Integrated Demand Management: Minimizing Unanticipated Excessive Departure Delay while Ensuring Fairness from a Traffic Management Initiative

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This paper introduces NASA's Integrated Demand Management (IDM) concept and presents the results from an early proof-of-concept evaluation and an exploratory experiment. The initial development of the IDM concept was focused on integrating two systems—i.e. the FAA's newly deployed Traffic Flow Management System (TFMS) tool called the Collaborative Trajectory Options Program (CTOP) and the Time-Based Flow Management (TBFM) system with Extended Metering (XM) capabilities—to manage projected heavy traffic demand into a capacity-constrained airport. A human-in-the-loop (HITL) simulation experiment was conducted to demonstrate the feasibility of the initial IDM concept by adapting it to an arrival traffic problem at Newark Liberty International Airport (EWR) during clear weather conditions. In this study, the CTOP was utilized to strategically plan the arrival traffic demand by controlling take-off times of both short- and long-haul flights (long-hauls specify aircraft outside TBFM regions and short-hauls specify aircraft within TBFM regions) in a way that results in equitable delays among the groups. Such strategic planning decreases airborne and ground delay within TBFM by delivering manageable long-haul traffic demand while reserving sufficient slots in the overhead streams for the short-haul departures. A manageable traffic demand ensures the TBFM scheduler does not assign more airborne delay than a particular airspace is capable of absorbing. TBFM uses its time-based metering capabilities to deliver the desirable throughput by tactically coordinating and scheduling the long-haul flights and short-haul departures. Additional research was performed to explore the use of Required Time of Arrival (RTA) capabilities as a potential control mechanism to improve the arrival time accuracy of scheduled long-haul traffic. Results indicated that both short- and long-haul flights received similar ground delays. In addition, there was a noticeable reduction in the total amount of excessive, unanticipated ground delays, i.e. delays that are frequently imposed on the short-haul flight in current day operations due to saturation in the overhead stream, commonly referred to as 'double penalty.' Furthermore, the concept achieved the target throughput while minimizing the expected cost associated with overall delays in arrival traffic. Assessment of the RTA capabilities showed that there was indeed improvement of the scheduled entry times into TBFM regions by using RTA capabilities. However, with respect to reduction in delays incurred within TBFM, there was no observable benefit of improving the precision of entry times for long-haul flights.

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Nomenclature

AAR	=	Airport Acceptance Rate
AC	=	Adjusted Cost
AFP	=	Airspace Flow Program
APREQ	=	Approval Request
ARTCC	=	Air Route Traffic Control Centers
ATCSCC	=	Air Traffic Control System Command Center
CDM	=	Collaborative Decision Making
CFR	=	Call-For-Release
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
ETA	=	Estimated Time of Arrival
EWR	=	Newark Liberty International Airport
FAA	=	Federal Aviation Administration
FCA	=	Flow Constrained Area
FH	=	Freeze Horizon (TBFM)
FSFS	=	First-Scheduled-First-Served
GDP	=	Ground Delay Program
GUI	=	Graphical User Interface
HITL	=	Human-in-the-loop
IAT	=	Initial Arrival Time
IDM	=	Integrated Demand Management
MACS	=	Multi-Aircraft Control System (NASA ATC simulation platform)
MFX	=	Meter Fix (TBFM)
MIT	=	Miles-in-Trail
NAS	=	National Airspace System
nCTOP	=	NASA CTOP emulation
nm	=	Nautical mile
NOAA	=	National Oceanic Atmosphheric Administration
PGUI	=	Planview Graphical User Interface (TBFM)
RAP	=	Rapid Refresh
RBS	=	Ration-by-Schedule
RTA	=	Required Time of Arrival
RTC	=	Relative Trajectory Cost
SME	=	Subject Matter Expert
STA	=	Scheduled Time of Arrival
STMC	=	Supervisory Traffic Management Coordinators
TBFM	=	Time-Based Flow Management
TFM	=	Traffic Flow Management
TFMS	=	Traffic Flow Management System
TGUI	=	Timeline Graphical User Interface (TBFM)
THD	=	Runway Threshold
TMI	=	Traffic Management Initiative
TOS	=	Trajectory Options Set
TRACON	=	Terminal Radar Approach Control
XM; XMP	=	Extended Metering; Extended Metering Point (TBFM)
ZNY	=	New York Center
ZOA	=	Oakland Center

I. Introduction

NASA Ames researchers working under the Airspace Operations and Safety Program are developing a near- to mid-term concept called Integrated Demand Management (IDM) [1]. The overarching goal of the IDM is to explore more effective ways of managing traffic demand proactively by preempting the potential mismatch between demand and resources with limited capacity in the National Airspace System (NAS). This improved performance is achieved by avoiding congestion while at the same time supporting safety, efficiency, and effectiveness of overall traffic management. Capacity constrained resources in the NAS include airport departure and arrival runways, airspace sectors, flow corridors, and air traffic facilities and staffing. Capacity represents the maximum number of aircraft that an identified resource, such as an airport, can safely transit or accept during a specified time interval. Capacity is normally measured as a flow rate or the number of aircraft per hour. Demand is the number of aircraft scheduled to transit into or out of the identified resource during a specified time interval. The roots of such capacity/demand mismatches can vary from spatial and temporal limitations on routes and waypoints while accepting the high traffic demand, to convective weather (e.g., severe thunderstorm) limiting the flow permeability of air sectors [1]. Such mismatches are the causes of approximately 88 % of all delays in the NAS, impacting the overall performance of air traffic operations [2].

Currently, there are several existing Traffic Management Initiatives (TMI), which are tools and techniques developed to resolve local capacity/demand imbalances by adjusting aggregate traffic flows to match scarce capacity resources [3]. For example, a Ground Delay Program (GDP) is one of the initiatives used to reduce the rate of arrival traffic into an airport when the demand is projected to exceed the airport capacity [4, 5]. Although TMIs, such as GDP, have been implemented in the field, these programs enforce centralized system architecture on the system operators and have resulted in inefficient uses of NAS resources which have maximum capacity limits determined by the Federal Aviation Administration (FAA) [6, 7]. To overcome the limitations of currently existing initiatives, a new type of program called CTOP is introduced to allow more input from flight operators [2]. Several past studies have shown the potential benefit that could be obtained by incorporating input from flight operators [2, 8]. This new CTOP program has potential to use both flight operators' preferred reroutes and ground delays simultaneously to produce a solution that result in better utilization of one or more Flow Constrained Area (FCA) based NAS resources. An FCA is a segment of the NAS in which a capacity/demand imbalance is anticipated [9].

However, prior to exploring CTOP's new rerouting capabilities with multiple FCAs, the initial development of the IDM concept primarily focused on proactively preventing anticipated airport arrival capacity/demand imbalances during high traffic, clear weather scenarios by the ground delay capabilities of CTOP to pre-condition traffic into Time-Based Flow Management (TBFM) with Extended Metering (XM) capabilities. In the initial concept development, a ring-shaped FCA was placed around the airport, at or near the TBFM arrival Meter Fixes (MFXs). CTOP was used to monitor the initial scheduled arrival demand at the FCA, then assign capacity limits to the FCA ring that delivers what was expected to be the Airport Acceptance Rate (AAR). CTOP strategically planned the arrival traffic demand to match the capacity limits at the FCA by controlling take-off times of both short- and long-haul flights. Such controlled take-off times are called, Expected Departure Clearance Times (EDCTs). In this paper, short-hauls indicate aircraft within TBFM regions, where long-hauls indicate aircraft outside the TBFM region. Although the FCA was placed at or near TBFM arrival MFXs, there was no direct coupling between CTOP and TBFM schedulers. Potential issues with reliance on distant projections of arrival times far in advance to generate spacing and sequencing have been identified [10]. Hence, CTOP strategically managed the traffic demand flowing into the FCA, and TBFM had the final authority on re-scheduling flights tactically for more precise final arrival schedules.

The initial IDM concept and results from an early proof-of-concept Human-In-The-Loop (HITL) experiment conducted in January 2016 were presented at the 2016 ATIO conference [1]. Valuable lessons were learned in the first HITL. For example, shortcomings in the original simulation set-up created challenges for conducting analyses. Therefore, a second refined HITL was conducted in August 2016. The modifications were made in the following five areas: 1) features of the traffic scenarios created greater mismatches between demand/capacity, 2) more realistic wind conditions, 3) longer simulation runs to capture more data points, 4) modifications of TBFM adaptations, and 5) use of formalized procedures for human operator inputs to minimize variabilities in the data. This paper presents the results from the August 2016 HITL experiment on evaluation of the IDM concept, and provides insights obtained during the HITL that could be applied to future research.

