interviews with FAA Air Traffic personnel there, and controller-in-the-loop real-time simulation activities have been conducted to observe the system dynamics, identify the constraints, and, from them, synthesize requirements for an operationally acceptable TMA–MC for PHL. This paper discusses the complexities, constraints and requirements identified during these activities, and outlines the issues to be investigated during field studies scheduled for 2002-2004.

OBJECTIVES

The overarching objective of the Multi-Center Traffic Management Advisor research is to develop a tool that enables traffic managers and controllers to improve arrival operations at Philadelphia International Airport. In operational terms, the objectives are to: (1) improve inter- and intra-facility coordination; (2) reduce the occurrence of airborne holding; (3) implement restrictions that are "just in time, and just enough;"[4] and (4) stabilize controller workload levels. Concomitant with these objectives is the requirement that the automation design be applicable to other capacity-constrained terminal areas, particularly those located in the northeast corridor (e.g., New York Tracon (N90)).

APPROACH AND METHODS

NASA's prior experience developing TMA–SC at Dallas–Ft. Worth International Airport (DFW) demonstrated the value of making the air traffic community—the eventual system operators—an integral part of the design and development team.[5] A similar approach has been adopted for TMA–MC, whereby researchers are teamed with a "cadre" of traffic management coordinators and sector controllers from each TMA–MC facility (i.e., ZBW, ZOB, ZNY, ZDC, and PHL Tracon). Researchers and cadre members collaborate to define the system requirements, critique the resulting design and, ultimately, evaluate system operation in the field.

Two types of research activity were conducted to help identify system requirements: site visits and controller-in-the-loop simulations. Multiple site visits were arranged at each of the five TMA–MC facilities to enable all of the researchers to observe live operations,

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[§] ERM is no longer in use.

interview cadre members, and begin to develop the requisite domain knowledge about Philadelphia arrival operations. Following the initial round of site visits, the cadre and research team convened at Ames for a technical interchange meeting. Researchers presented before the cadre what had been learned to date. Cadre members expanded on the findings, and corrected inaccuracies. The technical exchange also helped inform the cadre of the constraints and issues faced in the facilities other than their own. This elicited extended discussion of various practices, interpretations and perceptions that stands to benefit operations in the region, independent of TMA–MC. Ultimately, the meeting ensured that all members of the design team were operating under a consistent set of assumptions and with a common understanding of the air traffic system at and around PHL.

Based on the knowledge gained from the site visits and technical interchange meeting, a series of four controller-in-the-loop simulation activities was conducted. Progress was made in three key areas. First, in designing realistic simulation scenarios, researchers had to develop and demonstrate a more refined knowledge of each airspace sector, its relevant traffic flows (including crossing traffic), and the nominal control procedures employed there. Shortcomings in the accuracy of the simulated traffic and/or airspace were quickly identified by the cadre and corrected. Second, the simulations—which required sector controllers to meter arrival aircraft to PHL according to a schedule generated by TMA—helped flesh out requirements for the sequencing and scheduling functions of TMA–MC, and they provided an initial indication that time-based metering at PHL is feasible. Third, the simulations provided the cadre an opportunity to gain some familiarity and comfort with time-based metering, both in theory and in practice. It also enabled the TMCs to acquaint themselves with the features and operation of a TMA prototype.

RESULTS

Relative to the Centers at which TMA–SC is deployed, the northeast corridor presents a number of new challenges. Some are technical, and some are cultural. In this paper, we focus on the significant technical challenges. The many site visits, interviews, and simulation exercises have produced an extensive knowledge base of nominal and off-nominal operations, constraints and opportunities related to the PHL arrival process. By combining the operational experience gained with TMA–SC to this new PHL knowledge base, several technical challenges have been raised, and

many new design requirements have been identified. The most salient of these are presented in this section.

Operational Background

The TMA–MC design challenges and requirements are best understood in the context of the PHL operational environment. The results of observations and interviews at each site are presented here at a high level to provide some background for the discussion of the system design that follows. The discussion begins with the Philadelphia terminal area, works outward to the adjacent Centers (ZNY and ZDC), and finally to ZNY's first-tier Centers, ZOB and ZBW.

Philadelphia Traffic Management

Philadelphia International Airport is the sixth most delay-prone airport in the U.S.[**] As a hub airport for USAirways, PHL typically experiences seven arrival rushes per day, each containing a significant mix of turbojet and turboprop traffic. To contend with these rushes, PHL traffic managers typically impose miles-in-trail restrictions on each arrival flow. When in-trail restrictions prove inadequate, they resort to airborne holding at one or more arrival fix(es). Although less efficient than a time-based metering strategy, these measures are effective in maintaining safe separation and manageable controller workload levels, and the measures are implemented with great skill, developed from years of daily practice. Both of these measures occur routinely at PHL, even under the most favorable weather conditions.

