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Integrated Demand Management: Coordinating Strategic and Tactical Flow Scheduling Operations

Nancy M. Smith[*],

NASA Ames Research Center, Moffett Field, California 94035

Connie Brasil[#], Paul U. Lee[#], Nathan Buckley[§], Conrad Gabriel[§], Christoph Mohlenbrink[#], Faisal Omar[+], Bonny Parke[#], Constantine Speridakos[§], Hyo-Sang Yoo[+]

San Jose State University Research Foundation, NASA Ames Research Center, Moffett Field, California 94035

NASA Ames researchers are developing a near- to mid-term concept called Integrated Demand Management (IDM). The objective of IDM is to improve National Airspace System (NAS) performance when the capacity of major high-volume resources is insufficient for the expected demand, using procedural coordination of different NextGen traffic management capabilities. An arrival capacity problem involving Newark Liberty International Airport (EWR) served as a use case for concept development. Under IDM, Traffic Flow Management System (TFMS) tools are used to pre-condition traffic into the Time-Based Flow Management (TBFM) system, enabling TBFM to better manage delivery to the capacity-constrained destination. The proposed solution leverages three capabilities: (1) the Collaborative Trajectory Options Program (CTOP) tools within TFMS to condition arrival demand into TBFM, (2) required-time-of-arrival (RTA) flight deck capabilities to support conformance to CTOP-planned TBFM entry times, and (3) TBFM metering to manage delivery to the capacity-constrained airport. The solution was refined through a series of human-in-the-loop (HITL) simulation studies and demonstrations with input from the FAA, airline stakeholders and subject matter experts. This paper describes the concept and results from an early proof-of-concept HITL experiment that focused on the EWR traffic problem.

Nomenclature

AAR	=	Airport Acceptance Rate
AFP	=	Airspace Flow Program
ANSP	=	Air Navigation Service Provider
ARTCC	=	Air Route Traffic Control Center
ATC	=	Air Traffic Control
ATCSCC	=	Air Traffic Control System Command Center
CDM	=	Collaborative Decision Making
CSP	=	Constraint Satisfaction Point
CT	=	Crossing Time
CTOP	=	Collaborative Trajectory Option Program
EDC	=	En Route Departure Capability (TBFM)
EDCT	=	Estimated Departure Clearance Time
ERAM	=	En Route Automation Modernization

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[*]Research Psychologist, Human-Systems Integration Division, NASA Ames Research Center, MS 262-4
[#]Senior Research Associate, Human Systems Integration Division, SJSU/NASA ARC, MS 262-4
[§]Research Associate, Human Systems Integration Division, SJSU/NASA ARC, MS 262-4
[+]Research Engineer, Human Systems Integration Division, SJSU/NASA ARC, MS 262-4

ETA	=	Estimated Time of Arrival
FCA	=	Flow Constrained Area
FEA	=	Flow Evaluation Area
GDP	=	Ground Delay Program
GUI	=	Graphical User Interface
HITL	=	Human-in-the-loop
IDM	=	Integrated Demand Management
MACS	=	Multi-Aircraft Control System (NASA ATC simulation platform)
MF; MFX	=	Meter Fix (TBFM)
MIT	=	Miles in Trail
NAS	=	National Airspace System
nCTOP	=	NASA CTOP emulation
nm	=	Nautical mile
PGUI	=	Planview GUI (TBFM)
RTA	=	Required Time of Arrival (assigned to aircraft)
STA	=	Scheduled Time of Arrival
TBFM	=	Time-Based Flow Management
TBO	=	Trajectory Based Operations
TFMS	=	Traffic Flow Management System
TGUI	=	Timeline GUI (TBFM)
TMI	=	Traffic Management Initiative
TRACON	=	Terminal Radar Approach Control
XM; XMP	=	Extended Metering; Extended Metering Point (TBFM)

Background

NASA Ames researchers working under the Airspace Operations and Safety Program are developing a near- to mid-term concept called Integrated Demand Management (IDM). The objective of IDM is to improve National Airspace System (NAS) performance when the capacity of major high-volume resources is insufficient for the expected demand, resulting in bottlenecks that often have a NAS-wide impact. Reasons for these demand/capacity mismatches can vary from structural limitations (such as limited surface capacity at the airport or airspace complexity in the Northeast Corridor), to wind-related capacity changes, to the more severe, dynamic and less predictable mismatches that occur with convective weather. IDM introduces an approach to strategic coordination of different traffic flow management capabilities available within the NAS to improve system performance in all of these situations.

A traffic volume problem at Newark Liberty International Airport (EWR) provided a use case for IDM concept development. Among the three major airports that serve the New York (NY) metropolitan area, EWR routinely sees the most varied mix of short-haul and long-haul flights, with a load distribution across its three arrival gates that changes throughout the day. Scheduled demand is often at or near the airport's dual-runway VFR capacity, so adverse winds or reduced visibility can easily reduce capacity well below demand.[1] This is usually managed using miles-in-trail (MIT) spacing and Time-Based Flow Management (TBFM), however close-in departures often take a disproportionate share of the TBFM-assigned delay since MIT pre-conditioning is not an effective way to reserve capacity for these flights.[2,3] This inequitable delay impact is a problem anytime the local overhead flow is saturated, even during VFR conditions when the airport capacity is adequate.

NextGen traffic management tools and procedures associated with the TBFM system and with the more strategic Traffic Flow Management System (TFMS) are already used to address the problem of demand management within the NAS. Both systems represent a set of capabilities that manage flows into capacity-limited resources by modifying the 4-D trajectories of flights within those flows. They were developed for and continue to be used in different operational contexts and timeframes, however, with TFMS used by airline operators and NAS-wide traffic planners during pre-flight planning, and TBFM used by controllers and local facility traffic managers near the end of the flight. Plans for improving both systems, many of which are in the FAA's implementation pipeline or already in use,[4-6] suggest some potential overlap in functionality. To a large extent, however, these two systems still represent separate and uncoordinated solutions to different aspects of the traffic management problem. One significant NextGen challenge is to figure out how to effectively integrate them.

A. Time-Based Flow Management (TBFM)

TBFM, the more tactical of the two systems, was designed to improve traffic delivery into a capacity-constrained airport. It has since been enhanced to also support metering into high-volume en route and departure flows. TBFM works by building arrival time schedules to Constraint Satisfaction Points (CSPs) such as runways, meter fixes, and en route waypoints. The TBFM scheduler uses a first-come, first-served policy to establish an arrival sequence for inbound flights based on their estimated times of arrival (ETAs) at the CSP, then assigns a scheduled time of arrival (STA) to each flight that satisfies the CSP's inter-arrival spacing requirements. The flight sequence and assigned STA for individual flights adjust as ETAs change until the flight crosses the TBFM schedule's freeze horizon, defined as a particular time or geographic distance from the CSP. At this point the STA is 'frozen' and will no longer change without a manual entry by a controller or traffic manager. When en route facilities are metering, air traffic controllers are responsible for using vectors and speed clearances to absorb any TBFM-assigned airborne delay and meet the assigned STA. The resulting STA conformance is usually within a minute or less. The current TBFM adaptation for EWR has its freeze horizons located nearly 400 nm from the TRACON-entry meter fixes, which makes its effective planning horizon roughly 75-90 minutes before landing.

Departure times for TBFM-scheduled departures (flights that take off from airports inside or near their destination's TBFM freeze horizon) are obtained using a TBFM departure scheduling function that assigns a departure time which corresponds to an available arrival slot.

Recent enhancements called Coupled Scheduling (CS) and Extended Metering (XM) allow TBFM to be configured so that each arrival flow can include multiple coupled or uncoupled schedules to a series of CSPs, each with its own freeze horizon. With freeze horizons now placed closer to their CSPs, the ETAs used to provide input to the schedule will be more accurate, improving the acceptability of flight sequences, TBFM-scheduled departure times, and STAs.[7] The improved scheduling accuracy also means a CS or XM configuration can be used to effectively manage arrivals over much longer distances.

B. Traffic Flow Management System (TFMS)

TFMS includes a set of NextGen planning tools and capabilities that support a Collaborative Decision Making (CDM) approach to traffic flow management. Under CDM, Traffic Management Initiatives (TMIs) issued by the Air Traffic Control System Command Center (ATCSCC, or Command Center) enable system users and air navigation service providers (ANSPs) to work together to implement NAS-wide solutions to disturbances in the system. When airport capacity falls below the expected demand, for example, the Command Center can initiate a Ground Delay Program (GDP). The GDP uses Expect Delay Clearance Time (EDCT) advisories to reduce arrival demand by delaying inbound flights at their departure airports. Under a GDP, operators are provided advance notice about the reduced airport capacity and associated departure delays, and have an opportunity to 'swap slots' (exchange GDP-assigned arrival times) among flights to reduce the impact on their operations. The Airspace Flow Program (AFP) is another TMI that uses EDCTs to reduce demand through a congested or weather-impacted region of airspace, which is designated as a Flow Constrained Area (FCA).

The IDM concept will leverage a new TMI called the Collaborative Trajectory Options Program (CTOP) which can use multiple FCAs to build a more complex characterization of the reduced-capacity problem. The CTOP also provides operators the opportunity to submit a preference-weighted set of route alternatives called a Trajectory Option Set (TOS). CTOP-specific TFMS automation references the TOS to select a user-preferred combination of ground delay and route when building its solution, instead of relying solely on ground delay. This enables the CTOP to automatically re-distribute traffic to take advantage of available capacity on under-utilized routes.

Like TBFM, these three TFMS programs all use scheduling to regulate flow into a capacity-limited destination; however, unlike TBFM they are active well before departure. Their control mechanisms are also significantly different from TBFM, with GDPs and AFPs relying exclusively on EDCTs as their primary intervention, and CTOP adding pre-departure re-routes as a second method for redistributing demand. All of these interventions are made at least 45 minutes before takeoff, with no further action taken to control the aircraft's arrival time at the targeted resource. RTA crossing time advisories or clearances have been proposed as a third, in-flight control mechanism that could improve conformance to TMI demand targets.[8] Without RTAs, however, the CTOP planning window and control opportunity close roughly 45 minutes before departure, often hours before the flight will arrive at the controlled destination. A reasonable CTOP conformance objective is therefore roughly +/- 15 minutes from the target arrival time at the destination, according to subject matter experts (SMEs).

C. Comparison of TFMS and TBFM

TFMS and TBFM were designed for different purposes and operational environments. These differences – in planning horizons, control mechanisms, actors, and phase of flight or physical location where actions take place – mean that each system is better-suited to different aspects of the demand management problem.

TFMS has a significant advantage over TBFM with respect to the amount of delay it can manage, since its control actions are taken before departure and the delays are absorbed on the ground. Using CTOP route assignments, traffic demand can be redistributed or balanced across multiple sectors, fixes and arrival gates. TFMS also has two advantages with respect to operator impact: (1) its planning horizon is often hours before departure, so operators have time to plan how to minimize the impact of flight delays on their operations, and (2) it provides them a way to directly manage those delays by swapping arrival time slots to favor higher priority flights, or modifying routes to avoid congested airspace. However, its coarse and indirect pre-departure control mechanisms can over or under-deliver to the targeted capacity, a target which, since it is set hours in advance, may itself be poorly matched to actual capacity when the traffic arrives.