The remainder of the paper is organized in the following way: 1) overview of the IDM concept with descriptions of CTOP and TBFM, and how these were adapted and implemented, 2) evaluation of the IDM concept followed by the methods used in the HITL experiment, the results, and the discussion, 3) an additional assessment of the RTA capability and its findings, and finally, 4) overall conclusions and suggestions for future work.

II. Overview of the Initial Development of the IDM Concept

The focus of the initial development of the IDM concept was on the integration of two systems—CTOP and TBFM—to preempt the mismatch between high arrival traffic demand and airport capacity. CTOP and TBFM were developed for different operational contexts and timeframes. In addition, they are targeted for different users and purposes. For example, CTOP is used by airline operators and NAS-wide traffic planners, more strategically during pre-flight planning. However, TBFM is used by controllers and local facility traffic managers, more tactically, for arrival planning [1]. It is important to effectively integrate the systems to operate in a complementary way as there are limitations to each system—e.g., TBFM has less delay absorption capabilities than CTOP programs and other TMIs due to its relatively tactical operational contexts and timeframes. Furthermore, CTOP faces the challenge of accurately planning demand/capacity constraints over long distances with larger forecasted time horizons.

The rest of this section will present the descriptions of the two main components (CTOP and TBFM) of the initial IDM concept, followed by a description of the RTA capability. RTA was the major component that was investigated in the additional study as a control mechanism to improve the delivery accuracy of CTOP's scheduled traffic demand feeding into TBFM.

A. Collaborative Trajectory Options Program (CTOP)

Traffic Flow Management (TFM) is an effort to enable the Air Traffic Control System Command Center (ATCSCC), Air Route Traffic Control Centers (ARTCC), Terminal Radar Approach Control (TRACON) facilities, and airline operators to accomplish Collaborative Decision Making (CDM), which manages demand and capacity balancing for constrained airports and airspace within the NAS.

Currently, a number of tools known as TMIs are created to implement NAS-wide solutions to such disturbances. The IDM concept leverages a new TMI called CTOP. One of the key features of CTOP is the capability to incorporate the preferences of flight operators with respect to assigning ground delays and reroutes. This capability is enabled by allowing traffic demand flowing through multiple FCAs to be handled within a single CTOP program.

Prior to the issuance of the CTOP program, flight operators may submit a set of reroute options, called a Trajectory Options Set (TOS).One feature of a TOS is that it can reflect input from flight operators regarding their preferred options in the form of the Relative Trajectory Cost (RTC). The Ration-by-Schedule (RBS) algorithm, based on the First-Scheduled-First-Served (FSFS) principle, is used to allocate airport capacity in some of the current days' TMIs, such as GDPs and Airspace Flow programs (AFPs). The RBS has been shown to be in the set of system-optimal allocations pertaining to ground delay [2, 4, 11, 12]. Past work has also shown that RBS equitably allocates slots and minimizes the maximum delay imposed on a flight [13]. In order to apply the general scheme of the accepted practice of fair resource allocation, CTOP identifies the earliest arrival time at any of a CTOP's FCAs among any submitted TOS options, represented by an Initial Arrival Time (IAT), and uses the IAT of each non-exempt flight to order the flights for resource assignment. For a flight with no available slot, CTOP uses Adjusted Cost (AC), (i.e., the sum of RTC and potential ground delay assigned by taking the first available slot by flying TOS options) to determine the next available TOS option with the lowest AC to be flown.

This approach of submitting TOS options with preference directs the program to consider more input from flight operators while managing aircraft around constrained areas of airspace, instead of a system operator simply dictating ground delays and/or reroutes [6, 14]. Furthermore, featuring user preference inputs to manage resource assignment may lead to significantly different utilization of constrained NAS resources, such as airports and air sectors, rather than performing a traditional RBS algorithm in GDPs and AFPs.

The initial focus of IDM was to integrate CTOP and TBFM to regulate demand to a single FCA. In other words, no other FCAs in en route airspace were considered for potential reroute. Hence, no rerouting capabilities of CTOP were explored in the early phases of concept development.

In CTOP, four types of flights are excluded from the initial program—1) flights that may already be part of another program, 2) flights that are manually controlled by traffic managers, 3) flights that are airborne when the program is implemented, or 4) flights that are too close to departure time to take updates to their departure time or to their trajectories. These subsets of flights have exempt status during a CTOP program and are exempt from being ground delayed or rerouted.

B. Time-Based Flow Management (TBFM)

TBFM is a traffic management automation platform that includes trajectory modeling, scheduling and, user display functions. This tool uses a time-based metering approach to improve the delivery of arrival traffic demand to capacity constrained resources in the NAS, as an alternative to the more commonly practiced distance-based metering known as Miles-In-Trail (MIT) spacing [15]. It has the ability to efficiently generate Scheduled Times of Arrival (STA) of each aircraft to a Constraint Satisfaction Point (CSP), such as Meter Point (MP), MFX, and Runway Threshold (THD). This tool has been shown to reduce airborne holding, in-trail restrictions, and departure delays while increasing airport throughput and is currently operational at all 20 domestic Centers, select TRACONs and towers [16].

The current TBFM adaptation for EWR is designed to manage traffic within nearly a 400 nautical mile (nm) radius from the MFXs on the Center-TRACON boundary, which makes the traffic planning horizon to be roughly 75-90 minutes before landing. Previous research has demonstrated the difficulty of dealing with uncertainties in estimating aircraft arrival times when the prediction is made far in advance [10, 17]. It has been shown that the precision of Estimated Times of Arrival (ETA) prediction significantly degrades when the distance of the aircraft exceeds approximately 200 nm [18]. Hence, generating fixed schedules based on ETA in such far distance may result in inaccurate and unworkable outcomes due to estimation errors.

In order to overcome such limitations, the newly adapted XM capability was incorporated and explored in the IDM concept [19]. The XM region was developed to increase the effective operational range of TBFM. In the IDM, XM adds another type of MP, referred to as an Extended Meter Point (XMP), to the TBFM metering range, which divides a single long range metering area into two shorter ranges, controlled by two linked schedulers—an ‘inner’ MFX arrival scheduler and an ‘outer’ XM en route scheduler.

TBFM constantly re-computes STAs until a freeze arc, called the Freeze Horizon (FH), is reached. A FH is associated with a CSP, and is where the sequence and schedule are frozen for that CSP. STAs do not normally change once aircraft enter the FH. Frozen STAs can be manually changed by the Traffic Manager and controllers. STAs of flights freeze on the XM schedule after flights reach the XM FH. The frozen STAs subsequently become unfrozen after flights cross the XMPs. Next, the unfrozen STAs are rescheduled and become frozen again on MFX and runway schedules once the flights cross the MFX FH, located downstream of the XMP. This multi-stage process of generating STAs is called a ‘rolling freeze.’ The XM capability does not enforce the sequence of unfrozen STAs at the upstream CSP to be kept at the directly linked downstream CSP as it reduces the flexibility of the system. However, it is important to implement a way of coupling upstream and downstream schedulers, as not coupling may enable traffic demand to exceed the available capacity at the downstream CSPs. Coupling can ensure manageable traffic density downstream by positioning the aircraft upstream appropriately, where more resources are available for delay absorption. In TBFM with XM capability, the projected excess delay of a specific aircraft beyond the delay absorption ability of the MFX schedules is transferred to its directly linked XMP in the form of ‘Passback Delay.’

A particular function of TBFM departure scheduling capabilities includes reserved resources for short-haul departures. This TBFM scheduling function is accessible via the departure scheduling window within TBFM (see figure 1), which has a checkbox called "Delay Scheduled Flights for This Aircraft Only."

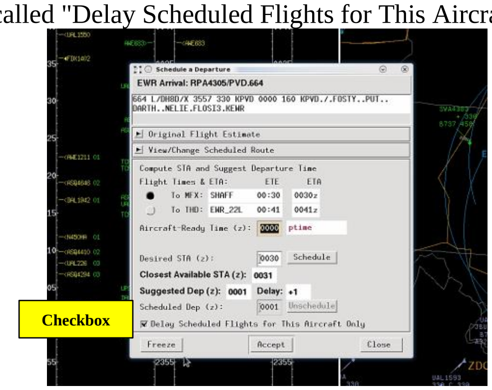

Fig. 1 TBFM departure scheduling window with “*Checkbox On*”

When the checkbox is checked, the function runs an algorithm that finds a slot in the overhead stream within the TBFM system for a short-haul departure by delaying the non-frozen airborne flights. By having the checkbox unchecked, the short-haul departures are delayed until the first *full* slot in the overhead stream is available. For the remainder of the paper, *Checkbox On* indicates having this function running and *Checkbox Off* represents this function was not operating.