Philadelphia Terminal Area Layout

Traffic flow management problems at PHL are compounded by virtue of the cartography of the region. The Philadelphia Tracon straddles the boundary between New York Center and Washington Center (see Figure 1). Approximately 60% of arrival aircraft flow into the Tracon from these two enroute Centers. The remaining 40% of arrivals enter the Tracon from six adjacent approach control facilities. Clockwise from the north, they are: Allentown, New York, Atlantic City, Dover, Baltimore, and Reading (see Figure 2). While most of these aircraft are destined for PHL, a significant proportion are bound for satellite airports (including Northeast Philadelphia (PNE), Trenton (TTN), Wilmington (ILG) and Navy Willow Grove (NXX)), and these satellite arrivals enter PHL Tracon through the same five arrival gates as the PHL arrivals. Roughly half of all PHL arrivals come from the west over

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[**] 44.5 delays (15 minutes or more) per 1000 operations in 2000, based on FAA OPSNET reported delays.
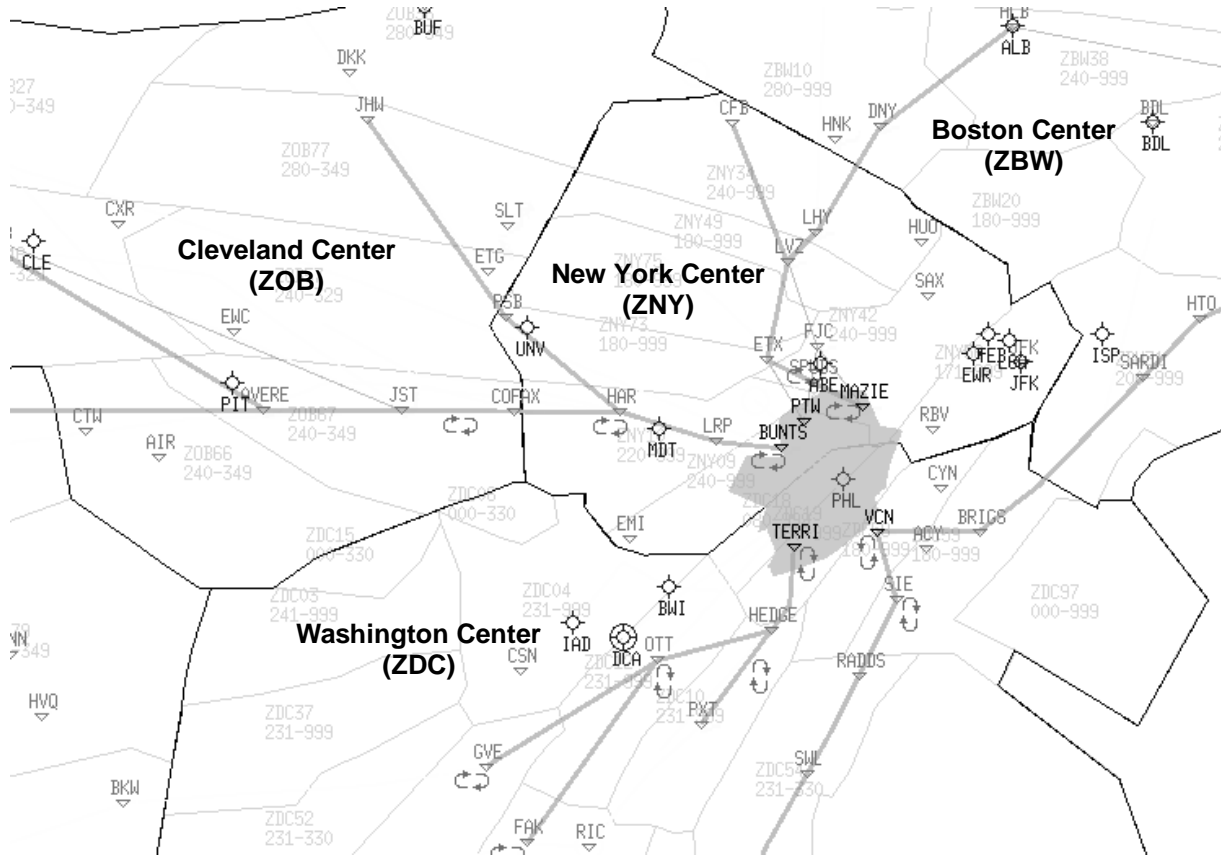
Figure 1. PHL Tracon (shaded region) overlaps ZNY and ZDC, each of which delivers arrival aircraft to PHL over the labeled arrival fixes: BUNTS, Pottstown (PTW), MAZIE, Cedar Lake (VCN) and TERRI. ZOB and ZBW are first-tier Centers to ZNY for PHL arrivals. Typical arrival routes and holding fixes are depicted.