In contrast, airborne delay provides a more tactical and responsive control mechanism. Thus, TBFM can be a much more effective and precise tool for managing the final stage of traffic delivery to the airport because of its shorter planning horizon (giving it better information) and finer control precision (less than a minute vs. quarter hours or more). There are practical limits, however, to the magnitude of arrival time adjustments that can be managed using airborne delay. Since most flights are airborne when they enter the TBFM scheduling region, this means that TBFM-scheduled close-in departures that attempt to join heavy arrival flows may receive large, last-minute ground delays to avoid causing excessive airborne delay.[2,3] In addition, first-come, first-served scheduling is insensitive to operator priorities; TBFM schedules are generally less visible, stable and predictable from the operators' perspective; and TBFM provides operators no mechanism to manage the impact of flight delays on operations.

I. Integrated Demand Management Ideas and Challenges

Integrated Demand Management (IDM) is based on the idea that a more effective solution to many of the capacity bottlenecks encountered in the NAS can be found by reconciling the strategic and tactical flow management interventions supported by TBFM and TFMS. Leveraging the complementary features of each system can improve system performance in terms of:

- Equity of ground delay assignment, avoiding excessive ground delay for TBFM-scheduled departures, without penalizing longer flights;
- Throughput, by distributing traffic to maximize use of available capacity;
- Predictability and flexibility for operators, providing advance notice about the impact on individual flights, and supporting mitigation strategies such as slot swapping or trajectory options;
- Efficiency of flight operations, using ground delay more effectively and reducing airborne delay.

New tools are not needed to implement this solution; instead procedural adaptation of existing capabilities and operational methods will use each system to its best advantage within its respective context.

This plan to harmonize these two traffic flow management systems represents the first of three challenges that are at the center of IDM research. The second challenge is to explore how advanced flight deck systems might be used to improve IDM outcomes and provide additional side-benefits to individual flights. The third challenge is to leverage as much as possible existing and near-term NextGen technologies, current research efforts, and the expertise of stakeholders and service providers from throughout the system.

A. Harmonizing TFMS and TBFM Configurations

We propose using the new CTOP capabilities within TFMS to pre-conditioning the traffic demand into TBFM. Unlike the miles-in-trail procedures or GDPs that may be used today, IDM procedures using CTOP can provide a more tailored delivery into TBFM. It might, for example, redistribute demand from an overloaded route, airspace or arrival gate to one with reserve capacity. It can also continue to balance and adjust that distribution as local conditions change. This should provide a more consistent feed into TBFM, allowing it to manage delivery to the capacity-constrained destination more efficiently.

B. CTOP Accuracy Requirements

One limitation of CTOP and other TFMS initiatives is their reliance on departure time management and pre-departure route assignment to control a downstream outcome. Using an in-flight RTA capability to conform to the CTOP schedule will improve the delivery accuracy to the TBFM entry targets, which could further improve overall outcomes. This method is also aligned with a strong interest within the operator community in seeing the FAA's NextGen automation support increased use of advanced flight deck performance-based navigation (PBN) systems to improve efficiency and throughput within the NAS.[9,10]

C. Research Approach

Our focus on operational integration of existing capabilities rather than development of new technologies has provided both opportunities and challenges. We have been able to draw upon a rich body of work and leverage ideas that were developed by the CDM Flow Evaluation Team (FET) and others within the operational and research communities. This prior work includes field trials exploring the use of AFPs and GDPs to condition arrival traffic into TBFM, and CTOP to distribute traffic across multiple arrival gates,[2,11,12] a series of simulations and field trials to investigate the use RTA clearances to meet TBFM crossing times,[13-17] and a concept for using RTA assignment to pre-condition traffic into TBFM.[8]

The challenge has been to figure out how to successfully synthesize this material. Input from stakeholders and researchers involved in this earlier work was actively sought through a series of meetings, telecons, and simulation demonstrations. Their involvement has been crucial for us in determining whether our characterization of the IDM problem is satisfactory, and whether our solution is operationally valid and provides meaningful benefit. It has been important for us to understand and address the interests and concerns of all affected parties, since IDM involves many different players (controllers, traffic managers and supervisors; pilots, dispatchers, and air traffic control coordinators), from different organizations and facilities (air traffic control and traffic management, airline and flight operations, professional unions and user organizations).

Human-in-the-loop (HITL) simulation prototyping has provided our primary method for concept development. The extensive capabilities available within the Airspace Operations Laboratory at NASA Ames Research Center have enabled us to work closely with subject matter experts (SMEs) familiar with NY air traffic management and air traffic control operations, CTOP, and TBFM to build a working model of IDM operations specifically for the EWR problem. This HITL environment has allowed us to iteratively evaluate and refine the concept, and to engage stakeholders in participatory workshops exploring how IDM might work.

II. The Integrated Demand Management Concept

The IDM solution can be summarized as follows:

1) A CTOP traffic management initiative manages demand into TBFM.

2) CTOP-derived RTA clearances supplement EDCTs to improve TBFM entry time conformance.

3) TBFM manages delivery to the capacity-constrained destination.

CTOP and TBFM provide two different demand management solutions that use schedules to manage access to capacity-limited resources. IDM loosely couples their two scheduling systems, with CTOP automation building an initial slot-allocation schedule for all Newark-bound flights that is used to pre-condition demand into TBFM. This pre-conditioning will involve managing departure times, routes and en route crossing times to distribute demand both temporally and geographically according to the CTOP plan. All of this takes place well before flights are scheduled in TBFM. After flights cross the TBFM freeze horizon, the CTOP plan is replaced by a new first-come, first-served schedule based on their destination ETAs at that time.

Using a CTOP instead of miles-in-trail conditioning can provide a more precise match of demand to TBFM capacity, and enable more effective blending of short and long-haul flights. The result should be more predictable and equitable delay impact, better utilization of available capacity, and a net reduction in airborne delay. A longer term objective of this concept for CTOP/TBFM integration is to provide a framework that can be extended to address the more complex and dynamic demand/capacity mismatches associated with convective weather.

Figure 1 provides a high-level illustration of IDM operations from the perspective of a flight departing from San Francisco International Airport (SFO) that is included in an IDM CTOP for Newark. CTOP automation assigns the flight an EDCT for its SFO departure, followed by an RTA to a flow evaluation area (FEA) located just outside the TBFM freeze horizon. After the aircraft crosses the FEA it transitions to TBFM-organized traffic control for the rest of the flight. The ground-side traffic management operations that support it are summarized in the boxes at the bottom of the figure. The sections below describe how the CTOP and TBFM structures and schedules are coordinated, and provide a more detailed description of the operations that are presented in Figure 1.

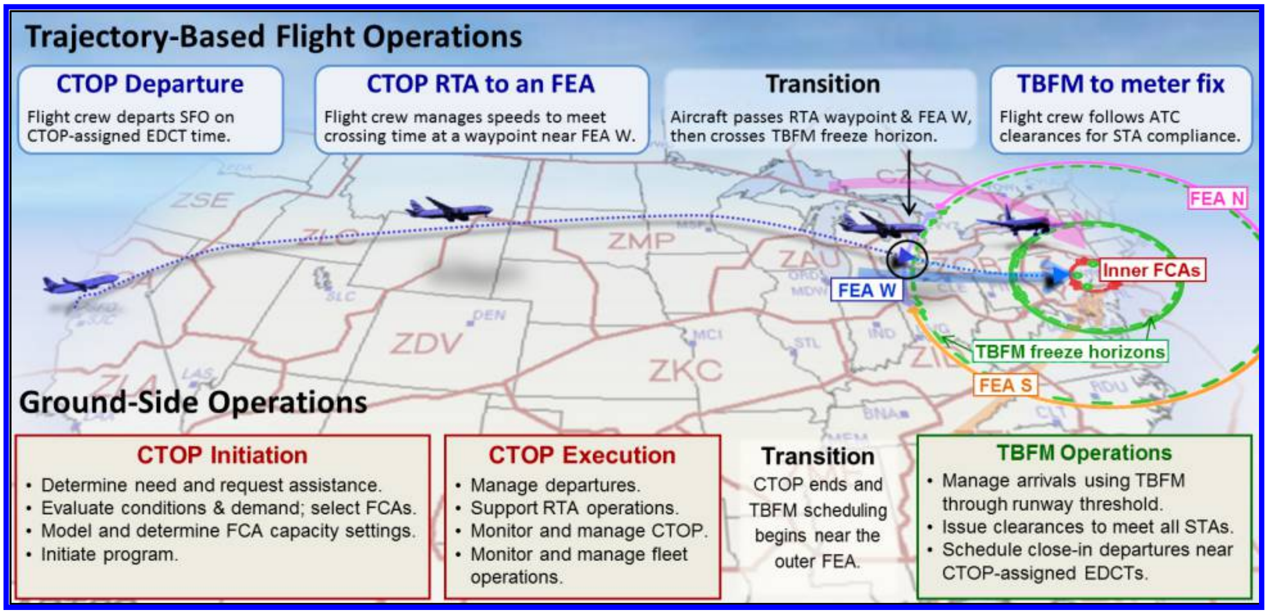

Figure 1. IDM air and ground operations for a sample flight from SFO to EWR.

A. Schedule and Constraint Coordination

1. CTOP and TBFM Control Structures

Under IDM, CTOP uses one or more 'inner' FCAs to build an initial schedule (or set of schedules) assigning each inbound flight an entry time (slot) for a specific constraint such as the TRACON boundary, arrival gate, or airport itself. Figure 2 shows a stylized representation of this solution, with one inner FCA that circles New York TRACON. All aircraft have an FCA slot based on this schedule, and those that are pre-departures also have an associated EDCT, including those that depart from airports within the TBFM region. This serves two purposes: (1) it should insure that airborne demand does not saturate the arrival flow and block access to close-in (TBFM-scheduled) departures, and (2) it gives operators advance notice and an opportunity to reduce the impact by changing TOS entries or swapping slots within the CTOP.

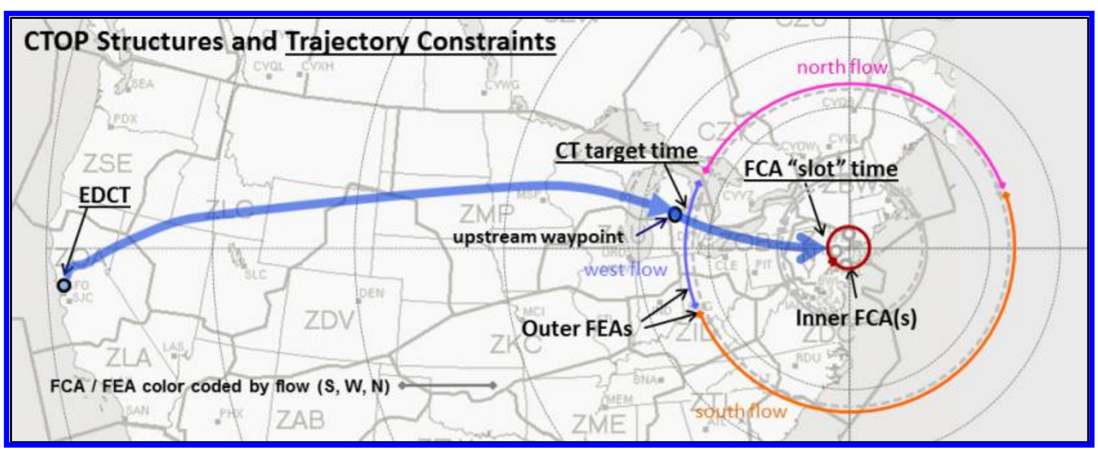

Figure 2. IDM CTOP structures, with trajectory constraints for a sample SFO-EWR flight.