C. Required Time of Arrival (RTA)

In the initial development of the IDM concept, CTOP is used to strategically plan the traffic departing both within and outside TBFM to deliver the demand that matches the capacity at the final destination. This strategic demand management is primarily performed by controlling take-off times of departure. However, once aircraft take-off according to their scheduled departure times, the aircraft are not actively controlled to ensure that they adhere to their planned schedule into the TBFM region. A past study has identified that the primary source of uncertainty in arrival traffic demand delivery is the departure errors, which is the difference between expected and actual departure times [20]. Accurate traffic demand delivery over long distances could be more challenging if the departure conformance time window for an aircraft departing outside TBFM is wide (+/- 5 minutes of their EDCT-scheduled departure times). Moreover, various other sources of uncertainties—e.g. aircraft performance modelling errors, wind severity and wind forecast error—may impede accurate delivery of demand for long en route flying aircraft [10].

Past studies have shown that a flight deck capability called, Required Time of Arrival (RTA), enables speed control to allow aircraft to cross a particular waypoint in the airspace at a defined time with more accuracy [9, 21, 22]. In addition, RTA capabilities have been explored as a potential control mechanism to mitigate uncertainty existing in arrival time of en route traffic, where the degree of uncertainty can be manipulated by varying wind severity and wind forecast errors that could affect the actual ground speed of the aircraft and projection [9]. Hence, RTA capability was selected as a way to improve delivery of strategically planned long-haul en route traffic demand entering TBFM.

III. Evaluation of Initial Development of the IDM

A. Overview

The IDM concept was tested in a human-in-the-loop (HITL) study at the Airspace Operations Laboratory at NASA Ames Research Center in August 2016. The focus of the study was: 1) to emulate the intended integration of CTOP and TBFM in a high-fidelity simulation environment, and 2) to evaluate the TFM under the initial phase of IDM operations in comparison to current day MIT operations. During evaluation, it was assumed that there was accurate capacity estimation of the airport shared across the CTOP and TBFM system, allowing effective coordination between the systems. Newark Liberty International Airport (EWR) was selected as a test case because EWR experiences one of the highest arrival delays in the NAS. EWR also has a varying mix of international and domestic traffic, as well as departures from various origination airports that are both near and far from EWR [1, 23, 24]. In addition, aircraft departing for EWR from close-in (200-300 miles) airports (e.g. Dulles or Boston) frequently incur excessive departure ground delay due to saturation in the overhead stream [23]. In current operations, scheduled demand at EWR is often at or near the dual-runway VFR capacity of the airport. However, high demand, adverse winds, or reduced visibility can easily reduce capacity well below demand which frequently results in mismatch [1]. Such mismatch is commonly managed using pre-determined MIT spacing, which does not always promise equity in terms of delays between short- and long-haul flights.

B. Hypotheses

The focus of the initial proof-of-concept evaluation for IDM was to determine whether integrating two systems (CTOP and TBFM) can manage projected heavy traffic demand into a capacity-constrained airport during clear weather conditions. Strategic planning of traffic demand (via CTOP) based on the FSFS scheme is structured to provide equitable treatment across all flights in terms of ground delay assignment regardless of departure origin (short-hauls vs long-hauls). Such strategic planning is also projected to deliver more manageable long-haul traffic demand into TBFM, preventing excessive airborne delays, while reserving slots in the overhead streams for short-haul departures to use. There are limits in amount of absorbable airborne delays within TBFM region, mainly restricted by controller's workload and airspace configuration. The effective integration of CTOP and TBFM is expected to result in delivering desired throughput and minimizing overall delays in arrival traffic. The following hypotheses were constructed to test whether such objectives were accomplished.

The first hypothesis was established to determine whether the initial IDM concept provides equitable treatment in ground delay assignment across all flights regardless of departing origin.

Hypothesis 1: the initial IDM CTOP operation will provide equity in ground delay assignment between short- and long-haul departures.

The second hypothesis was constructed to determine whether CTOP delivers more manageable long-haul traffic demand into TBFM, indicated by the amount of airborne delay incurred within TBFM.

Hypothesis 2: the IDM CTOP strategically schedules traffic demand, which will deliver manageable long-haul traffic demand into TBFM.

The third hypothesis was examined to identify whether there were indeed reserved resources in the long-haul traffic demand fed into TBFM for the short-haul departures, where non-available resources in the overhead stream can be measured with unexpected, excessive ground delay among short-hauls departures.

Hypothesis 3: the IDM CTOP will reserve slots for the short-haul departures within TBFM in its strategic traffic demand planning, alleviating unexpected last-minute ground delays.

The effective coordination of the CTOP and TBFM is expected to deliver throughput that is desired at the airport. In addition, it is important to verify that regulated long-haul traffic demand by CTOP does not result in under-delivery. Hence, the fourth hypothesis was established to examine whether desirable throughput at the airport was attained during IDM operations. This can be measured with the average final frozen aircraft STAs per hour.

Hypothesis 4: IDM operations will enable effective traffic demand management, achieving target demand delivery (throughput) to the final destination.

Finally, the fifth hypothesis was constructed to determine whether TFM under the IDM concept minimizes overall cost induced by delays in arrival traffic, bringing more efficiency to the TFM operations. This can be measured by applying a cost function to the overall airborne and ground delay for each condition.

Hypothesis 5: IDM operations will reduce cost associated with overall delays in arrival traffic management.

C. Method

C.1. Participants

There were a total eight participants in the study. Three participants were retired FAA facility personnel with extensive traffic management backgrounds who served as Subject Matter Experts (SME). Two participants had worked as Supervisory Traffic Management Coordinators (STMCs) and/or traffic management officers at New York Center (ZNY) and Oakland Center (ZOA). The third SME participant was a retired air traffic manager from the ATCSCC. In addition, there were three retired ZOA air traffic controllers who managed traffic into and within the XM TBFM arena. Finally, two experienced pseudo-pilots monitored all the in-flight aircraft during the study.

C.2. Procedures

The study required two of the participants to rotate through two TFMS planner stations, representing the ATCSCC. This two-person team was responsible for managing the demand/capacity mismatch of the EWR arrivals. The team monitored and strategically resolved the projected mismatch between scheduled high arrival demand and capacity constrained airport with the provided TFMS and CTOP tool emulations. In the study, the AAR of EWR was set to be 44 aircraft per hour, which was provided as the target throughput to achieve during the simulation run. CTOP was used to monitor initial scheduled arrival demand at the FCA and assign capacity limits to the FCA ring drawn near EWR at the MFXs. CTOP strategically planned the arrival traffic demand to match the capacity limits at the FCA by controlling take-off times (EDCTs) of both short- and long-haul flights.

The capacity limits of the FCA were set at 11 for each 15 minute bin to achieve the target throughput. Upon execution of the CTOP program, EDCTs were sent to the non-exempt pre-departure flights to ensure that the traffic demand would match the capacity limits. Flights that were airborne when the program was implemented, and flights that were too close (within 30 minutes) to departure time to take updates to their departure time held exempt status. The strategic demand planning by CTOP took place well in advance of flights getting scheduled within TBFM. Once the CTOP program was initiated, one ATCSCC SME remained to observe the TFMS planner stations, while another TFMS SME (with extensive TBFM knowledge) joined a TBFM SME to observe the two TBFM positions.

The two TBFM positions for the study included one en route and one arrival STMC position. The en route STMC was responsible to manage the XM schedule from the XM FH to the XMP and scheduled departures that departed within the XM regions. In current field operations, three separate XMP positions would be required to manage the north (Boston Center), west (Cleveland Center), and south (Washington Center) flows from the three facilities. In the IDM study, these three XM positions were combined and were controlled by one participant. The New York Center arrival STMC was responsible for managing the MFX schedule from the MFX FH to the MFXs and scheduled departures that took off within the MFX region. The SMEs managed the pre-defined 44 AAR buffer settings in the aircraft separation matrix to ensure delivery to the target demand. Although frozen STAs can be manually changed by the Traffic Manager and controllers, this authority was not granted in order to minimize variability. For departure scheduling within TBFM, Call-For-Release (CFR) procedures, also known as Approval Request (APREQ) procedures, were used to manage the release of departures within the TBFM regions. These procedures require the Tower controllers from airports to call the en route facility to request CFR departure times when an aircraft is ready to take-off. Since air traffic towers were not staffed in this study, a procedure was developed that allowed the TBFM controllers to systematically schedule all MFX or XM departures. Once an aircraft was within 20 minutes of pre-departure, the controllers were asked to pretend a call had come from a tower and proceed to schedule the departure.