BUNTS. These are primarily turbojet aircraft from the Midwest and West Coast. Another third of PHL traffic, a mix of jets and props, arrives from the south and east over TERRI and Cedar Lake (VCN), respectively. TERRI captures traffic from Atlanta, Memphis and the Gulf states; Cedar Lake is the entry point for flights originating on the Atlantic Coast, from Boston to Miami. MAZIE is the entry point for jets from upstate New York and parts of New England; prop traffic from those areas is routed over Pottstown (PTW).

Cleveland Center and Boston Center lie within 130 nautical miles of PHL. These upstream facilities play an important role in the arrival process. The close proximity of these facilities to PHL also means that upsets in the PHL arrival process quickly ripple back upstream to affect operations in these Centers. Furthermore, chronic congestion in this region increases the interaction and dependency of the traffic streams. As a result, upsets in the PHL flows frequently impact flows to other destinations, setting off a domino effect of additional delay and workload throughout the

region. Because all of these facilities have a role and an interest in the PHL arrival process, formulating and executing a coordinated arrival plan among all of them poses a significant challenge, but one with potentially far-reaching benefits.

Arrival Centers

PHL Tracon is delivered arrival aircraft by two centers: New York Center and Washington Center. New York Center is commonly characterized as a "big Tracon." A large percentage of its traffic is in transition to/from major airports in the New York metro area (e.g., LaGuardia (LGA), Newark (EWR), Kennedy (JFK)). The airspace is comprised of narrow corridors which funnel aircraft in and out of the metro area. Its small sectors, high traffic density, and diverse traffic mix of aircraft in transition make ZNY a highly complex operation. ZNY owns the BUNTS, PTW, and MAZIE arrival fixes, and therefore has a role in controlling PHL arrivals from the west and north. In addition, ZNY has a role in descending Cedar Lake arrivals from New England, accepting flights from ZBW and passing them
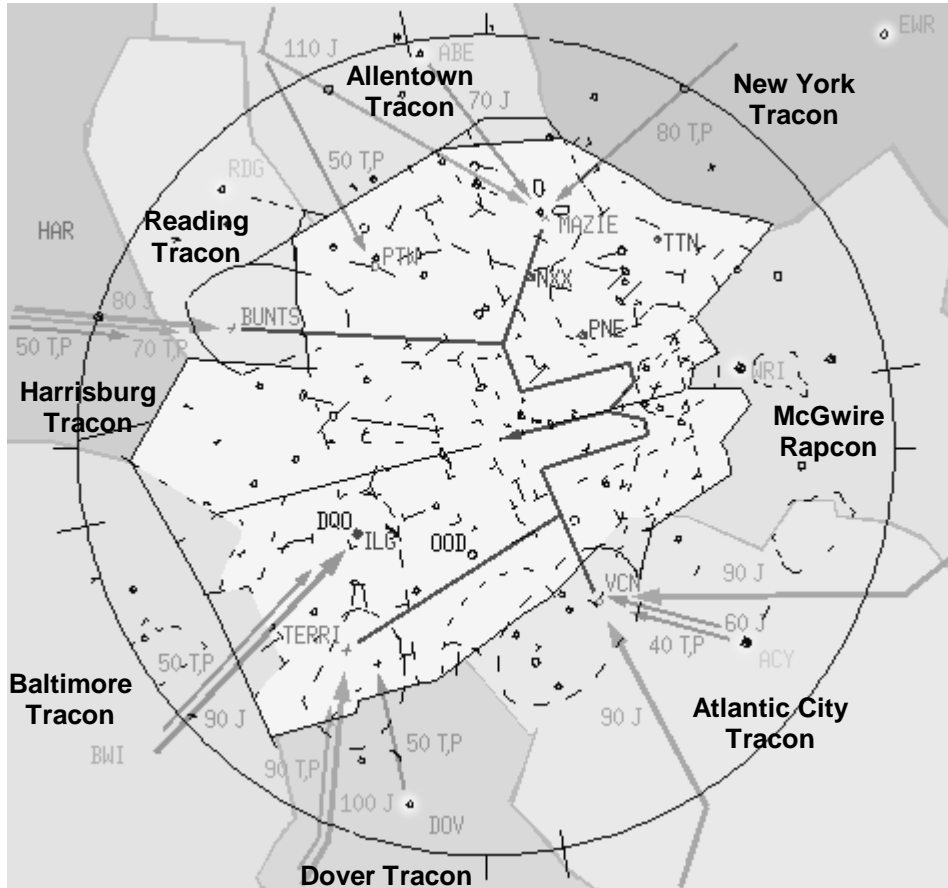
Figure 2. PHL Tracon and surrounding Tracons (shaded). Arrows indicate arrival flows and crossing restrictions for turbojets (J), turboprops (T), and props (P). Interior Tracon routes are shown reflecting that PHL is in a west flow runway configuration.

off to ZDC (jets) or Atlantic City approach (props) prior to Cedar Lake.