All flights that cross the outer TBFM freeze horizon also have a target crossing time (CT) for an 'outer' Flow Evaluation Area (FEA) reference arc that is located just upstream from the TBFM freeze horizon. The target CT represents the CTOP estimate of when the flight trajectory is predicted to cross the arc if the flight is in conformance with its FCA slot time. This target CT may be assigned to the aircraft, which can use RTA speed management to more tightly control TBFM entry time.

The IDM setup for EWR TBFM uses a custom research adaptation that has been configured to use Extended Metering (XM) schedules in the adjacent ARTCCs to feed an inner Meter Fix (MF) schedule that delivers traffic into NY TRACON. Figure 3 provides a simplified representation of these TBFM scheduling structures.

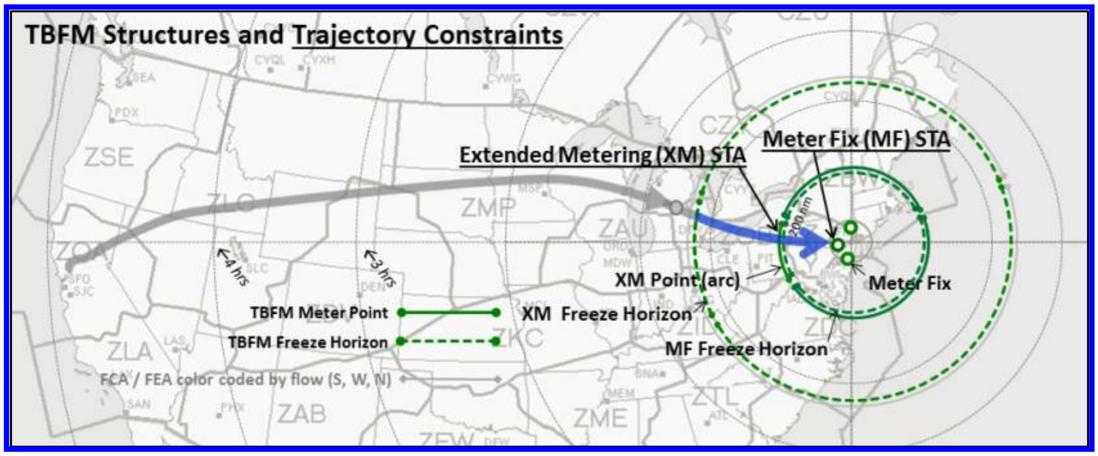

Figure 3. TBFM structures, with trajectory constraints for a sample SFO-EWR flight.

2. Trajectory Constraints

All active IDM flight trajectory constraints are initially associated with CTOP. Figure 2 shows what these specific constraints are and where they might be located for the sample San Francisco-to-Newark (SFO-EWR) flight from Figure 1. They include an initial CTOP derived slot time for the inner FCA (which roughly surrounds NY TRACON), an EDCT at the departure airport based on that slot time, and a target CT to the reference arc (FEA) that represents the estimated FEA crossing time of an aircraft meeting its downstream FCA slot-time constraint.[†]

After the flight crosses the XM Freeze Horizon and enters the TBFM region (Figure 3), the XM schedule provides the active metering target and replaces the CTOP schedule. Our SFO-EWR flight now has an XM STA that is based on a first-come, first-served scheduling logic for the XMP. The XM STA may also include additional 'passback' delay from the downstream MF schedule.

Shortly after passing the XMP the flight crosses the MF Freeze Horizon and is assigned a MF STA. The STA provides adequate separation from other flights utilizing the same meter fix and runway, and is compatible with a runway threshold (THD) time associated with a runway schedule for arrivals from all flows.

3. Departure Scheduling

Flights that are within 45 minutes of departure are considered to be 'exempt' from the CTOP and (like airborne flights) will not see any additional delay when an IDM-related CTOP is initiated. All 'non-exempt' departures will be assigned an EDCT based on their inner FCA slot time. Depending on where their departure airport is located, however, they will be handled somewhat differently after that:

- A long-haul flight whose departure airport is well outside the TBFM region will also receive an RTA clearance (assigned CT) for the outer FEA in addition to the EDCT.
- A shorter flight that originate outside the TBFM region will not receive an assigned CT if its departure airport is too close for the CT assignment to be feasible or useful.

[†]The actual CT assigned to the aircraft references a named upstream waypoint that is close to the FEA, making it easier to communicate by voice and to enter into the on-board flight management system.

- A close-in flight that departs from within the TBFM region has its final departure time scheduled by TBFM, using the CTOP EDCT as a reference.

B. Ground Operations

As indicated by the three boxes at the bottom of Figure 1, the ground operations that support IDM's trajectory-based flight operations can be organized into three phases: (1) CTOP Initiation, a planning phase; (2) CTOP Execution, and (3) TBFM Operations. The CTOP Execution phase applies to flights that are outside the TBFM scheduling horizon either physically or temporally (i.e., close-in departures) where they are subject to CTOP trajectory constraints. TBFM constraints become active in phase 3. This section describes the activities associated with each of these phases, how they differ from current-day operations, and who is involved in these activities.

1. CTOP Initiation

This phase begins when the supervisory traffic management coordinator (STMC) at an air route traffic control center (ARTCC) who is responsible for TBFM schedule management compares expected demand to estimated airport and airspace capacity and determines that a CTOP is needed. The STMC contacts the Command Center to request assistance, describing where and when the problem is expected to occur and providing an airport acceptance rate (AAR) and/or other capacity estimates. The request may involve reducing the overall arrival rate, redistributing traffic across multiple fixes or flows, or internal-to-external TBFM demand coordination.

A Command Center traffic planner identifies the bottlenecks and assesses their possible impact and duration. This assessment considers the forecast winds and weather conditions at the airport and the upstream airspace, the requested AAR, runway configuration, and expected demand. The planner then chooses an FCA or set of FCAs that best supports demand management and load distribution objectives. These will be used to (1) control demand into the destination airport, inbound sectors, or arrival gates, and (2) reserve gate and airspace capacity for the TBFM-scheduled close-in departures. The solution will probably require two or more FCAs to enable traffic load balancing, unless the airport is the only constraint and local airspace, arrival gates, or runways are not a concern.

The planner uses TFMS capabilities to evaluate the match between demand and capacity over the period of concern, and to compare different solutions before setting FCA capacity. Target capacity values are set for each FCA. These values may vary throughout the day to maintain satisfactory throughput and to balance as needed across EWR's north, south and west arrival gates.

The planner coordinates as needed with the appropriate ATC facilities and with airline operators, who submit a TOS for each flight that may be included in the CTOP.

The Planner initiates the CTOP. CTOP automation then builds a schedule that assigns an arrival slot (time) at the FCA to each inbound flight, referencing the TOS to build an ATC clearance that includes an EDCT and assigned route. This clearance represents the lowest cost TOS option that meets CTOP scheduling objectives. Flights that are exempt from the CTOP are assigned a slot time that corresponds to their current ETA on the CTOP schedule.

→ *What's new:* Only the specific application – using CTOP for TBFM pre-conditioning – is new. The methods and procedures match today's practices.

→ *Who is involved:* The parties involved include an STMC at the ARTCC controlling the destination airport (facility that controls the TBFM arrival schedule), a flow planner at the Command Center, and airline dispatchers responsible for the affected flights.

2. CTOP Execution

CTOP execution activities involve controlling individual flights according to the CTOP, managing CTOP impact on airline operations, and monitoring and managing the CTOP itself.

Pre-departure Flight Management. After the CTOP is initiated, airline operators or dispatchers can review the impact of the CTOP on each affected flight, and may revise its TOS or swap its arrival slot with that of another flight. Tower controllers manage the aircraft's departure in conformance with its assigned EDCT.

Post-Departure Flight Management.[‡] An en route controller assigns each eligible flight a CTOP-associated RTA clearance after it reaches cruise altitude. The flight crew confirms that they can meet the assigned CT, then uses on-board capabilities to manage the aircraft's speed to achieve that objective. The crew is responsible for conforming to the assigned time and for informing the controller if they are unable to do so. If the flight crew reports that they are unable to meet the assigned CT, the controller will determine what time can be achieved and take appropriate action to ensure the integrity of the CTOP plan. Downstream controllers are informed through ATC ground automation or pilot communications when the flight is managing its speeds to meet an assigned CT.

CTOP Management: CTOP automation monitors the predicted demand and alerts the planner at the Command Center if over- or under-delivery thresholds are exceeded. A CTOP revision may be used to update the schedule and assign new EDCTs to non-exempt flights. TMCs at the destination ARTCC monitor airport and airspace throughput and capacity forecasts and contact the Command Center if CTOP changes are needed.

Operator Fleet Management. Airline dispatchers monitor the status of all TMI-involved flights and may swap flights or revise TOSs to manage the impact on their operations.

→ *What's new:* (1) RTA assignment. The use of CT targets to support in-flight management of aircraft conformance to a downstream CTOP scheduling objective is new, as is the use of FEAs as intermediate control targets to manage CT delivery at a downstream FCA. Assignment of a target CT to the flight crew as an RTA clearance is also new, along with the controller's need to manage flights that are controlling to an assigned time that is several sectors or facilities downstream. (2) CTOP automatic revision exists, but its proposed use in a 'monitor-and-alert' mode is new.

→ *Who is involved:* Tower controllers and traffic management at the departure airport; TRACON and en route controllers, and traffic management coordinators; pilots and dispatchers or ATC coordinators at flight operations centers; Command Center traffic/flow planner.

❖ *CTOP-to-TBFM Transition*

Aircraft resume normal speeds after passing the CT reference location (the last active CTOP trajectory constraint), and around the same time they appear on the TBFM XM timeline with an unfrozen STA. Shortly after that, aircraft cross the XM freeze horizon and are assigned an XM STA. This transition from CTOP to TBFM should be seamless and transparent to both flight crew and controllers.

→ *What's new:* the idea of explicitly transitioning from flight deck-managed to controller-managed crossing time conformance is new, but should not be problematic, since the two activities do not overlap.

→ *Who is involved:* Pilots who have been assigned RTA clearances; air traffic controllers in the facilities adjacent to the transition boundary.