Three retired ZOA air traffic controllers worked as confederate controllers to ensure the high fidelity of the aircraft flying into TBFM. 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. They were instructed to use speed control and, if that was not enough, vectors or route modifications to meet the XMP STAs. The third controller acted as a super-sector confederate during current day MIT operations, where no CTOP was issued to manage the traffic flowing into TBFM regions. This controller worked to maintain the pre-determined TFMS SME assigned 30 MIT spacing of airborne flights and managed departure time clearances into the EWR overhead flow. The TBFM MFX area was not staffed with controllers as the area of interest ended upon the freezing of the STAs in the MFX arrival area.

Two pseudo-pilots were responsible for monitoring and managing all aircraft flown in the simulation. In order to make this an achievable two-person task, all aircraft were controlled with data link clearances issued by the controllers and auto-processed by the aircraft flight management system.

C.3. Apparatus

The simulation was run on the Multi-Aircraft Control System (MACS) software, which provides a high fidelity air traffic control simulation environment, with prototyping scheduling systems and simulating air traffic [25]. The TFMS planner stations were provided with a customized MACS En Route Automation Modernization (ERAM) display emulation that allowed planners to monitor and manage traffic (see figure 2). The MACS simulation also exchanged flight data and schedule information with an internally developed CTOP emulation, called 'nCTOP' that provided the desired functions for the initial IDM concept (see figure 2). The ring-shaped FCA was placed approximately 40 nm around EWR airport, at or near the TBFM arrival MFXs (see figure 2). The CTOP strategically planned arrival traffic demand to match the capacity limits at the FCA by controlling EDCTs. The CTOP generated traffic demand schedules to the FCA located at the TBFM CSPs. However, there was no direct linkage between the CTOP and TBFM schedulers, to ensure flexibility of the two systems.

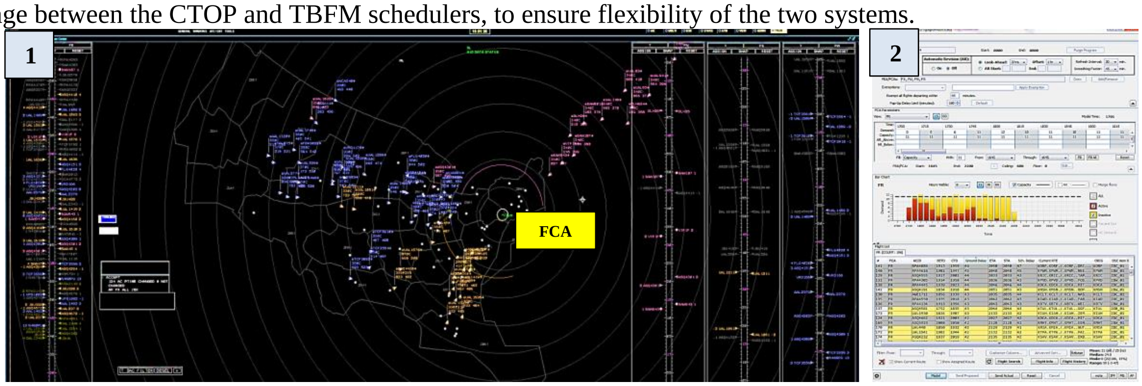

Fig. 2 The TFMS planner station: 1) macs ERAM display, 2) nCTOP.

An operational version of TBFM (release 4.2.3) was modified and adapted to provide a high-fidelity simulation environment within the TBFM area for EWR. TBFM is currently designed to manage traffic within nearly a 400 nm radius from the MFXs on the New York Center-TRACON boundary. For the IDM concept, XM added another type of MP to the TBFM metering range which divided the long range metering area into two shorter ranges controlled by two linked schedulers—i.e., MFX arrival scheduler covered about a 140 nm radius from each MFX, and the XM en route scheduler covered the remaining outer TBFM region. Figure 3 illustrates the schematic representations of the locations of the ring-shaped FCA around TBFM MFXs and the TBFM adaptation. In figure 3, the FHs are represented as the dotted arcs, the XMPs and FCA are represented as solid arcs, and the MFXs are indicated as the dots.

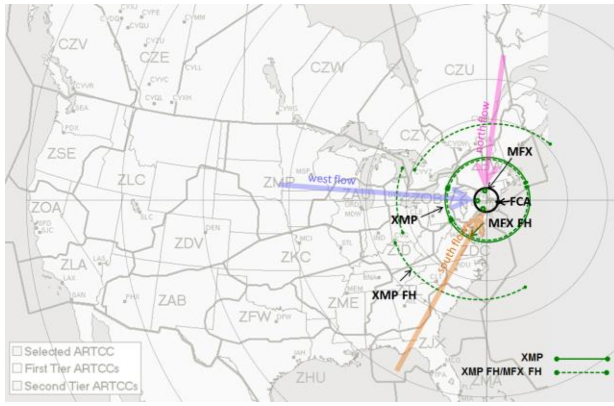

Fig. 3 Schematic representation of the TBFM adaptation (XMP, XMP FH, MFX, and MFX FH) and the FCA

There were two TBFM positions, MFX and XMP STMC positions, as shown in figure 4. Each TBFM position had a Timeline Graphical User Interface (TGUI) and a Planview GUI (PGUI). The TGUIs displayed the traffic volume across each MFX and XMP for the selected CSP in the form of arrival timelines. ETAs (green) appeared on the left of the timelines and STAs (yellow) appeared on the right of the timelines. Aircraft that passed the associated FHs received final STAs were colored blue. The PGUIs displayed the actual aircraft color coded by each flow, TBFM MFX and MFX FHs, and XMP and XMP FHs were shown as cyan arcs on their PGUIs.

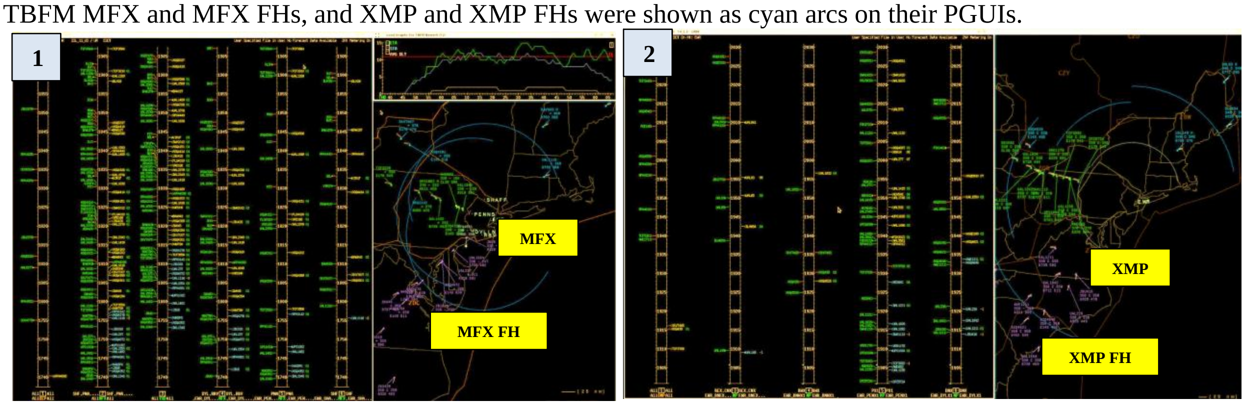

Fig. 4 The TBFM stations: 1) arrival STMC position, 2) en route STMC position.

There were three confederate controller positions that were provided with a customized MACS ERAM display emulation. Two of them performed as 'super-sector controllers' to manage the traffic in the TBFM XM region. These controllers were provided with XM meter lists on their scopes, which displayed the delay times coming from the TBFM XM scheduler. The displays were configured so that one controller could manage all of the West flow, and the other controller could manage both the North and South flows inside the TBFM XM regions (see figure 5).

Fig. 5 The 'confederate' controller positions: 1) west flow control station, 2) north and south flow control station.

During the current day MIT conditions, when no CTOP was issued to manage the traffic flowing into TBFM regions, the third controller acted as a super-sector confederate who issued MIT spacing and departure clearances to the aircraft in the TFMS region.

Fig. 6 MIT confederate controller.