Washington Center serves predominantly north–south traffic flows headed to/from the Washington or New York metro areas. Major ZDC airports include Dulles (IAD), Baltimore/Washington (BWI), Reagan National (DCA), and Raleigh/Durham (RDU). ZDC also handles significant volume associated with Atlanta–Hartsfield (ATL) and Charlotte (CLT). Because of the significant workload associated with the flows in and out of New York and Washington, PHL traffic is not a major part of their focus. ZDC owns the TERRI and Cedar Lake (VCN) arrival fixes, and therefore has a role in controlling PHL arrivals from the south and southeast. In addition, ZDC merges converging streams of arrival traffic from the Atlantic Northeast and the Atlantic Southeast at Cedar Lake.

<u>First-Tier Centers</u>

Cleveland Center and Boston Center are responsible for the initial descent of aircraft on arrival to Philadelphia from the west and north, respectively. Cleveland Center handles more aircraft per day than any ARTCC in the NAS. Most of these flights are long-haul flights from major hub airports such as San Francisco, Denver, St. Louis, and Chicago–O'Hare (eastbound) and Boston, Philadelphia and the New York airports (westbound). A significant volume of traffic originates or terminates at one of its three major internal airports: Cleveland–Hopkins (CLE), Detroit–Wayne (DTW), or Pittsburgh (PIT). Cleveland Center is responsible for organizing the predominant stream of traffic into PHL, the BUNTS arrival. Cleveland sets up this flow for New York Center, handing off aircraft at the ZOB–ZNY boundary at 25,000 feet, approximately 125 n.m. from PHL. Although fairly homogeneous (mostly jets on a dedicated PHL arrival airway), this flow is made complex by heavy crossing traffic in/out of the

Washington metro airports and Cincinnati (CVG), and by departure/arrival traffic associated with Pittsburgh, Columbus (CMH) and Dayton (DAY). Also, Cleveland Center is responsible for a secondary flow (approximately four aircraft per rush) into New York Center (and BUNTS) from upstate New York (Rochester (ROC), Buffalo (BUF)) and Toronto (YYZ). Although the secondary flow is light, it is a critical contributor to workload and delay (see "Workload" below). These primary and secondary flows must be merged in a small sector in ZNY. To reduce the odds of two aircraft arriving in a tie over the ZNY boundary, heavy in-trail restrictions are levied on the secondary flow. This is a natural application for time-based metering, which could eliminate these restrictions.

Boston Center handles a diverse mix of operations. In addition to major airline service in and out of the primary airports (Boston (BOS), Providence (PVD), Bradley (BDL), and Manchester (MHT)), it also acts as a gateway facility for international flights over the Atlantic. A large proportion of its traffic is turboprop/commuter aircraft bound for New York airports. Boston Center handles two arrival flows destined for PHL. The first collects flights from southern New England (e.g., Boston, Providence, Bradley, Islip (ISP)) which are routed along the Atlantic Coast into New York Center. This flow is complicated, because it is mixed with another flow of traffic in the opposite direction sharing the same airway. One flow is southbound to destinations along the Atlantic Coast; the other is a major northbound artery into New York and New England. Thus, there is traffic in transition in both directions along the same airway. The second PHL arrival flow collects flights from northern New England (e.g., Burlington (BTV), Manchester), Canada (e.g., Montreal (YUL), Ottawa (YOW)) and western New York (e.g., Syracuse (SYR), Albany (ALB)), all of which are brought over upstate New York to New York Center.

Technical Challenges

The technical obstacles to time-based metering at Philadelphia are largely generic to all of the major airports in the northeast corridor. Broadly categorized, they include obstacles to coordination, limited ability to absorb delay in the arrival sectors, uncertainty in the estimated times of departure of short-haul flights bound for the adapted airport, and the potentially-significant operations and workload implications of incorporating a new control paradigm, time-based metering. Each is discussed in turn in the subsections that follow.

Inadequate infrastructure for coordination

As alluded to earlier, the NAS infrastructure is not set up to support inter-facility coordination. Inaccurate or inaccessible information, poor feedback mechanisms, and cumbersome communication protocols contribute to an environment of "protectionism" in most facilities that is not conducive to productive collaboration. These problems are not limited to inter-facility interaction; they also exist within facility walls between areas and between specialties.[††] NASA researchers are working in cooperation with researchers from MITRE's Center for Advanced Aviation Systems Development (CAASD) to develop system requirements for TMA–MC that are expected to raise the level of common situation awareness among and within the facilities to facilitate more productive planning of arrival rush operations.