3. TBFM Operations

TBFM procedures are unchanged under IDM. Controllers manage the traffic in their sectors to absorb the delays shown on their displays. Tower controllers from airports within both TBFM regions call the en route facility to request 'call-for-release' departure times when an aircraft is ready to depart. STMCs use the TBFM interface to schedule these departures, and should follow these two 'best practices' during IDM operations:

- Inter-arrival spacing within the CTOP-conditioned inbound flow will include slack capacity intended to accommodate the TBFM-scheduled departures. STMCs should use the TBFM departure-scheduling option that allows the pre-departure to be scheduled ahead of unfrozen airborne flights that have XM or MF STAs that are later than its STA. This practice will help the pre-departure capture its intended slot and avoid a possible loss of throughput.[18]

[‡]The post-departure phase may include en route management of the flight's conformance to a target CT for an FEA located near the first TBFM freeze horizon. CT conformance may be managed by the flight crew (e.g., using the flight management system's RTA capabilities), or by the en route controllers using speed clearances and vectors. The flight crew, controller, traffic management, and dispatcher roles and responsibilities have not yet been decided for this activity, and different options are currently being explored with stakeholders. The description in this document represents a solution that assigns CT conformance to the flight crew as RTA clearances, and represents the procedures that were used during the proof-of-concept HITL.

- STMCs should check that the TBFM-scheduled departure time is reasonably close to the EDCT to maintain integrity of the original CTOP plan.

→ *What's new:* Departure scheduling 'best practices.'

→ *Who is involved:* Air traffic controllers and STMCs at the ARTCCs responsible for TBFM scheduling and metering to the destination airport.

III. Proof-of-Concept Simulation

A. Experiment Design

A proof-of-concept HITL was conducted in January 2016 in the Airspace Operations Laboratory at NASA Ames Research Center to evaluate IDM operations in a human-in-the-loop simulation of the EWR arrival problem.

The experiment had two high-level goals. One was to explore potential IDM benefit in terms of the following operational objectives:

- Demand Management (how close observed throughput and demand are to target values)
- Efficiency (reduced airborne and total delay)
- Predictability (stability of arrival and departure schedules)
- Equity (of delay impact between the close-in TBFM-scheduled departures and longer flights)

The second goal was to assess the importance of CT assignment to the flight deck in the form of RTA clearances. Although RTA clearances should improve CT conformance, it is not clear how much that will affect observed IDM benefits.

The experiment used a within-subjects 3x2 design with the independent variables *operational condition* and *traffic scenario*. Each combination of condition and scenario was run once, for a total of six runs. Runs lasted three hours with two runs completed per day. Experimental data collection was completed in three days.

1. Conditions

The three operational conditions were:

- Baseline: which simulated today's use of miles-in-trail metering to pre-conditioning traffic for TBFM
- EDCT: an IDM condition that used CTOP-derived EDCTs to control TBFM entry times
- EDCT+RTA: an IDM condition that used CTOP-derived EDCTs plus RTA clearances to control TBFM entry times

2. Traffic Scenarios

Only EWR arrival traffic was included in the traffic problem to manage the scope of the simulation. Two traffic scenarios were created. Both had a realistic distribution of domestic arrivals with local peaks and valleys in the traffic demand. The heaviest flows arrived from the south through Washington Center (ZDC) and the west through Cleveland Center (ZOB), and the load distribution between these flows varied throughout the run. A third, lighter flow from the north through Boston Center (ZBW) included a mix of domestic short haul flights and international arrivals that crossed the North Atlantic. These international arrivals were mostly wide-body jets in the 'heavy' weight class that require larger inter-arrival spacing at the runway and therefore reduce arrival throughput.

The two traffic scenarios, identified as 'Distributed' and 'Gaggle,' differed in terms of timing of the North Atlantic international traffic within the problem. In the Distributed scenario, these arrivals were distributed throughout the simulation run, while in the Gaggle scenario they were clustered near the end of the run, causing a late spike in demand when this gaggle of heavy jets arrived.

Average demand was the second characteristic that differed between the scenarios. During the Gaggle run it averaged 44 aircraft/hour (matching the requested AAR or 'called rate' of 44) and in the Distributed run it exceeded the called rate, averaging 48 aircraft/hour.

At the beginning of each run there were only a few airborne flights in the TBFM region, but traffic built up fairly quickly as aircraft crossed the XM freeze horizon and took off within the TBFM regions. The first aircraft landed after 90 minutes of run time. TBFM-scheduled departures comprised about 30% of the traffic in both scenarios, and the same light winds were present in all runs. Scripted departure errors were added to the scheduled departure times, so that actual departure time conformance had a similar distribution to that observed among EWR arrivals today during EDCT or TBFM departure time control.

3. Participants

Eight retired FAA facility personnel with extensive and varied traffic management backgrounds served as SME participants during the simulation. Seven of them had worked as STMCs and/or traffic management officers at NY TRACON, ZOB, ZBW, ZDC, New York Center (ZNY), Fort Worth Center (ZFW), and Oakland Center (ZOA); two of these individuals were involved in the design of TBFM adaptations for New York's airports. The other participant was a retired traffic manager from the Command Center. Four of the SMEs rotated through the two TFMS Planner positions, and four through the two TBFM positions.

Three retired controllers worked 'confederate' controller positions that supported the simulation. Two acted as 'super-sector controllers' whose responsibility was to issue clearances to aircraft in the TBFM XM region to meet assigned STAs at the XMP. The third acted as a super-sector confederate who issued MIT spacing clearances to the aircraft in the TFMS region during the Baseline condition. All simulated aircraft were flown by experienced pseudo-pilots.

B. Simulation Environment

1. TFMS Station

Multi-Aircraft Control System (MACS) software[19] was used to prototype the Command Center 'TFMS' Planner stations as well as the supporting sector controller and pseudo-pilot stations. MACS software provides a high fidelity environment in which to prototype scheduling tools, simulate air traffic, and collect data. The Planner stations included a customized MACS En Route Automation Modernization (ERAM) display emulation that allowed the Planners to view and manipulate traffic, FCA/FEAs, and FCA/FEA timelines. Planners could enter commands to assign departure times (CTOP EDCTs), send RTA clearances, and exempt pre-departures or airborne flights from CTOP delays. The MACS simulation also exchanged flight data and schedule information with an in-house CTOP emulation called 'nCTOP' that provided the interface for CTOP capacity and demand management operations during the simulation. Finally, the planners also had a separate display that allowed them to monitor TBFM operations. The Planners' different tools and displays are shown in Figure 4.

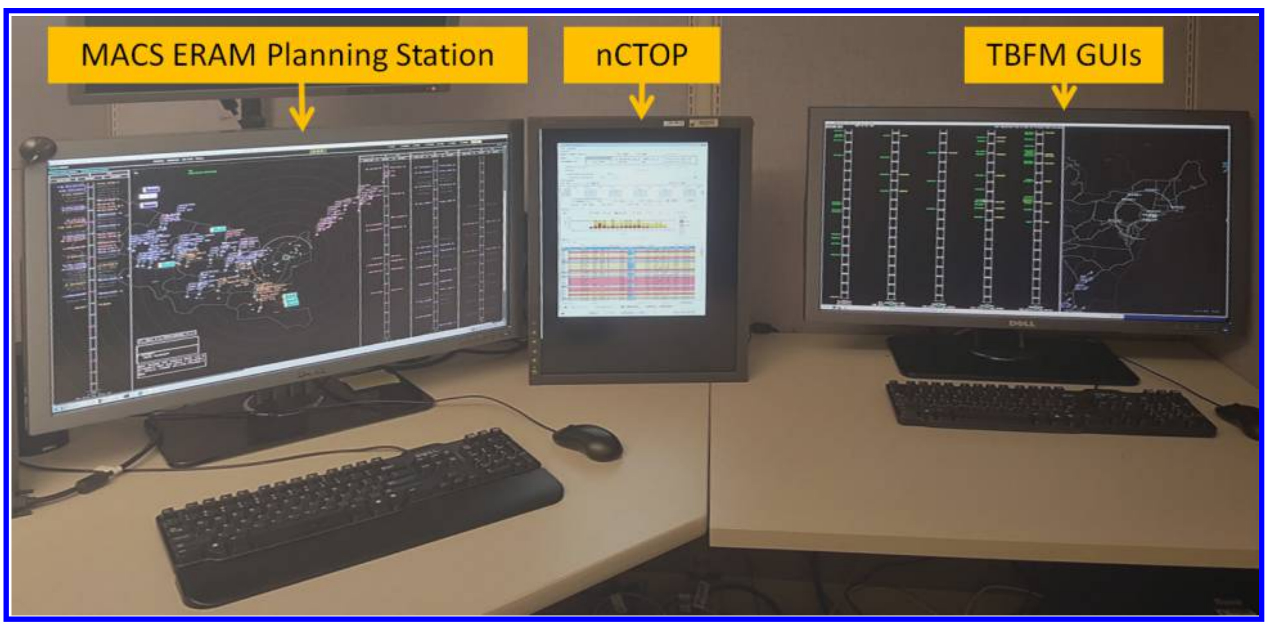

Figure 4. IDM planning tools: 'MACS' ERAM Planning Station, nCTOP and TBFM.

nCTOP presented the predicted demand for one or more user-selected FCAs in 15, 30 or 60 minute time bins, and provided an interface for entering capacity values to manage the demand. Figure 5 shows an nCTOP display with demand and capacity values presented in tables and bar graphs, and a flight list that includes scheduled departure times, FCA expected and scheduled crossing times, scheduled delays, and current flight plans. The traffic demand bar charts color-coded all airborne flights in red and non-TBFM pre-departures in yellow, and TBFM pre-departures were shown in gray. nCTOP also provided the interface for Planners to enter capacity values for 15 minute bins that were then sent to MACS and used to adjust settings on the MACS FCA schedule.

During the simulation nCTOP was used to manage the EWR arrival rate by limiting the capacity at the inner FCA Ring (FR) located at a 40 nm radial distance from EWR. Implementing the CTOP TMI involved setting the capacity values in nCTOP, then sending them to MACS, where the FR schedule would then be adjusted and new EDCTs sent to eligible pre-departures. After the EDCTs were processed, and FR ETAs had changed, MACS sent the new departure times and ETAs back to nCTOP and its demand predictions and flight list contents were updated.