The MIT controller was responsible for managing the SME determined 30 MIT feeds for each of five main traffic flows entering TBFM from the west and the south. North flows were not controlled with MIT due to the International Arrivals that dominate the flow, mimicking typical current day operations. The controller maintained 30 MIT with airborne aircraft using speeds and vectors (i.e., issued via data link capabilities), as well as controlling departure times of aircraft that were departing outside of TBFM into the overhead flow. Figure 6 shows all five scheduling timelines on the scope of the MIT controller.

C.4. Independent Variables

The HITL experiment was conducted with a total of six (3 × 2) conditions. The conditions were created to examine the effect of initial development of the IDM concept on TFM operations. There were three different tool conditions (*MIT + Checkbox Off*, *MIT + Checkbox On*, and *CTOP + Checkbox On*). Each tool condition was conducted using two different traffic scenarios (distributed and gaggle).

The three tool conditions were defined as:

1) *MIT + Checkbox Off (MIT+CB Off)*: This was a baseline condition designed to analogously mimic current day MIT operations. The MIT metering technique was used to pre-condition traffic entering TBFM airspace. A number of arrival tracks associated with north, west, and south flows into EWR were identified based on inputs from SMEs, and the traffic was delivered to 30 MIT for those given flows. In this tool condition, no CTOP was introduced, and TBFM did not have the function that is designed to create slots in the overhead stream for short-hauls. This tool condition represented current day operations, as current day operations typically have the *Checkbox Off* to ensure less airborne delay.
2) *MIT + Checkbox On (MIT+CB On)*: This second tool condition was intended to operate in the same way as the first MIT tool condition. The only difference was that the TBFM function for creating slot in the overhead stream for short-hauls was active.
3) *CTOP + Checkbox On (CTOP+CB On):* In this condition, the CTOP was used. Hence, there was no MIT feeding traffic into TBFM. Traffic was managed solely with EDCT times assigned by CTOP. Also, the TBFM function for creating slots in the overhead stream for short-hauls was active.

Two traffic scenarios (distributed and gaggle) were derived from actual recorded EWR traffic during busy hours on July 22, 2014, a date that had nominal clear weather operations. Based on SME feedback, several modifications to the traffic were made to artificially generate heavy traffic demand that would induce a demand/capacity mismatch. Meanwhile, representative EWR arrival traffic characteristics, such as realistic scheduled demand ratio between short-hauls and long-hauls flowing into EWR, were maintained. The distributed scenario had an original scheduled demand averaging 51.5 flights/hour and the gaggle scenario had an original scheduled demand averaging 53 flights/hour. The major difference between these scenarios came from the attributes of how Trans-Atlantic traffic arrived. In the distributed scenario, Trans-Atlantic traffic arrived in a dispersed manner throughout the run. In the gaggle scenario, a group of crowded Trans-Atlantic traffic arrived near the end of the simulation run, simulating a frequently occurring situation in which a gaggle of international heavy jets flows into Boston Center (ZBW) via the north gate. Both scenarios were designed to last for about 5.5 hours after being controlled. The scenarios included only EWR traffic (196 aircraft each) landing at a single runway (EWR 22L). The distributed scenario consisted of 43 airborne aircraft in the beginning of the simulation run, 86 long-hauls departing outside TBFM, and 67 short-hauls departing within the TBFM (40 departures within XM regions + 27 departures within MFX regions). The gaggle scenario included 42 airborne aircraft, 84 long-hauls, and 70 short-hauls (47 departures within XM regions + 23 in MFX regions).

To ensure a full fidelity simulation, three other factors were introduced: departure errors, wind severity, and the associated wind forecast errors. The departure errors remained the same for each scenario. Departure error, i.e. the difference between scheduled departure time and actual take-off time, were generated by randomly drawing from the departure errors that were seen during 10-days of actual departure data when GDPs were placed on the traffic flowing into EWR. For the distributed scenario, about 64 % of the short-hauls departures within TBFM were pre-scripted to take-off within the regulation three minute window of the CFR procedure [2 minutes early, 1 minute late]. Most of the remaining departures were to depart outside conformance standards [4 minutes early, 4 minutes late]. About 69 % of the long-haul departures outside TBFM regions were set to depart within the EDCT conformance range, [5 minutes early, 5 minutes late], with the remaining departures outside of conformance [16 minutes early, 20 minutes late]. For the gaggle scenario, 69 % of the short-hauls departed within CFR conformance range and the rest departed within the non-standard range [4 minutes early, 4 minutes late]. Finally, 68% of the long-hauls were pre-scripted to depart within the EDCT conformance range where the remaining departures were also non-conforming [16 minutes early, 20 minutes late].

The wind severity and the associated wind forecast errors were kept static throughout all conditions and did not change during the simulation runs to avoid more variabilities being induced. To simulate the wind condition, a 40 km resolution Rapid Refresh (RAP) file from the National Oceanic and Atmospheric Administration was used. A previous study explored the effect of wind severity and wind forecast errors on the traffic delivery accuracy in IDM [23]. Based on the lesson-learned, and feedback from SMEs, a RAP wind file from May 10, 2014 11:00:00 Zulu was selected. The one hour forecast RAP wind file was used as the “true wind” in the simulated environment. The three hour forecast wind was used as the two hour wind forecast typical for the TBFM schedulers, and the six hour forecast wind was used to insert the five hour wind forecast errors in the CTOP scheduler and the flight-deck operations. The wind forecast errors of the selected wind condition were computed using the following Eq. (1) as a form of Root Mean Square Vector Error (RMSVE) and the computed wind forecast errors (two and five hour forecast errors) at different altitudes (10000, 20000, 30000, and 40000 ft) are displayed in figure 7.

$$RMSVE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}\left(u_f - u_o\right)^2 + \left(v_f - v_o\right)^2} \tag{1}$$

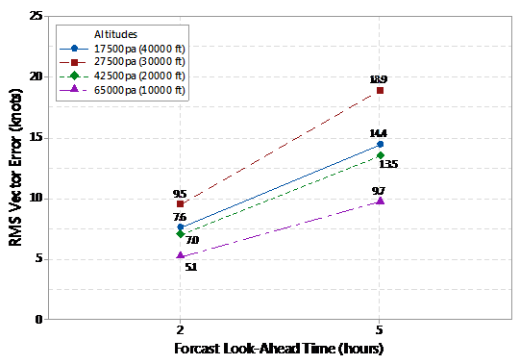

Fig. 7 Wind forecast Errors (knots) at 2 and 5 hours of look-ahead time.

Figure 8 displays the “true wind” condition at about 30,000 feet used for the study. At that attitude, the wind speed ranged from 1.4 to 133.2 knots, where the average and SD are 47.3 and 24.4 knots, respectively. The arrows in figure 8 indicate the speed (m/s) and the direction of the wind.

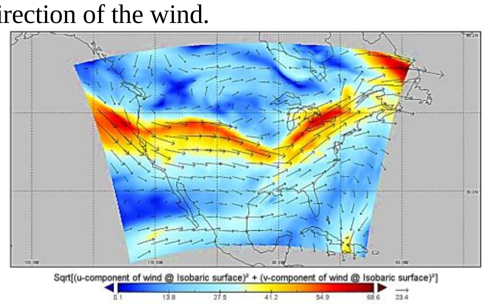

Fig. 8 True wind condition: RAP 40 km resolution winds (m/s) at 10-May-2014 11:00:00 Z 27500.0 pa (≈ 30,000 feet).

C.5. Dependent Variables

There were three dependent variables, throughput, airborne delay, and ground delay. During the simulation runs, the number of aircraft landed per hour was collected to represent the throughput. Since the TBFM MFX area was not staffed with controllers, the final STA threshold times from the TBFM MFX schedulers were used to project the number of landings.