As discussed, four different Centers and six different Tracons handle PHL arrival traffic. PHL Tracon, in consultation with ZNY, ZDC and the System Command Center (SCC), has responsibility for establishing the arrival plan, setting the necessary restrictions at the arrival fixes, and coordinating them with its adjacent facilities, ZNY and ZDC. Those facilities, in turn, pass back restrictions to their upstream facilities (e.g., ZOB, ZBW) based on the restrictions PHL has imposed. However, once the plan is established and the arrival rush is underway, there is little feedback available to TMCs with which to monitor the development of the rush or the adequacy of the plan. As a result, the local and regional situation awareness of the TMCs regarding the performance of the arrival operation tends to erode as the rush progresses. Furthermore, even if good situation awareness could be maintained, the time and workload required to negotiate and communicate a coordinated multi-facility response to a developing over- or under-capacity situation is generally too great. Therefore, amendments to the arrival plan tend to be reactionary, over compensatory, and late. In the worst case, traffic demand builds until the north and/or south arrival controller(s) at PHL Tracon must call for immediate airborne holding at the arrival fix. This action, referred to as "no-notice holding" or (in less polite conversation) as "slamming the door," causes considerable stress and workload in the upstream sector, and the upheaval can ripple quickly upstream

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[††] An "area" is a cluster of adjacent sectors whose controllers are co-located in a single bay on the control room floor; a "specialty" refers to a controller's role as either an air traffic control specialist or a traffic management specialist.

through adjacent sectors and facilities, contributing to frustration and misplaced blame.

By sharing information across all five facilities, the TMA–MC design promises to improve situation awareness and facilitate strategic coordination of the PHL arrival plan. First, TMA–MC will provide to each TMU continuously-updated PHL arrival demand forecasts (up to 90-minute look-ahead) that are more accurate than anything currently available. It further will provide TMCs with continuous, unambiguous feedback regarding the development of the rush and the quality of the arrival plan. Second, this information is shared instantly throughout the TMA–MC network. This may facilitate a level of implicit coordination, as traffic managers at adjacent sites—even if not actively coordinating per se—will make decisions based on consistent information. There may be an attendant workload benefit, too, since better initial decisions should reduce the need to replan later. Third, the TMA–MC timeline and load graph displays will provide TMCs at each facility with a common picture of the status and plan, and common scheduling tools with which to evaluate options. It is envisioned that the timelines may become the context for discussion and negotiation between facilities. In this way, TMA–MC can facilitate simple, direct collaboration among the involved TMUs. Fourth, within each facility, the TMA–MC automation interface to the ARTCC infrastructure will enable TMCs to instantly distribute the coordinated plan to the appropriate sector controllers in his/her facility. This will facilitate real-time conformance actions that respond to the newly-generated plan.

Better situation awareness may improve coordination inside PHL Tracon as well. The Tracon arrival airspace is divided into two sectors, north and south. During an arrival rush, each controller's "gameplan" is affected by the volume and spacing of traffic inbound to the *opposing* sector. Presently, no information is available to either controller to indicate arrival demand to the opposing sector. As a result, controllers tend to adopt an overly conservative, and often more workload-intensive, gameplan for the rush. The availability of TMA–MC timelines to the arrival controllers in the Tracon may arm them with a more useful picture of north- and south-side arrival demand upon which to base their control actions.

Limited "delayability"

To implement an arrival metering plan, TMCs depend on Center sector controllers to delay arrival aircraft such that each aircraft crosses a pre-defined metering reference point at its scheduled time of arrival. Controllers typically conform to metering delays by assigning vectors, speed restrictions and/or early descent clearances. The amount of delay that can be absorbed in a sector is a direct function of the time and space a controller has in which to execute these tactics. For the purposes of this paper, "delayability" is defined as the aggregate delay that all controllers along an arrival path can be expected to absorb on a per-aircraft basis.

Delayability along the arrival streams to PHL is significantly less than that found at TMA–SC sites outside the northeast corridor. It is limited by two principal factors: the fragmented control of the arrival flows, and the large segment of arrival traffic that enters PHL Tracon from its adjacent approach control facilities. Both factors are explained next.

Fragmented control is best explained with an example. At Fort Worth Center, arrival flights are metered through two sectors, spanning as much as 250 n.m., prior to entering the DFW Tracon. At Philadelphia, depending on the arrival route, arrival flights descend through as many as four sectors over the same distance. This fragmentation of control limits each controller's opportunity to absorb delay, because s/he has control over a flight for only a short time, and because the small sector dimensions constrain his/her room to vector. Therefore, an aircraft's total delay must be absorbed in piecemeal fashion, in small increments by several controllers over several sectors in series.

This dynamic became apparent in simulation, and it has driven two design modifications. First, the amount of delay each sector is expected to absorb has been revised downward. Second, the metering horizon has been expanded well beyond our original expectation.[‡‡] Expanding the horizon has revealed an additional benefit, as sectors tend to be larger further from PHL, enabling disproportionately more delay to be absorbed there. Note also that the need to "expand the metering horizon" (i.e., initiate metering further upstream) has

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[‡‡] The metering horizon refers to the perimeter of the region in which time-based metering is applied. As each aircraft crosses the metering horizon, TMA–MC assigns it a slot in the arrival schedule and a corresponding amount of delay required to meet that slot. If the assigned delay is greater than the delayability along that route, the controllers cannot be expected to conform to the schedule. Expanding the metering horizon increases delayability, decreasing the likelihood of a scenario as just described.

been a recurring conclusion pertaining to several different issues, as will become evident through the remainder of this paper.