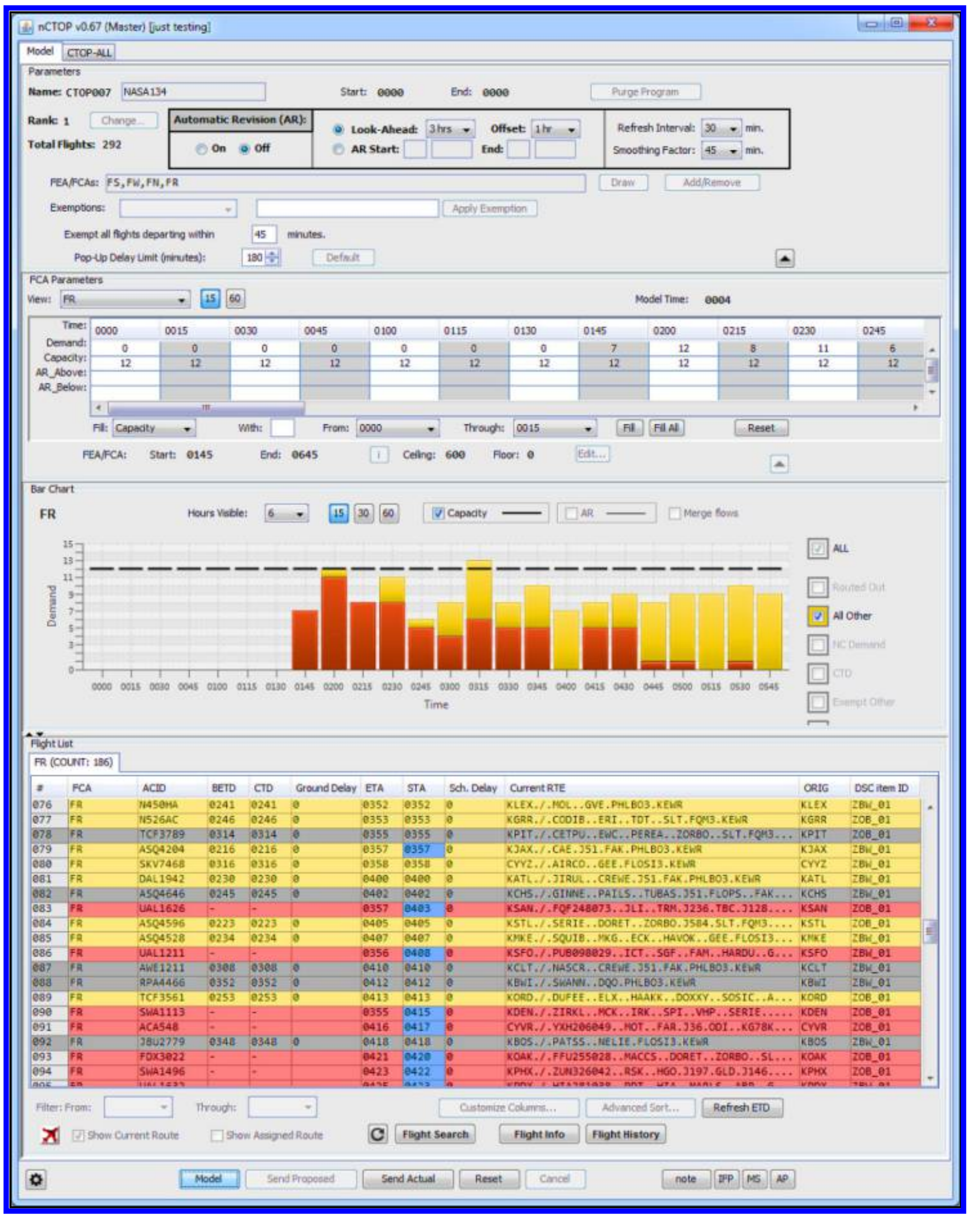

Figure 5. nCTOP Interface.

2. *TBFM Stations*

The TBFM software used for this evaluation was a NASA-modified version of operational release 4.2.3. Each TBFM position had a Timeline Graphical User Interface (TGUI) and a Planview GUI (PGUI), as shown in Figure 6. The TGUI (left) shows multiple timelines for the EWR arrival meter fix scheduler. The PGUI (right) shows the TBFM freeze horizons as cyan arcs along with the meter fixes and the incoming traffic.

The IDM simulation used a custom TBFM adaptation for EWR that included an 'outer' Extended Metering (XM) en route scheduler, and an 'inner' Meter Fix (MFX) arrival scheduler, with MFX freeze horizons (FHs) placed 140nm from their respective meter fixes.[11] A 'rolling freeze' was implemented in which flights were frozen on an XM schedule after they crossed the XM FH, then subsequently unfrozen after crossing the XMP. Shortly after that they crossed the MFX FH and froze on the MFX and runway schedules. For the rolling freeze, a gap of 5 nm was placed between the XMPs and MFX FHs. All flights were scheduled to land on Runway 22L.

In the two-stage XM and MF scheduling system, any airborne delay exceeding the 2 minute delay thresholds in the MF schedule was delegated to the XM schedule as *passback delay*, meaning that the excess delay from the MF schedule should have been transferred (or passed back) to the XM schedule.

TBFM-schedule departure airports were defined in the adaptation so that all departures from airports within or immediately outside the MFX FHs, were scheduled from the MF TGUI, and all departures from airports within or just outside the XM region were scheduled from the XM TGUI.

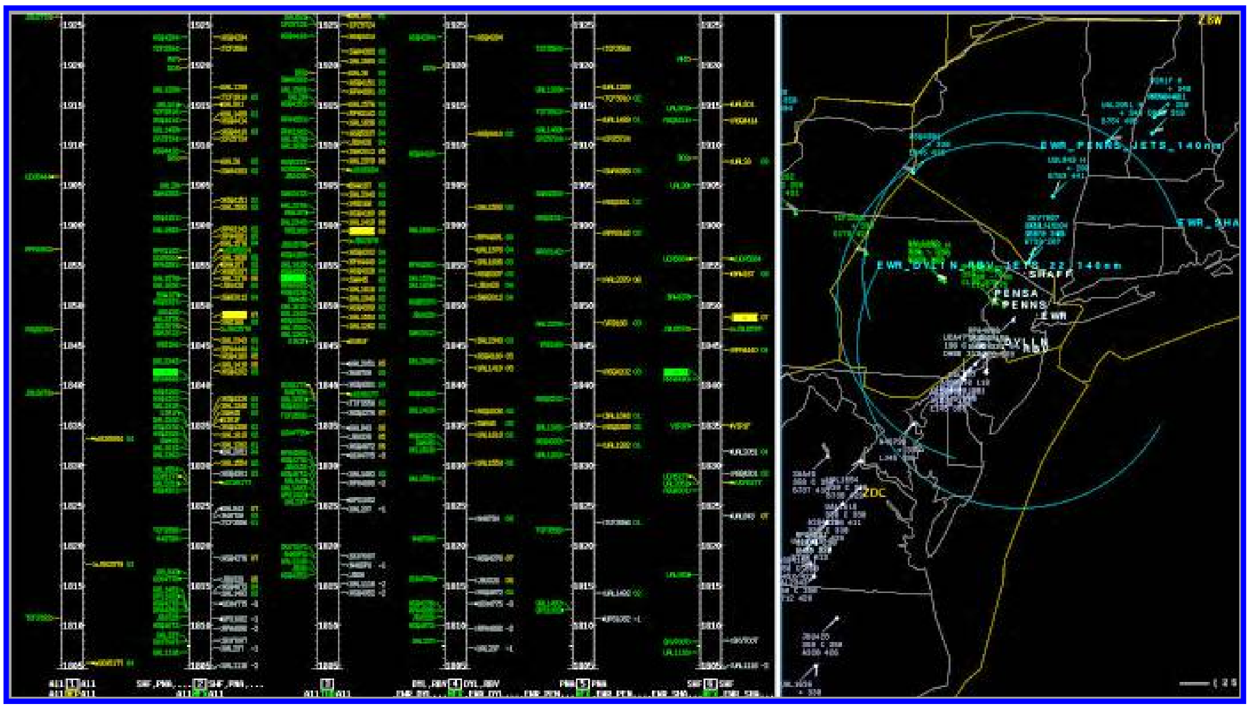

Figure 6. Arrival TGUI (left) and PGUI (right) for EWR airport.

C. Procedures

In this study, the traffic problem was worked at the traffic flow management level, with the TFMS and TBFM teams using nCTOP and TBFM schedules for scheduling departure times, FCA entry times, and TBFM STAs according to the procedures described in the Operations section. After the schedules were set, confederate controllers and pseudo-pilots used MACS automation to execute the plan by assigning and responding to clearances for individual flights so they would conform to the nCTOP and TBFM schedules. Schedule conformance was their primary task and separation assurance was not a concern.

1. *TFMS Traffic Management*

Two TFMS Planner positions were set up in a room to represent the Command Center. The two-person team included an nCTOP manager and an RTA coordinator. The team's responsibility was to manage traffic demand over time from pre-departure to entry into TBFM region.

During the two IDM conditions (EDCT and EDCT+RTA), the nCTOP manager was responsible for initiating an nCTOP TMI at the beginning of each run. As soon as the run began, the nCTOP manager sent a command to make sure that airborne flights and pre-departures that were 30 minutes or less from their departure times were flagged as exempt, which made them ineligible for receiving nCTOP delay. The inner FR FCA capacity was then set to the airport acceptance rate of 44 aircraft per hour through the nCTOP interface. Next, an FR FCA schedule was created to deliver to this rate. After each exempt flight was assigned a target crossing time or 'slot' corresponding to its FR ETA, the remaining slots were allocated to the non-exempt departures on a first-come, first-served basis based on their arrival times. Once the schedule was established, EDCTs corresponding to the FR target crossing times were assigned to each non-exempt pre-departure. Every aircraft would then automatically depart on its assigned time plus a pre-scripted departure error that was used to approximate the conformance distribution observed in operational data. For the rest of the simulation run, the nCTOP manager's tasks were to continue to monitor the traffic conformance to the FR schedule and to respond to any requests from the other traffic managers.

During the Baseline condition the nCTOP manager monitored the traffic situation and responded to requests from the TBFM traffic managers, but otherwise did not have an active role.

The RTA coordinator position managed RTA clearance delivery and monitoring during the EDCT+RTA condition, and was not staffed during the EDCT or Baseline runs. Target times for the RTAs were generated by setting up three outer FEAs outside of the TBFM XM freeze horizons (one for each of the three major arrival flows). When nCTOP set the capacity for the FR FCA, the outer FEA crossing times were automatically anchored to the FR slot times. Once the target FEA crossing times were established, RTAs could be sent to an airborne flight. The RTAs were issued to the nearest upstream waypoint on the aircraft's flight plan prior to the FEA. In order to simplify the simulation operations, RTA clearances were sent directly to the pseudo-pilot stations and bypassed the controllers. This simulation was not intended to test procedures for RTA clearance delivery, but to look at the impact of active RTA conformance on the overall concept.

In a number of instances, the aircraft failed to meet its RTA conformance target of +/- 1 minute, usually when the scripted departure error was large. When this occurred, the RTA manager could replace the target FEA crossing time with a more achievable time, then send a revised RTA clearance. In most of these cases, however, the RTA time deviation was still within +/- 5 minutes of the scheduled time, a conformance window that our SMEs believed was adequate for TBFM to build a reasonable schedule.

2. TBFM Traffic Management

The working positions for the TBFM team included one En Route and one Arrival STMC position. The En Route STMC managed the XM schedule from the XM freeze horizon to the XMP. In the field, there would be three separate XMP positions (located at the three facilities managing the north, west, and south flows); these positions were combined for the simulation. The primary task for the En Route STMC was to manage the three XMP schedules and schedule departures that took off within the XM regions. Similarly, the Arrival STMC managed the MF schedule from the MF freeze horizon to the meter fixes and scheduled departures that took off within the MF region.

Departures were scheduled via a dialog box on the En Route or EWR Arrival TGUI (see Figure 7). EDCTs that had been assigned earlier by nCTOP would appear in the "Aircraft-Ready Time" (ptime) field. When scheduling a departure, STMCs could choose to give priority to a departing flight and delay other airborne traffic whose unfrozen STA was later than the departure. This function is activated using the "Delay Scheduled Flights for This Aircraft Only" checkbox shown in Figure 7.