To quantify airborne delays assigned during the study, the airborne delays of the aircraft that were directly assigned by TBFM were obtained. This was done by recording the assigned airborne delays (difference between ETA and STA) to the XMPs and MFXs when the aircraft crossed their perspective XM and MFX FHs. In order to translate what it means to be an operationally manageable traffic demand (particularly, in relation to controller workload and provided airspace configuration), airborne delays were categorized into three types (acceptable, marginal, and unacceptable) based on SME feedback. Acceptable delay represented the airborne delay that could be absorbed within the given airspace and had relatively low task load. The marginal airborne delay category indicated the demand imposed by absorbing assigned airborne delay that lead to moderate workload. Multiple aircraft with the marginal airborne delay can rapidly lead to significant increase in workload. Unacceptable delay simply indicated a delay that exceeded the ability of the controller to perform within given contextual resources. Hence, unacceptable delays may result in holding and/or noncompliance. There is a structural difference between XM and MFX regions: XM has more delay absorbability as it has larger airspace. Therefore, the acceptability values used for each category are different between XM and MFX. For XM regions, the acceptable range was defined to be from -5 to 5 minutes. For MFX regions, the acceptable range was bounded by 4 minutes, [-2, 2). The marginal acceptable range for XM regions was [5, 10) and [2, 4) for MFX regions. Airborne delays greater than the marginal acceptable range were identified as unacceptable. In addition to TBFM assigned airborne delay, the total airborne delays were obtained by comparing the flight time of an unconstrained trajectory with no input from human operators, to the observed controlled flight time for each aircraft during each simulation run. Moreover, the ground delay assigned to each aircraft was recorded within the source (i.e., TBFM MFX scheduler, TBFM XM scheduler, CTOP EDCTs, or MIT controlled departure times) where it was initiated.

In addition to the three dependent variables described above, participants were asked to provide any operational comments and mark those observed times during the operations. In this study, TBFM SME operator inputs were limited to follow basic procedures equally across all conditions in order to minimize variability in the outcomes gathered during the evaluation, where different SME inputs (more operationally pertinent) could have changed the outcomes.

D. Results

D.1. Overview of Results

This section presents the results from the initial IDM concept evaluation. The following are the summary results of the hypotheses testing: 1) the IDM CTOP strategically allocated constrained NAS resources equitably that led to fair ground delay assignment between short- and long-haul departures. Such equitable allocation allowed 2) manageable long-haul traffic demand to flow into TBFM which, 3) contained reserved slots for the short-haul departures within TBFM, which alleviated last-minute excessive ground delay that the short-hauls may have received. Moreover, 4) efficient delivery of traffic demand to its target throughput was achieved, while 5) reduction in overall expected cost of delays in arrival traffic was obtained. In addition, the comments from SMEs were reported, which describe what different types of inputs they would have provided that may have resulted in different outcomes.

D.2. Results of Hypothesis 1: the initial IDM CTOP operation provided equity in ground delays assignment between short- and long-haul departures.

In order to determine whether the IDM CTOP provided equitable treatment across all flights regardless of origins of the departing airports (short-hauls vs long-hauls), the actual CTOP assigned ground delays to both short- and long-haul departures were visually compared (see figure 9).

In figure 9, the "×" represents the total amount of CTOP ground delay assigned to the short-hauls in minutes. The green dot represents CTOP delay assigned to the long-hauls. In the figure, aircraft that received no ground delays were exempt flights, when CTOP was initiated and assigned ground delay. Overall, it was observed that the ground delays allotted by CTOP were fairly distributed between the non-exempt short- and long-haul departures. Also note that no aircraft crossed the THD before an hour and a half into the run.

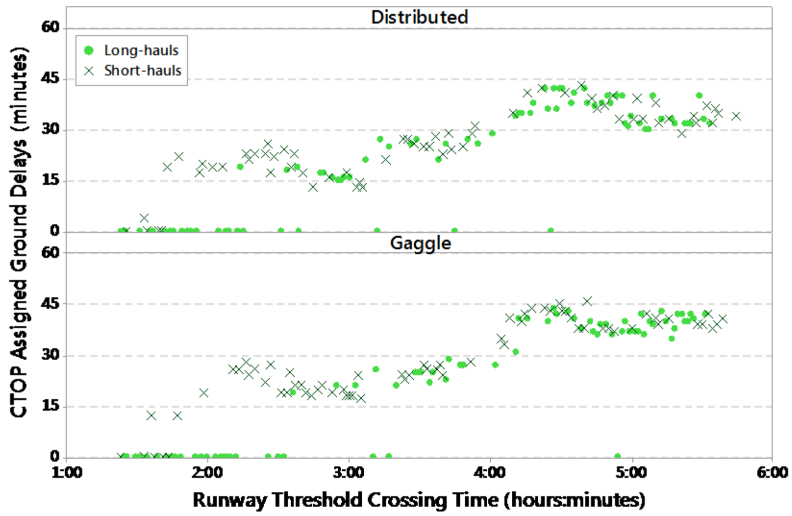

Fig. 9 CTOP assigned ground delays (minutes) as a function of runway threshold crossing time (hours:minutes) for distributed and gaggle scenarios

Table 1 presents the summary statistics of ground delay assigned by CTOP to the long-haul departures in the IDM (*CTOP+CB On*) condition. The table includes mean, standard deviation (SD), median, maximum, and the total number of aircraft that received ground delay (N).

Table 1 Ground delay assigned by CTOP to the long-haul departures in the IDM (*CTOP + CB On*) condition (hours:minutes:seconds)

Scenarios	Mean	SD	Median	Maximum	N
Distributed	0:23:30	0:15:33	0:30:00	0:42:00	86
Gaggle	0:27:34	0:16:10	0:37:00	0:44:00	76

Table 2 presents the summary statistics of ground delay assigned by CTOP to the long-hauls departures in the IDM (*CTOP+CB On*).

Table 2 Ground delay assigned by CTOP to the short-haul departures within TBFM in the IDM (*CTOP + CB On*) condition (hours:minutes:seconds)

Scenarios	TBFM Regions	Mean	SD	Median	Maximum	N
Distributed	XM	0:25:43	0:11:49	0:26:00	0:43:00	45
	MFX	0:25:46	0:08:37	0:26:00	0:42:00	22
Gaggle	XM	0:27:31	0:13:20	0:27:00	0:46:00	47
	MFX	0:29:44	0:10:18	0:26:00	0:44:00	23

The results provided in the Tables 1 and 2 support that CTOP strategically provided equal treatment between short- and long-haul departures pertaining to the ground delays.

D.3. Results of Hypothesis 2: the IDM CTOP strategically scheduled traffic demand, which allowed manageable long-haul traffic demand to flow into TBFM.

To assess the second hypothesis, airborne delays incurred within TBFM regions under the three tool conditions were compared. The airborne delay assigned by TBFM during the IDM condition (*CTOP+CB On*) showed delays that were more acceptable to controllers, in comparison to the *MIT+CB Off* and *MIT+CB On* condition, indicating support for hypothesis two.

Table 3 presents the airborne delay assigned by TBFM XM schedulers. For both traffic scenarios (distributed and gaggle), it was found that the IDM condition (*CTOP+CB On*) showed the most number of acceptable airborne delays. Additionally, one of the emulated current day operations of the *MIT + CB On* condition, showed the most unacceptable and marginal airborne delays.

Table 3 Airborne delays assigned by TBFM (XM scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-5, 5)	[5, 10)	[10, ∞]	
Distributed	*MIT + CB Off*	133	32	9	174
	MIT + CB On	71	65	38	174
	CTOP + CB On	169	5	0	174
Gaggle	*MIT + CB Off*	128	36	9	173
	MIT + CB On	39	32	102	173
	CTOP + CB On	168	3	0	171

Table 4 provides the airborne delay assigned by TBFM MFX schedulers. For both traffic scenarios, it is observed that the IDM condition (*CTOP+CB On*) showed the highest amount of acceptable airborne delay. Once again, unacceptable and marginal airborne delays were most frequently assigned in the (*MIT + CB On*) condition.

Table 4 Airborne delay assigned by TBFM (MFX scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-2, 2)	[2, 4)	[4, ∞]	
Distributed	*MIT + CB Off*	89	62	42	193
	MIT + CB On	56	62	74	192
	CTOP + CB On	100	70	22	192
Gaggle	*MIT + CB Off*	121	59	12	192
	MIT + CB On	65	47	78	190
	CTOP + CB On	124	54	13	191

In the table 3 and 4, there was no noticeable difference in airborne delays due to scenario differences (distributed vs. gaggle). Hence, figure 10 and 11 were constructed using the results from the combined scenarios to best identify the distribution of airborne delays assigned by XM and MFX schedulers. Each bar in the figures are color-coded by the three acceptability categories (acceptable is green, marginal is yellow, and unacceptable is red). The IDM condition (*CTOP+CB On*) provided more acceptable airborne delays, particularly, within XM regions.