The second factor affecting delayability is the large component of PHL arrival traffic which comes to PHL Tracon from an adjacent approach control facility (e.g., Atlantic City Tracon, Reading Tracon). Roughly 40% of all PHL arrivals, mostly turboprops, are routed this way. Once these aircraft descend out of Center airspace and into approach control, their arrival times are no longer influenced by Center actions. Thus, TMA loses its only means by which to control these aircraft to their metering times. As a result, the delay assigned to each of these aircraft must be absorbed prior to this transition. To compensate, metering of these aircraft must be initiated further upstream (i.e., the metering horizon must be expanded). [§§]

In simulation, researchers were able to experiment with expanding the TMA–MC metering horizon. Unanimously, controllers and TMCs felt that the expanded metering horizon was an improvement, as it more equitably distributed the workload across more sectors, and they were better able to meet their metering times. However, expanding the metering horizon in simulation also highlighted some expected side-effects. From a technical standpoint, expanding the metering horizon increases the uncertainty and error in the system, as the algorithms must make projections further into the future over greater distances. As a result, the system becomes more prone to error in the sequences it generates, and sequence errors cause controllers to quickly lose faith in the system. From a cultural standpoint, expanding the metering horizon places the burden of delay absorption further from PHL and into the operations of a facility and/or sector that is less focused on PHL traffic issues.

To address the technical problems, researchers are in the process of defining new requirements that will incorporate additional metering reference points (MRPs) along each arrival stream. Creating upstream MRPs will anchor the TMA–MC sequencing and scheduling algorithms to a reference point much closer to the outlying sectors, thereby reducing uncertainty and error. The location chosen for upstream metering points is important, as it can affect the overall

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[§§] One could argue that the metering horizon does not need to be expanded if, instead, the upstream sectors were to absorb the additional delay. However, the limited delayability in the upstream sectors makes this approach infeasible.

efficiency of the schedule and impact controller workload. Preliminary experiments in simulation with controllers from ZOB and ZNY suggested that an additional MRP along their shared boundary (at COFAX) did improve the sequencing performance, and controller feedback on the subject was favorable.

Uncertainty associated with internal departures

In order to earn the confidence and acceptance of air traffic personnel, the metered arrival schedule must reflect a reasonable arrival sequence, it must remain stable, and it must not create undue workload. A technical challenge in meeting these operational requirements is incorporating short-haul flights, referred to as "internal departures," into the plan without upsetting the sequence and schedule, and without delaying these departures unduly. An internal departure is a PHL-bound flight departing from an airport lying inside the TMA–MC metering horizon. There are three options for scheduling internal departures in TMA–MC: (1) automatically reserve slots for them based on their proposed departure times; (2) reserve slots for them manually based on the most current information in the TMU; or (3) do not reserve slots for internal departures, and leave it to the sector controller to fit them into the stream as they become airborne. The relative operational advantages and disadvantages of each approach are discussed in the paragraphs below.

The first option is for TMA–MC to automatically reserve a place in the arrival sequence for each internal departure based on that flight's proposed departure time (P-time). Experience in developing TMA–SC has shown this to be a flawed approach. P-times are notoriously unreliable. Experiments with TMA–SC at DFW found P-time errors on the order of hours, in some cases.[6] However, even a 5-minute inaccuracy in the P-time is enough for the aircraft to miss its reserved slot, thereby causing undue workload for the controller(s) to fit the aircraft into the stream.

The second option is to manually schedule each internal departure. This approach is analogous to the Enroute Spacing Program (ESP) procedure, also called Approval Request (ApReq), used between TMUs and local control tower personnel to coordinate the release of departure aircraft. Using this approach, when a PHL-bound aircraft is ready to depart, a Tower controller would call the TMC at the local ARTCC to request a wheels-up time. The TMC would refer to the appropriate TMA–MC timeline to find an open slot in the overhead stream, and assign that slot to the pending

departure. TMA–MC would compute the required wheels-up time to effect a smooth merge into the reserved slot in the overhead stream. That wheels-up time would be relayed by the TMC to the local controller, who would release the aircraft accordingly.