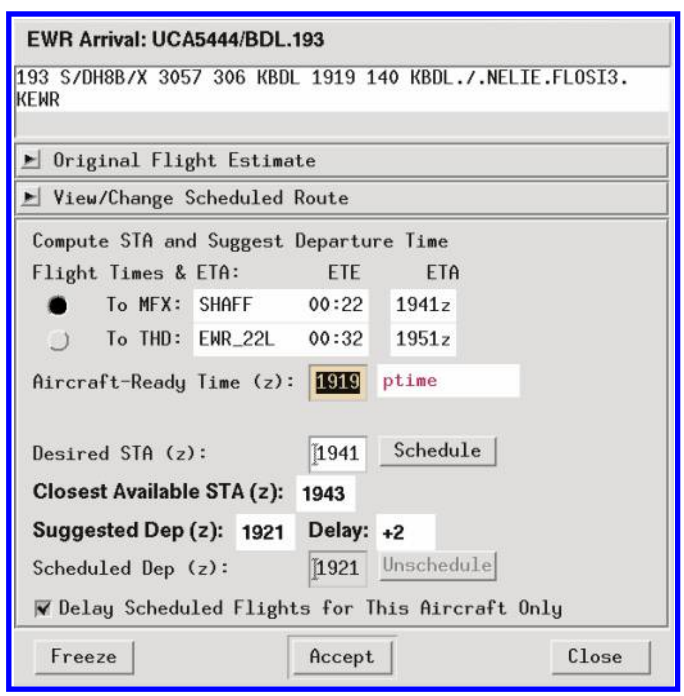

Figure 7. Arrival TGUI schedule a departure dialog.

This option was defaulted with box checked for the study, but the TBFM STMC had the authority to turn off the option on a case-by-case basis if it resulted in excessive airborne delays.

3. Air Traffic Control Support

In order to support the simulation environment in all test conditions, two controllers acted as 'super-sector controllers' to control the traffic in the TBFM XM region. These controllers were given XM meter lists on their scopes and were asked to meet the delay times coming from the TBFM XM scheduler. One controller worked the West flow and the other controller worked both the North and South flows inside the TBFM XM regions. They were instructed to use speed control and, if that was not enough, vectors or route modifications to meet the TBFM XM STAs. No controllers staffed the TBFM MF area as it was deemed unnecessary for the study objectives.

During the Baseline condition, one other controller acted as a super sector controller for aircraft in the TFMS region. This was a critically important position since this one controller was responsible for establishing the 30 MIT feeds for each of five different traffic flows entering TBFM from the west and the south. Figure 8 shows the MIT controller's scope with all 5 scheduling timelines. To manage this task given the large number of flights in the scenario, the controller used MACS support automation to set up the spacing and send clearances to the aircraft. This position also acted as the call-for-release scheduler for all departure airports outside of TBFM. At the beginning of each run he would be presented with a schedule across each flow that used a 280 second interval to approximate 30 MIT spacing. All pre-departures that were scheduled to take off 30 minutes after the start of the simulation were given slots on their respective scheduler that would result in a 30 MIT restriction per flow. As the run progressed, the MIT controller could continue to issue departure delay as needed if the overhead flow was full.

Figure 8. 'Miles-in-trail' confederate controller.

IV. Results and Discussion

High level results related to throughput, demand management, airborne delay, and ground delay are presented in this paper. The interactions between these measures for the different operational conditions are discussed. Most of the results presented below are associated with the subset of flights that crossed the meter fix before the end of the 180 minute simulation run. The exception is the Ground Delay analysis, which presents delay data for all flights that were either assigned EDCTs or 'call-for-release' departure times during the simulation.

A. Demand Management

1. Throughput

Unconditioned demand averaged 48 aircraft/hour for the Distributed scenario and 44 aircraft/hour for the Gaggle scenario. The requested AAR (called rate) for all runs was 44 aircraft/hour (11 aircraft/quarter hour). The scenarios were constructed so that participants would have an opportunity to pre-condition most of the traffic before it entered the TBFM scheduling region; hence the first arrival did not cross the EWR runway threshold until after 90 minutes of simulation run time had elapsed. Table 1 shows the number of flights that landed every fifteen minutes per condition and scenario between 90 and 195 minutes of simulation time, with the last bin including traffic that had already crossed the meter fix before the 180 minute cutoff. Table 1 also shows the total number of flights landed within 195 minutes, and the hourly landing rate for the last 90 minutes (i.e., excluding the first 15 minutes when traffic was still building up).

Within the Distributed scenarios, the landing rate of 46 aircraft/hour was higher for the Baseline run than for either the EDCT or EDCT+RTA conditions, which both landed 43.3 aircraft/hour. For the Gaggle scenario, where the unconditioned demand matched the called rate of 44, the landing rate was more similar across conditions, with 44.7 aircraft/hour for the Baseline and EDCT condition, and 43.3 aircraft/hour for the EDCT+RTA condition.

We also observed that the traffic arrived earlier in the Baseline condition: with 3 to 5 more aircraft landing within the first 150 minutes of simulation time in the Baseline runs compared to the same time period in the IDM runs. This was observed in both the Distributed and Gaggle scenarios.

Table 1. Runway Throughput per 15 Minute Interval

Condition Scenario	90-105	105-120	120-135	135-150	150-165	165-180	180-195	# of flights landed (150 min)	# of flights landed (195 min)	Hourly landing rate (105-195 min)
Baseline Distributed	9	10	13	12	12	12	10	44	78	46.0
EDCT Distributed	8	11	11	10	11	11	11	40	73	43.3
EDCT+RTA Distributed	10	10	12	9	11	12	11	41	75	43.3
Baseline Gaggle	14	12	12	10	9	12	12	48	81	44.7
EDCT Gaggle	11	13	11	8	12	13	10	43	78	44.7
EDCT+RTA Gaggle	13	11	10	9	12	11	12	43	78	43.3

We expected to see similar throughput across all three conditions, since we assumed that the called rate of 44 aircraft/hour corresponded to the actual TBFM capacity during the simulation. Instead we observed a higher throughput during the Baseline runs, which used MIT instead of CTOP to pre-condition the TBFM feed. This higher throughput was caused by a combination of factors, including (1) higher demand delivery to the TBFM freeze horizon by the confederate MIT controller during the Baseline runs, and (2) higher than expected TBFM capacity. Throughput results show that the IDM conditions did a better job pre-conditioning demand to the called rate of 44.

2. Outer Arc Crossing Time Conformance

The second demand management metric was CT conformance at the outer arc FEAs for the two IDM conditions. Table 2 shows the conformance error (Actual CT – Reference CT) for two different reference values. The 'Target CT' was the predicted outer arc crossing time associated with the inner FCA slot schedule. The Target CT was available in both the EDCT and EDCT+RTA condition, and enabled a direct between-condition comparison of conformance to the original nCTOP plan. The Target CT conformance error was larger in the EDCT condition than in the EDCT+RTA condition for both scenarios.

Assigned CT was the CT associated with the RTA clearance issued to the aircraft after it reached its initial cruise altitude. The Assigned CT was usually the same as the Target CT, but could be changed by the controller if the flight crew reported that they were unable to meet the original CT.

Table 2. Outer Arc (FEA) Crossing Time Conformance Error for all Flights

Condition Scenario	Reference	n	min	mean	SD	median	max
Baseline Distributed	Target CT	36	-13	1	4	0	19
EDCT Distributed	Target CT	36	-4	1	3	1	17
EDCT+RTA Distributed	Assigned CT	36	-1	1	3	1	16
Baseline Gaggle	Target CT	33	-5	2	5	1	19
EDCT Gaggle	Target CT	33	-1	2	4	1	24
EDCT+RTA Gaggle	Assigned CT	33	-1	1	1	1	8

The histograms in Figure 9 show the distribution of conformance errors for the Target and Assigned CT. Plots for both the Gaggle and Distributed scenarios show a similar pattern as Table 2. Comparing the conformance to crossing time target distributions, one sees a larger variance in the EDCT runs (SDs 4 and 5) than in the EDCT+RTA runs (SDs 3 and 4). This is highlighted by the aircraft counts in the 0-2 minute bins, which is 11 and 14 for the EDCT condition, and 27 and 25 for the EDCT+RTA condition. For the EDCT+RTA condition, the metric 'conformance to assigned target' shows similar, but even tighter conformance, with 0-2 minute bin values of 32 (Distributed) and 26 (Gaggle).

These results indicate that, as expected, active in-flight RTA control will result in tighter conformance to the Target CT, and thus the CTOP-planned demand for the TBFM scheduling region. Furthermore, the difference between the Target and Assigned CT was small, suggesting that there were only a few cases in which the CT based on the inner FCA slot times needed adjustment to provide a more achievable CT.

Although the RTA clearances improved the crossing time conformance, it was already fairly accurate in the EDCT condition, within +/- 4 minutes for most flights. Since this is probably within the margins of the delivery error that could easily be absorbed by the downstream TBFM scheduling, one might conclude that RTA clearances would provide only incremental benefits.

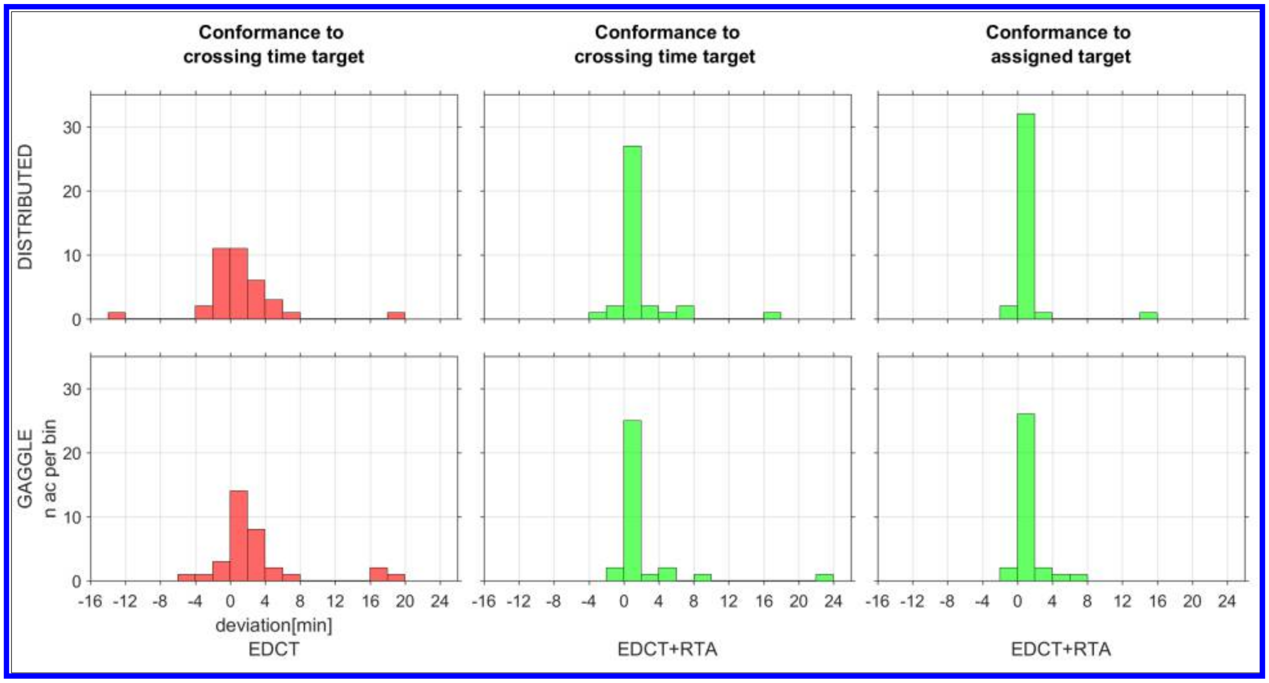

Figure 9. Histogram of the crossing time conformance error.