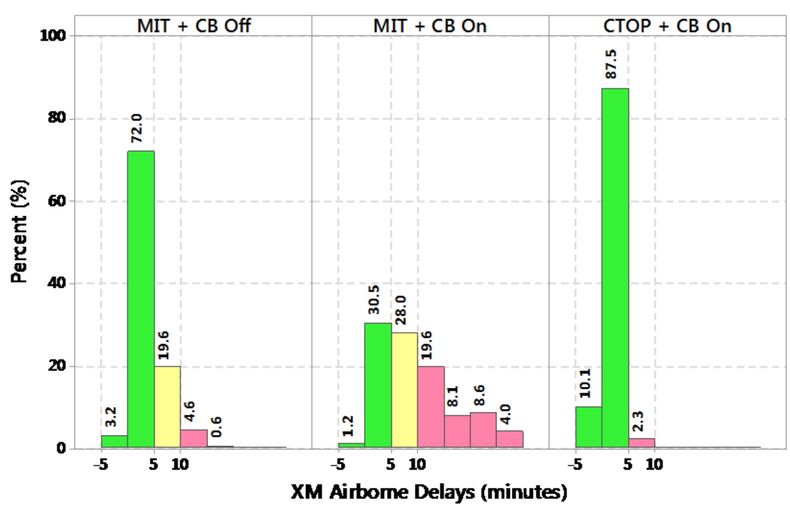

Fig. 10 XM Airborne Delays (minutes) by condition for both gaggle and distributed scenario combined.

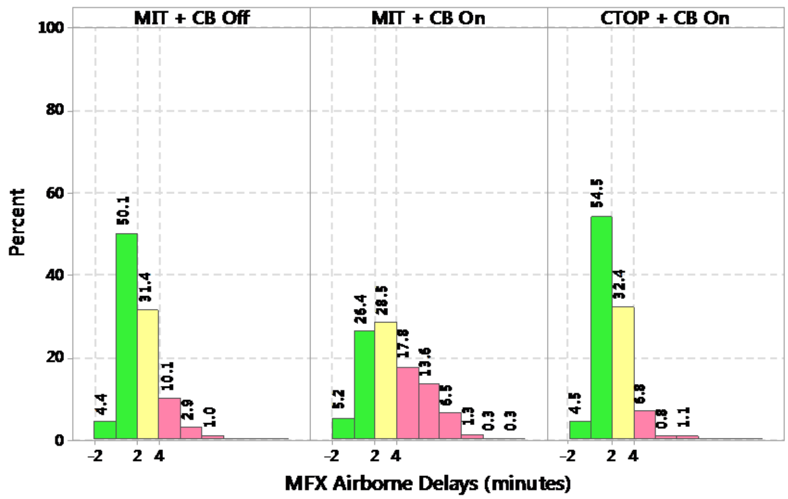

Fig. 11 MFX Airborne Delays (minutes) by condition for both gaggle and distributed scenario combined.

D.4. Results of Hypothesis 3: the IDM CTOP reserved slots for the short-haul departures within TBFM in its strategic traffic demand planning, alleviating unexpected last-minute ground delays.

The third hypothesis was tested to see whether traffic demand fed into TBFM had reserved slots in the overhead stream for short-haul departures in the IDM (*CTOP+CB On*) condition.

In the *MIT+CB Off* and *MIT+CB On* condition, there was no effectively operational control mechanism in the process of strategic traffic demand planning that considers reserving slots for the short-haul traffic demand. Hence, the results from the three different tool conditions were compared by the amount last minute assigned TBFM delay.

The results of the hypothesis testing supported that there was less unexpected, last-minute ground delay assigned to the departures within TBFM during the IDM (*CTOP+CB On*) condition, implying that there were slots available in the overhead stream to be utilized with its strategic traffic demand planning capabilities.

The following Tables (5 and 6) present the summary statistics of ground delays that were assigned by both XM and MFX schedulers. There were noticeably less last-minute ground delays assigned by TBFM under the IDM condition (*CTOP+CB On*) compared to the *MIT+CB Off* and slightly less than the *MIT+CB On* condition.

Table 5 Ground delay assigned by XM scheduler of TBFM (hours:minutes:seconds)

Scenarios	Tool Conditions	Mean	SD	Median	Maximum	N
Distributed	*MIT + CB Off*	0:24:27	0:18:01	0:21:00	1:08:00	45
	MIT + CB On	0:04:57	0:04:17	0:04:00	0:13:00	45
	CTOP + CB On	0:00:24	0:01:01	0:00:00	0:05:00	45
Gaggle	*MIT + CB Off*	0:30:11	0:21:00	0:31:00	1:05:00	47
	MIT + CB On	0:10:41	0:10:03	0:09:00	0:41:00	47
	CTOP + CB On	0:00:10	0:00:29	0:00:00	0:02:00	47

Table 6 Ground delay assigned by MFX scheduler of TBFM (hours:minutes:seconds)

Scenarios	Tool Conditions	Mean	SD	Median	Maximum	N
Distributed	*MIT + CB Off*	0:43:33	0:25:11	0:48:30	1:21:00	22
	MIT + CB On	0:05:08	0:04:09	0:04:30	0:16:00	22
	CTOP + CB On	0:01:16	0:01:23	0:01:00	0:04:00	22
Gaggle	*MIT + CB Off*	0:51:50	0:19:58	0:52:00	1:21:00	23
	MIT + CB On	0:11:03	0:07:57	0:09:00	0:28:00	23
	CTOP + CB On	0:02:00	0:01:44	0:03:00	0:05:00	23

Figure 12 was constructed to visually portray the TBFM assigned ground delay to each departure from XM and MFX regions under three conditions (*MIT + CB Off*, *MIT + CB On*, *CTOP + CB On*). Each dot in the figure indicates the total amount of ground delay that an aircraft received either from XM for MFX scheduler. The figure contains the results from combining both scenarios (distributed and gaggle).

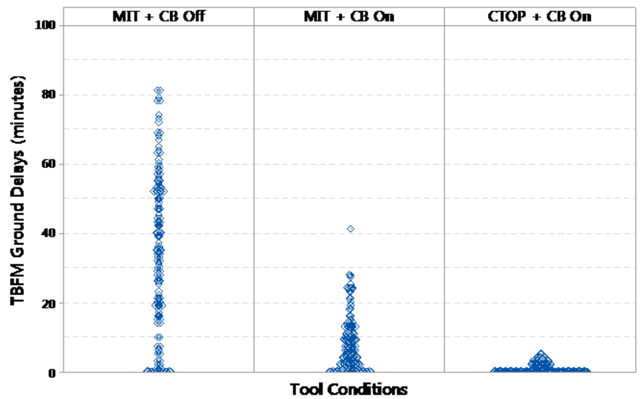

Fig. 12 TBFM ground delays (minutes) assigned to each aircraft in both distributed and gaggle scenarios combined in all three tool conditions.

In figure 12, it can be seen that the TBFM assigned last-minute ground delay was wide spread from zero up to 81 minutes in the *MIT + CB Off* condition. The *MIT + CB On* condition ranged from zero to 41 minutes. However, the results of the IDM (*CTOP + CB On*) condition shows narrowed distribution ranges from zero to five minutes.

Figure 13 shows the total ground delays assigned by TBFM and CTOP to each short-haul departure during the IDM (*CTOP + CB on*) condition. The purple areas indicate ground delay assigned by CTOP initially at the strategic level. The yellow areas represent the total amount of ground delays assigned by both TBFM and CTOP. It can be observed that there were minimal last-minute ground delays by TBFM contributing to the total amount of ground delays that the short-hauls received.

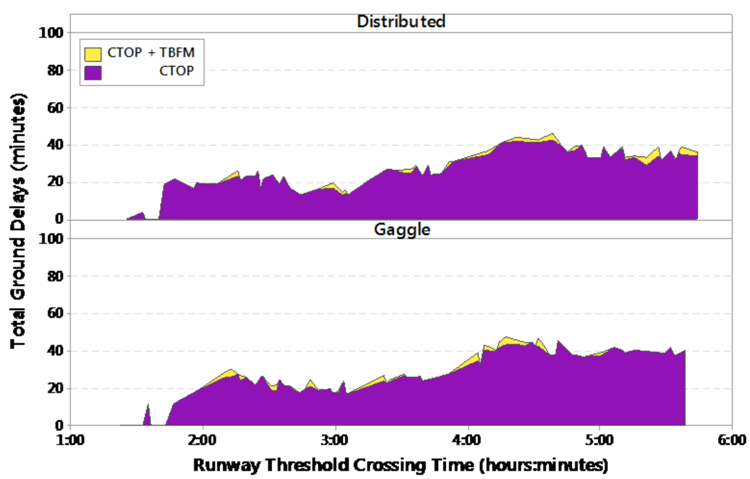

Fig. 13 Total ground delays (from TBFM and CTOP) assigned to each aircraft in the IDM (*CTOP + CB On*) condition, in minutes.