This approach drastically improves the reliability of the departure time as compared to the use of P-times. Because both Cleveland Center and Boston Center use ESP during rush periods for their PHL-bound departures, an effort was made to assess this procedure in simulation using Pittsburgh (PIT) departures. Unfortunately, the simulation adaptation for PIT was not of sufficient fidelity to draw any conclusive results. Feedback gathered from Boston and Cleveland TMCs indicates a strong predisposition toward this approach, because it mirrors their current operational procedures, and because it holds the promise of improving the accuracy of the wheels-up times that they currently assign, thereby reducing workload at the sectors.[***]

The disadvantage of this approach is that, if the overhead stream is full, the traffic management alternatives are unpalatable. The TMC can squeeze the departure into the stream, effectively creating a slot by bumping the rest of the stream back by one position (or "rippling the sequence"). In TMA–SC experience, rippling the sequence has been found to be disconcerting for the sector controllers, because it changes the schedule to which they were conforming, generally resulting in additional workload. The other alternative available to the TMC is to assign the pending departure a slot at the end of the line, just beyond the metering horizon. This is a reasonable solution when the departure airport is near the metering horizon. However, for departure airports two- or three-hundred miles inside the horizon, this alternative could mean a prolonged wait for the departing aircraft. Future simulation and field test activities are planned to assess the utility of the manually-scheduled option for internal departures, and to measure the potential workload and/or delay incurred when the arrival stream is full.

The third option for handling internal departures is to generate the arrival schedule without consideration of internal departures. Instead, the schedule is relaxed to some degree to build in enough of a buffer such that the sector controllers are able to work these aircraft into the arrival stream as they pop up. Because limited staffing prevents PHL Tracon from operating an ESP position, this approach may be appropriate with respect to their

"Tower Enroute Control" (TEC) arrivals from the Washington and New York metro areas, for example.[†††] PHL Tracon is accustomed to accommodating TEC flights on a pop-up basis and working them into the arrival flow ad hoc. They are generally adept at doing this, but personnel there report that a single pop-up at an inopportune time can disrupt a controller's planned flow, forcing him/her to impose airborne holding at the arrival fix in order to resolve the problem.

Simulation exercises with PHL Tracon controllers and traffic managers demonstrated that they are indeed able to accept, sequence and land several pop-up aircraft during an arrival rush. They accomplish this by taking advantage of several techniques that are useful for delay absorption under conditions of limited time and space. These include the fanning of arrivals, extending the base leg, and going to a squared-off downwind pattern as opposed to a direct intercept to base. These techniques may be used alone or in combination to delay an aircraft by as much as six minutes. Currently, these techniques are used to accommodate excess arrival volume inside the Tracon, be it due to a TEC arrival, a missed approach, or excessive arrival demand from the adjacent Centers.

TMA–MC has scheduling parameters which can be adjusted to ensure that arrival demand from the adjacent Centers is acceptable while allowing for unforeseen events such as a TEC arrival or missed approach. These scheduling parameters will be tuned to suit the PHL operation based on the results of future simulation and field test activities. These activities will also examine the robustness of the TMA–controller team in terms of its ability to gracefully process all reasonable permutations of arrival demand and unexpected events (pop-ups, go-arounds, etc.).

It should be noted that the three options introduced here for managing the uncertainty of internal departures are not mutually exclusive. It is possible, for example, to employ manual scheduling for internal departures in Boston and Cleveland Centers while allowing TEC

[***] Under ESP, wheels-up times are computed by the TMC using dead reckoning.

[†††] TEC is an ATC program to provide service to aircraft proceeding between neighboring metropolitan areas at low altitude (generally below 10,000 feet). TEC flights proceed through the approach control airspace of multiple terminal facilities, never transitioning into Center airspace. In this way, the TEC program serves as an overflow resource to the standard en route system. TEC flight plans are denoted as such when filed. [Source: Aeronautical Information Manual, FAA, 2001.]

flights to depart for PHL Tracon unregulated. It is expected that full-scale simulations and/or field investigations will be required to evaluate and identify the best combination.

Finally, the TMA–MC research team is staying abreast of developments in the deployment and operational use of the Departure Sequencing Program (DSP). DSP, a product of the Computer Sciences Corporation (CSC), is being deployed to FAA facilities (Control towers, Tracons and ARTCCs) throughout the northeast corridor to help coordinate departures in the region. Although there are no current plans to interface DSP with TMA–MC, doing so may result in operational benefits. For example, DSP may be able to provide better departure time estimates for internal departures.

Workload

Until it is shown that use of TMA–MC and time-based metering for Philadelphia arrivals reduces workload in the arrival sectors and in the Traffic Management Units, it will be difficult to earn the confidence and acceptance of air traffic personnel. This is a significant challenge, as just one of these facilities (Boston Center) has experience with time-based metering. It is important, however, to distinguish between the temporary workload associated with introducing metering into the operational environment (i.e., training and refinement of skills and procedures) and the steady-state workload associated with a mature time-based metering operation using TMA–MC.

The temporary (or "transitional") workload may be significant. Spacing aircraft by time as opposed to distance requires a different mindset and approach. The control problem changes from a pairwise, spatial separation task to a one-by-one, temporal spacing task. The transition to this new paradigm will exact a workload premium on the controllers over the short term. Their training and initial experience will benefit from the lessons learned at TMA–SC facilities, some of which also have had to transition from miles-in-trail spacing to time-based metering.