There are, however, *two* significant sources of error in the absence of RTA assignment. The first is poor EDCT conformance; i.e., if the flight takes off 8 minutes later than its assigned EDCT, it is likely to arrive 8 minutes late. The second is an incorrect ground speed estimate: a 5% mismatch between estimated and actual ground speeds (caused, for instance, by a wind forecast error), could result in a 6 minute error after 2 hours of flight time. Although the simulation did include a realistic distribution of departure errors, the simulated winds were unusually light, and the wind forecast errors were small. A follow-up study is underway that will test a range of different wind conditions to better understand the potential importance of RTA clearances to IDM.[20]

B. TBFM-Assigned Airborne Delay

As described in the previous section, throughput during the Baseline Distributed run averaged 46 aircraft/hour, indicating that TBFM capacity was higher during the simulation than the target AAR of 44. This higher capacity resulted in delays that were *lower* than expected during the Baseline, although observed between-condition differences in TBFM airborne delays indicate that Baseline runs still over-delivered to TBFM. These delay differences were, however, much more modest than they would have been had the TBFM capacity actually been 44 aircraft/hour.

TBFM-assigned airborne delay values were classified as 'acceptable,' 'marginal' or 'unacceptable,' based on a workload and impact assessment by the SME specialists on the team. The maximum 'acceptable' delay was set to the maximum-delay-time parameter setting for the TBFM scheduling region. The maximum 'marginal' delay was set at a value that the SMEs thought would probably be manageable for a few flights for short periods of time, but not sustainable due to workload. ‘Unacceptable’ delays were high enough to result in holding or noncompliance. These values differed for the two TBFM regions because of structural differences between the XM and MF sectors.

1. Airborne Delay in the Extended Metering Region

Table 3 shows the assigned airborne delay categories in minutes for all aircraft that entered the XM region by crossing its freeze horizon in level flight; i.e., their departure airports were located well outside the XM freeze horizon. Airborne delay for 37 of these aircraft was classified as ‘acceptable’ and for 11 aircraft as ‘marginal’ during the Baseline Distributed run. By contrast, the airborne delay was ‘acceptable’ for all 50 aircraft in the EDCT Distributed run and all 48 aircraft in the EDCT+RTA Distributed run. Between-condition differences for the Gaggle runs were smaller: with 43 (Baseline), 41 (EDCT) and 45 (EDCT+RTA) ‘acceptable’ delays; 1 (Baseline), 4 (EDCT) and 0 (EDCT+RTA) ‘marginal’ delays, and no ‘unacceptable’ XM airborne delays.

Table 3. Extended Metering Region Airborne Delay, in Minutes

Condition Scenario	‘acceptable’		‘marginal’	‘unacceptable’	N
	-5 < D ≤ 0	0 < D ≤ 5	5 < D ≤ 10	10 < D	
Baseline Distributed	0	37	11	0	48
EDCT Distributed	8	42	0	0	50
EDCT+RTA Distributed	1	47	0	0	48
Baseline Gaggle	3	40	1	0	44
EDCT Gaggle	6	35	4	0	45
EDCT+RTA Gaggle	0	45	0	0	45

The same data are shown in the histograms in Figure 10. The figure shows airborne delays for most aircraft between 0 to 2 minutes during the EDCT and EDCT+RTA runs. The distribution for the Baseline run was similar to the two IDM runs for the Gaggle scenario, but flatter than the IDM runs for the Distributed scenario. This flatter delay distribution was likely due to the additional spacing needed to reduce the 48 aircraft/hour demand delivered into TBFM to a lower runway threshold capacity. All other runs, including the two IDM Distributed runs, had incoming TBFM demand that was lower than the actual TBFM capacity, so airborne delays were fairly modest overall. The higher airborne delays for the EDCT condition when compared to the EDCT+RTA condition might indicate that better-controlled entry times have a positive impact on airborne delay.

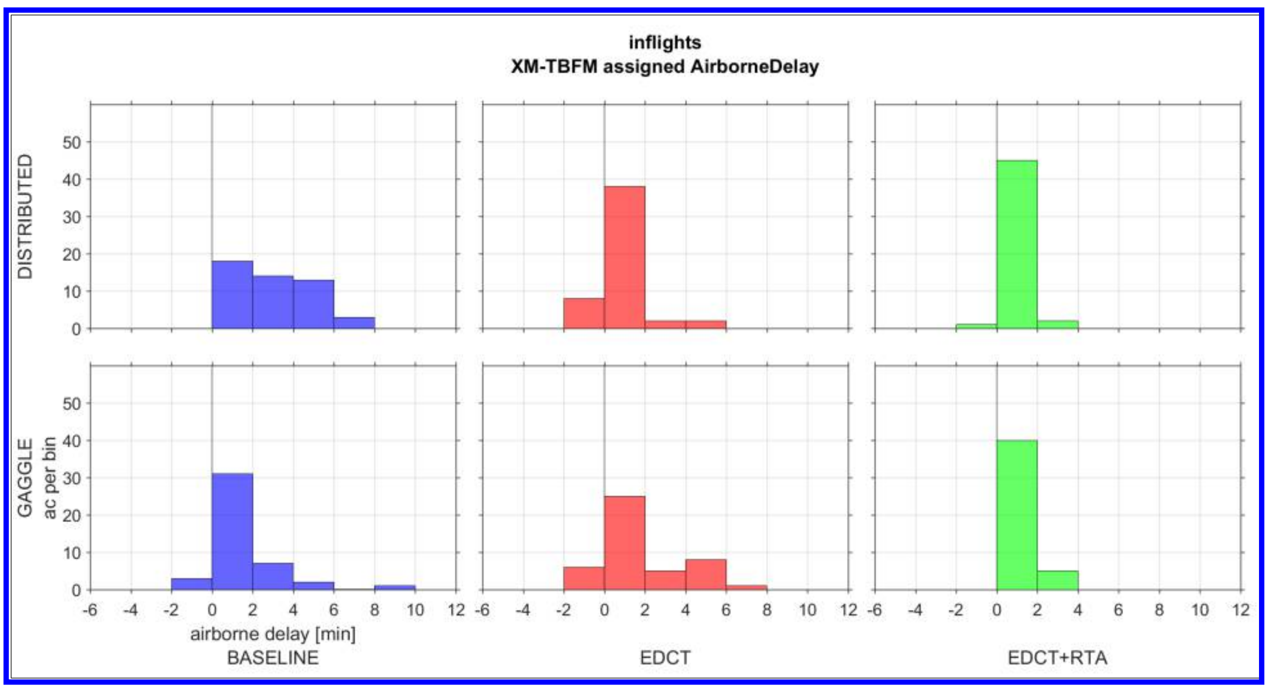

Figure 10. Histogram of airborne delays in the extended metering region.

2. Airborne Delay in the Meter Fix Region

Table 4 presents the assigned airborne delay categories in minutes for the meter fix region. As with the previous extended metering results, all aircraft included in the analysis flew across the MF freeze horizon. For the Baseline Distributed run, 29 aircraft had 'acceptable' airborne delays, and 29 aircraft had 'marginal' delays, compared to 40 'acceptable' and 22 'marginal' for both the EDCT and EDCT+RTA Distributed runs. Delays for the Baseline Gaggle and EDCT Gaggle runs in the MF region showed the same trend as they did in the XM region, with fewer 'acceptable' delays in the Baseline (41) than in the EDCT condition (54). This time, however, the EDCT+RTA condition had only 43 'acceptable' airborne delays, more closely resembling the Baseline than the EDCT condition. In addition, the Baseline and EDCT+RTA runs both had 22 aircraft classified as 'marginal', compared to 11 in the EDCT condition. And finally, unlike the earlier XM results, we now observed airborne delays rated as 'unacceptable.' With more 'unacceptable' delays assigned in the Baseline (9) compared to the EDCT (6) and EDCT+RTA (5) runs for the Distributed scenario, and one in each condition during the Gaggle scenario.

Table 4. Meter Fix Region Airborne Delay, in Minutes

Condition Scenario	'acceptable'		'marginal'	'unacceptable'	N
	-2 < D ≤ 0	0 < D ≤ 2	2 < D ≤ 4	4 < D	
Baseline Distributed	1	28	29	9	67
EDCT Distributed	2	38	22	6	68
EDCT+RTA Distributed	0	40	22	5	67
Baseline Gaggle	3	38	22	1	64
EDCT Gaggle	2	52	11	1	66
EDCT+RTA Gaggle	3	40	22	1	66

These data are also depicted in the set of histograms in Figure 11. Once again, the delay distribution patterns are similar for five of the six runs, with the Baseline Distributed run showing a flatter distribution. The Baseline Distributed also had the highest airborne delay values, and many more 'marginal' and 'unacceptable' delays compared to the two IDM Distributed runs.

It should be noted that the IDM concept assumes that TBFM coupled scheduling will pass most of the excess airborne delay in the MF region back to the XM scheduler where it can be managed more effectively. In this simulation, however, the passback delay function was not working correctly for TBFM-scheduled departures in the XM region. With fully functional delay passback in effect, the numbers of 'marginal' and 'unacceptable' delays in both regions is expected to decrease, since more delay will be absorbed on the ground in the XM region.

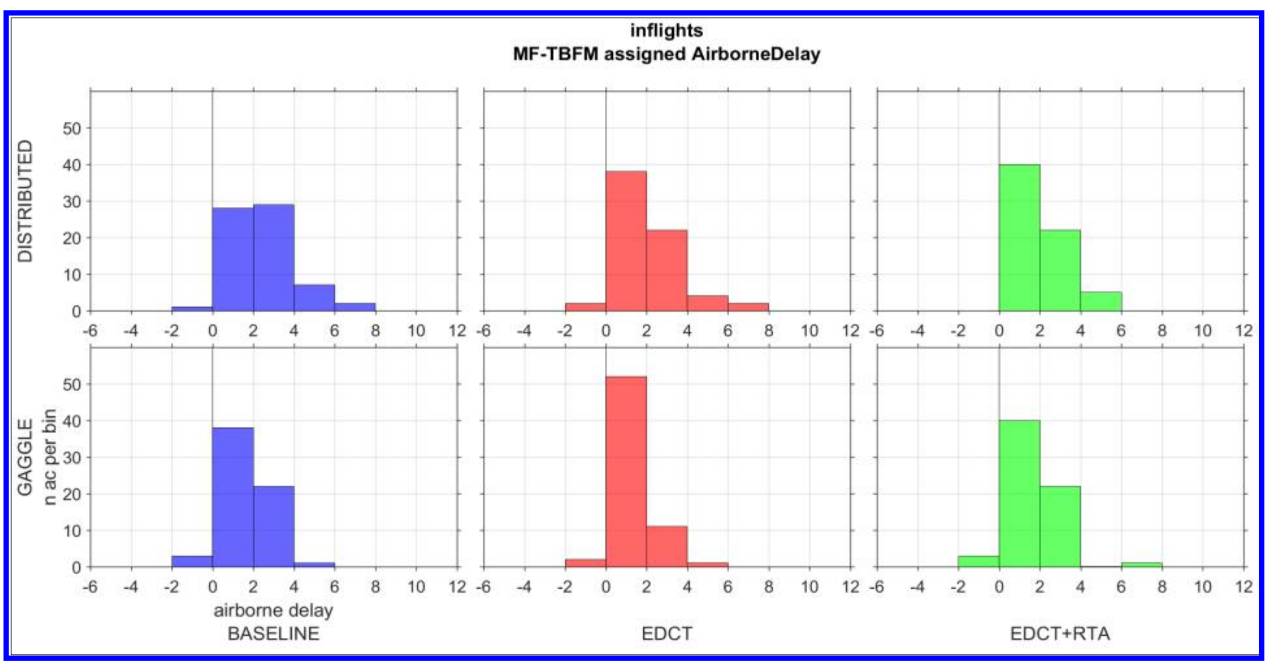

Figure 11. Histogram of airborne delays in the meter fix region.