Clearly, there will be a workload burden incurred as air traffic personnel climb the learning curve. In the end, however, the relevant workload indicator—the one upon which TMA–MC will be measured—is whether controller workload will be sustainable in a mature, time-based metering operation under TMA–MC.

This is still an open question. For example, consider that controllers will still need to ensure spatial separation, as a first priority, for all traffic including their unmetered (parallel and/or crossing) streams. In some cases, metered aircraft may be in-trail with unmetered aircraft. A controller's ability to accomplish in-trail spacing and time-based metering concurrently on multiple aircraft sharing a common stream is an important human factors consideration that has not been encountered in previous TMA research. Further study of this issue is planned as part of this research program.

A primary benefit of arrival metering with TMA–MC is expected to be a more steady workload profile. In operational use of TMA–SC at Fort Worth Center, researchers observed a beneficial redistribution of controller workload. Peak workload subsided and was shifted to less demanding times. The overall result was a more consistent and less stressful operation. With the anticipated reductions in airborne holding and improvements in the regularity of the arrival flows, TMA–MC facilities are expected to realize a similar stabilization in controller workload.

During observations at the Centers and in simulation, several sources of excess workload were identified that TMA–MC has the potential to alleviate. Those workload sources include the following: (1) Tracon sector workload derived from the unavailability of information about current arrival demand at the opposing arrival sector; (2) enroute sector workload incurred when a controller, with little advance notice and little free airspace, must hurriedly vector an aircraft for a downstream merge; (3) arrival sector workload incurred while establishing, maintaining, and terminating holding patterns (apart from the disruption that holding patterns can have on adjacent sectors and traffic streams).

Workload item (1) is driving a requirement for timeline displays on the Tracon floor, as discussed previously. Item (2) supports the requirement for additional Metering Reference Points, also discussed previously. Item (3) is sure to become the yardstick by which TMA–MC is judged: how often does PHL go into holding? The design of the scheduler, including the placement of the metering horizon and the allocation of delay along the arrival routes/sectors, is focused on achieving fewer occasions of airborne holding, fewer and less-onerous enroute restrictions, and a smoother, more efficient flow of air traffic. The cumulative workload reduction from these steps is expected to outpace the incremental workload required to execute a time-based metering plan.

CONCLUDING REMARKS

The arrival operation to Philadelphia International Airport presents a challenging opportunity for the application of time-based metering. It is characterized by complex traffic flows, airspace, and procedures for coordinating the operation. Research activities have generated a knowledge base from which a design for the Multi-Center Traffic Management Advisor decision-support tool has been drafted. A networked approach has been adopted for TMA–MC to enable personnel at multiple facilities to acquire better shared situation awareness with regard to arrival rush operations. More productive negotiation and coordination of the PHL arrival plan is expected using TMA–MC.

Controller-in-the-loop simulations have highlighted the need for several requirements changes to ensure that the arrival metering schedule is stable and workable. Principal among these changes are the expansion of the metering horizon, the incorporation of upstream metering reference points, and offloading delay from downstream to upstream sectors. The design lays the groundwork for further investigation of the technical, operational and cultural issues through human-in-the-loop simulations and on-site studies of the fielded prototype system. The simulations and studies will be used to refine the TMA–MC prototype for field trials. In addition, they will provide an opportunity to assess the system and associated procedures for their expected benefits: less effort to coordinate the arrival operation to Philadelphia, more effective arrival planning and management, and reduced workload in the TMU and arrival sectors. The product of this research is expected to be applicable to other major airports in the northeast corridor and beyond.

[1] Sokkappa, B. G.: "The Impact of Metering Methods on Airport Throughput". MITRE MP-89W000222. 1989.

[2] Erzberger, H., "Center-TRACON Automation System (CTAS)", presented at the Capacity Technology Subcommittee, FAA Research and Development Advisory Committee, Washington, DC, July 1994.

[3] Swenson, H. N., T. Hoang, S. Engelland, D. Vincent, T. Sanders, B. Sanford, and K. Heere, "Design and Operational Evaluation of the Traffic Management Advisor at the Fort Worth Air Route Traffic Control Center", 1st USA/Europe Air Traffic Management R&D Seminar, Saclay, France, June, 1997.

[4] Green, S. M., R. A. Vivona, "Local Traffic Flow Management Concept for Constrained En Route Airspace Problems", Presented at the AIAA Guidance, Navigation and Control Conference, September 2001.

[5] Harwood, K., B. D. Sanford, and K. K. Lee, "Developing ATC Automation in the Field: It Pays to Get Your Hands Dirty", Air Traffic Control Quarterly, Vol. 6(1), pp. 45-70, 1998.

[6] Wong, G. L., "The Dynamic Planner: The Sequencer, Scheduler, and Runway Allocator for Air Traffic Control Automation" NASA/TM-2000-209586, April 2000.