In Table 5 the TBFM airborne delay acceptability data is consolidated by condition to highlight the potential for IDM to deliver more manageable traffic demand into TBFM. In today's operations, an over-delivery of traffic into TBFM can result in a high number of aircraft with either 'marginal' or 'unacceptable' airborne delays; as indicated by the results in Table 5, CTOP pre-conditioning should reduce this problem. Furthermore, since the Baseline condition landed more aircraft than the IDM conditions in our simulation, we expect that if the 'true' TBFM capacity had actually been 44 as we intended, the observed difference between Baseline and IDM would have been even larger.

Table 5. TBFM Airborne Delay Acceptability by Condition (Regions and Runs Combined)

Condition	'acceptable'	'marginal'	'unacceptable'	N
Baseline	150	63	10	223
EDCT	185	37	7	229
EDCT+RTA	176	44	6	226

C. Ground Delay

The scatter plots in Figure 12 show the ground delays assigned by TBFM and TFMS to all non-exempt flights, plotted against the flight's final TBFM-scheduled runway threshold STA. Based on the flight's departure location, data were sorted into three different groups: TBFM XM Departures, TBFM MFX Departures, and 'non-TBFM' Departures, whose departure airport was upstream and outside the TBFM scheduling regions. TFMS delays were assigned either by CTOP (in the IDM conditions) or by the MIT confederate controller for miles-in-trail spacing (Baseline condition). During the EDCT and EDCT+RTA conditions, all flights received an EDCT, and those departing from within the two TBFM regions could receive an additional TBFM departure delay. During the Baseline condition, the ground delay was due *either* to miles-in-trail pre-TBFM conditioning (for the non-TBFM departures) *or* to TBFM (for the XM and MF departures).

These plots show how the ground delay magnitude changes through the run. Note, for example, how it continues to build up throughout the two IDM Distributed runs, since the demand exceeded the called rate throughout the scenario. Note also that these plots include an hour of data (hours 3-4) from flights that would have arrived after the run had ended. Although these flights were excluded from the earlier demand management and airborne delay analyses, their threshold STAs were assigned before the 3 hour run ended, and the additional samples clarify the patterns observed in the data. Although it is difficult to draw strong conclusions, there are several observations that can be made.

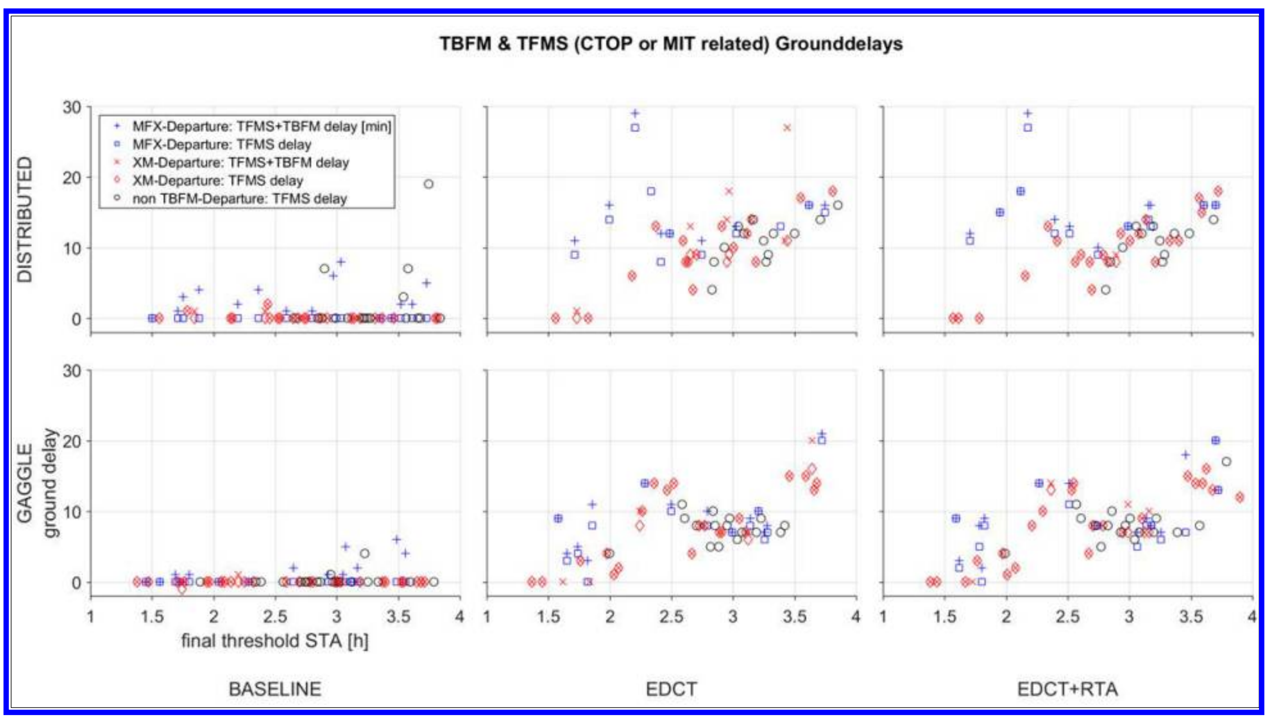

Figure 12. Scatter plot of TBFM and TFMS ground delays.

Baseline Runs. Prior to the study, the Baseline condition was expected to show lower ground delays for the aircraft departing from the TFMS region (since no EDCTs were assigned), and much higher airborne and ground delays in the TBFM region when demand exceeded 44 aircraft/hour. Because the TBFM capacity was higher than expected, however, the impact on TBFM delays during the Baseline runs was greatly reduced. A follow up study will be conducted with the TBFM arrival rate more closely calibrated to the intended value, and with more realistic MIT emulation procedures, which should provide a better comparison of IDM to the Baseline.

EDCT and EDCT+RTA Runs. Comparison of the TFMS vs. TFMS+TBFM delays show that most of the ground delay assigned to the XM and MFX departures came from TFMS (i.e., CTOP EDCTs), with little or no additional delay contributed by the TBFM system. Note also that although the delay distributions for the two IDM conditions were remarkably similar for both the Distributed and Gaggle scenarios, the somewhat tighter spacing between paired TFMS and TFMS+TBFM values suggests that the RTA component may have had a modest impact on TBFM ground delays.

As expected, the delays increased through the course of the simulation for the Distributed runs since the demand significantly exceeded the target capacity. During the Gaggle runs, however, the delay appeared to build up during the first 2.5 hours of the run, then dissipate, then build up again during the last half hour when the gaggle of heavy jets showed up.

Many of the longer flights that landed earlier in the run were exempt from the CTOP when the EDCTs were first assigned, either because they were within 30 minutes of departure, or already airborne. Non-TBFM departures do not appear on these plots until around 2.5 hours into the simulation (the first black circle in Figure 15). After 2.5 hours, however, the ground delays assigned to flights from all three scheduling regions appear to vary in a similar fashion as a function of their threshold STA. This suggests that IDM can distribute ground delays equitably across aircraft with varying flight distances once the program is well established. Between hours 1.5-2.5 earlier in the run, however, large ground delays are associated with the TBFM departures, particularly in the MFX region, when those were the only flights eligible for delay assignment. Although more analysis is needed to fully understand these delays that occur early in the run, it is worth noting that they were primarily CTOP and not TBFM-assigned delays, indicating that the operators would have had more opportunity to react to their anticipated impact.

D. Summary of Results

The simulation had two high level goals. The first was to explore the potential benefit of CTOP pre-conditioning of demand into TBFM and the second was to assess the importance of RTA assignment (in-flight control of crossing time conformance) to the IDM concept.

Due to the mismatch of the throughput between conditions, comparisons of both airborne and ground delays were not straightforward, and the delay metrics and potential benefits of IDM would have been much easier to assess with a comparable landing rate for all three conditions. These interactions between demand management, assigned airborne delays, and actual ground delay have been discussed extensively. We argue that with a better match between the target demand and actual TBFM capacity the ‘excess’ demand in the Baseline condition would have resulted in much higher airborne delay, instead of an apparent improvement in throughput with only a modest delay increase. Nevertheless, with respect to the first high level goal, the closer match to the target demand in the IDM conditions nicely illustrates the advantage of using CTOP to pre-condition traffic into TBFM. Further potential benefits of CTOP pre-conditioning such as equity and predictability have not been analyzed yet.

In spite of the complications that were just described, the airborne delays observed in the TBFM region were lower and more operationally acceptable in the two IDM conditions compared to the Baseline. When the EDCT condition was compared to EDCT+RTA, the benefits of RTAs were not clear in the simulation runs that utilized realistic departure errors but light winds. The results showed higher conformance to the outer arc FEAs with the RTAs but the overall patterns of throughput and delays at the runway threshold were quite similar between the two conditions. Both IDM conditions also delivered similar magnitude delays for the TFMS, XM, and MF region departures after the CTOP preconditioning had taken effect, showing IDM's potential for distributing delays more evenly across the regions. With respect to the second high-level goal of evaluating the importance of RTA assignment, it can only be concluded that although RTAs did not show a strong impact in this simulation, the results are somewhat inconclusive and need further exploration under more realistic conditions.

Finally, our under-estimate of the simulated TBFM capacity also called our attention to the potential for IDM to under-deliver if the targeted demand is less than the available capacity. One solution to this, of course, is to bias the demand towards a slight over-delivery. More interesting, however, is the way it highlights the need for a tool that could provide a closer estimate of true capacity. Along with more tactical methods for fine-tuning the demand, an improved ability to estimate capacity over both long and short planning horizons could help prevent both over and under-delivery, and warrants further exploration.

V. Conclusion

High-level results from a proof-of-concept human-in-the-loop simulation suggest that the IDM concept shows promise of delivering some of its intended benefits. Two immediate follow-up simulations are planned. One is a targeted study that will more thoroughly characterize crossing time conformance improvements that might be gained when comparing EDCT and EDCT+RTA control methods for a CTOP TMI. The other is a second proof-of-concept data-collection HITL, with changes to several features of the scenario and simulation environment (including stronger winds, longer run duration, and a modified TBFM setup) based on the insights described in this paper.

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