D.5. Results of Hypothesis 4: the initial IDM operation enabled effective traffic demand management, achieving target demand delivery (throughput) to the final destination.

It is important to assure that none of the objectives that were tested through the previous hypotheses should be achieved by negatively affecting the throughput at the airport. Hence, the throughputs at the airport were recorded under all three tool conditions. In the study, the AAR at EWR airport was set to be 44 aircraft per hour, which could be identified as the target throughput.

The simulation ran for approximately 5.5 hours with no aircraft landing for the first 90 minutes. Table 7 presents the total number of aircraft which landed during the last four hours of the simulation run across each condition. The results indicate that the target throughput was achieved in the IDM (*CTOP + CB On*) condition as well as in both baseline (*MIT + CB Off* and *MIT + CB On*) conditions.

Table 7 Runway throughput based on total number of flights landed in last 4 hours (90 – 330 minutes)

Scenarios	Tool Conditions	Mean	SD	Total number of Flights Landed in last 4 hours (90 - 330 minutes)
Distributed	*MIT + CB Off*	44.25	2.92	177
	MIT + CB On	45.75	1.58	183
	CTOP + CB On	44	1.33	176
Gaggle	*MIT + CB Off*	44.75	0.92	179
	MIT + CB On	43.25	2.92	173
	CTOP + CB On	43.75	3.58	175

D.6. Results of Hypothesis 5: the initial IDM operation reduced cost associated with overall delays in arrival traffic management.

In order to assess the fifth hypothesis, total delays that were assigned throughout the operations under each tool condition were compared. Figure 14 provides the sum of total delay (total airborne delays + total ground delays) assigned in hours in terms of expected cost. There is a relative cost difference in airborne and ground delays. It is considered that airborne delays are much costlier than ground delays [26, 27]. Three sets of expected costs of the total delays under three tool conditions were computed. In the first set, the cost of ground vs airborne delay ratio was at a ratio of 1:1. This ratio was set to compare the absolute magnitude of assigned delays in all three tool conditions. In the second set, the ratio of 1:1.5 was set, assuming airborne delay is 1.5 times more expensive than ground delay at the fixed rate. This is based on airline reported costs from 2015 [28, 29]. In the third set, the ratio of 1:2 was assumed to set a little bit higher cost ratio standard [26, 29].

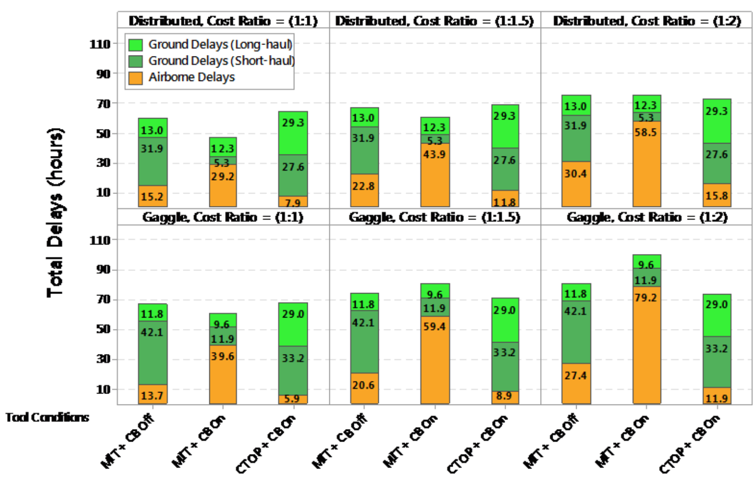

Fig. 14 Total delays assigned to each aircraft in all three tool conditions, ground delay vs airborne delay = 1:1, 1:1.5, and 1:2.

In the IDM (*CTOP + CB On*) condition, CTOP strategically assigned ground delays to both short- and long-haul departures to control the projected mismatch between scheduled traffic demand and the capacity. This process was done proactively and strategically to ensure efficiency in operations by transferring the potential airborne delays into more manageable and predictable ground delays. Hence, the results showed that overall airborne delay incurred in the IDM (*CTOP + CB On*) condition was noticeably lower compared to the *MIT + CB Off* and *MIT + CB On* condition. Consequently, there was an increase in ground delays in the IDM (*CTOP + CB On*) condition. Although the absolute magnitude of ground delays was observed to be lower in both baseline (*MIT + CB Off* and *MIT + CB On*) conditions, the unpredictable nature of the last minute delays is not acceptable to the operations community.

Also, even though the ground delays might have been lower, the airborne delays were much higher leading to their expected total cost being higher than the IDM (*CTOP + CB On*) condition.

D.7. Results: Comments from SMEs

SMEs were asked to comment, observe and identify instances when they would have operationally introduced several other TMI techniques (e.g., extended MIT, holding, internal and external ground stops) to manage the traffic. These various inputs were seen specifically in the Baseline MIT tool conditions (*MIT + CB Off* and *MIT + CB On*). Figure 15 and 16 show the total delay assigned to each aircraft in both *MIT + CB Off* and *MIT + CB On* conditions for distributed and gaggle scenario, respectively. The orange line indicates the sum of total airborne delay and total ground delay of each aircraft. The green line indicates the connected line of total ground delay assigned to each aircraft. In the graph, the triggering events for implementing potential different techniques were indicated next to the relevant run time and delay event with red arrows and marked by a number. Table 8 and 9 present what techniques the SMEs would have implemented at each indicated triggering event.

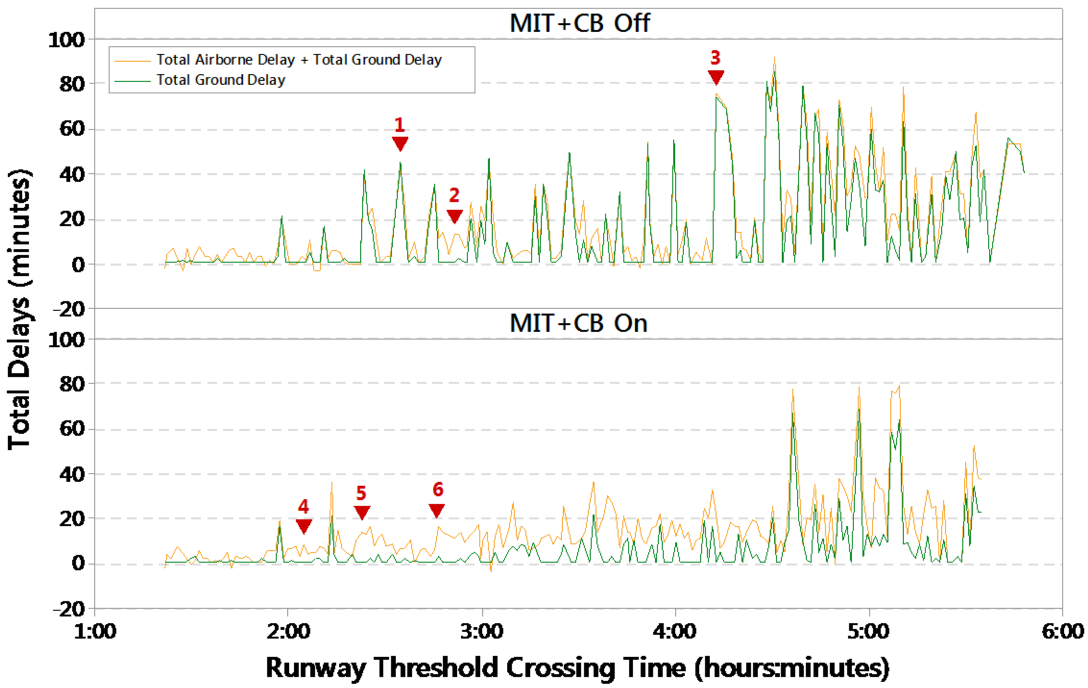

Fig. 15 Triggering events for possible different TMIs (distributed scenario).

Table 8 Description of triggering event and possible TMIs (distributed scenario)

Triggering Event	Event Description	Techniques
1	Short-hauls received ground delays (> 40 minutes)	Increase MIT
2	Airborne delays started to build up (> 5 minutes)	Ground Stop Tier 1-3 as needed, followed by EDCTs
3	Short-hauls received ground delays (> 60 minutes), airborne delays (>5 minutes)	Full Ground Stop
4	Airborne delays started to build up (> 5 minutes)	Turn *Checkbox Off*
5	Airborne delays started increasing (> 5 minutes)	Increase MIT, possible airborne holding
6	Incursion of unacceptable airborne delays (> 10 minutes)	Full Ground Stop

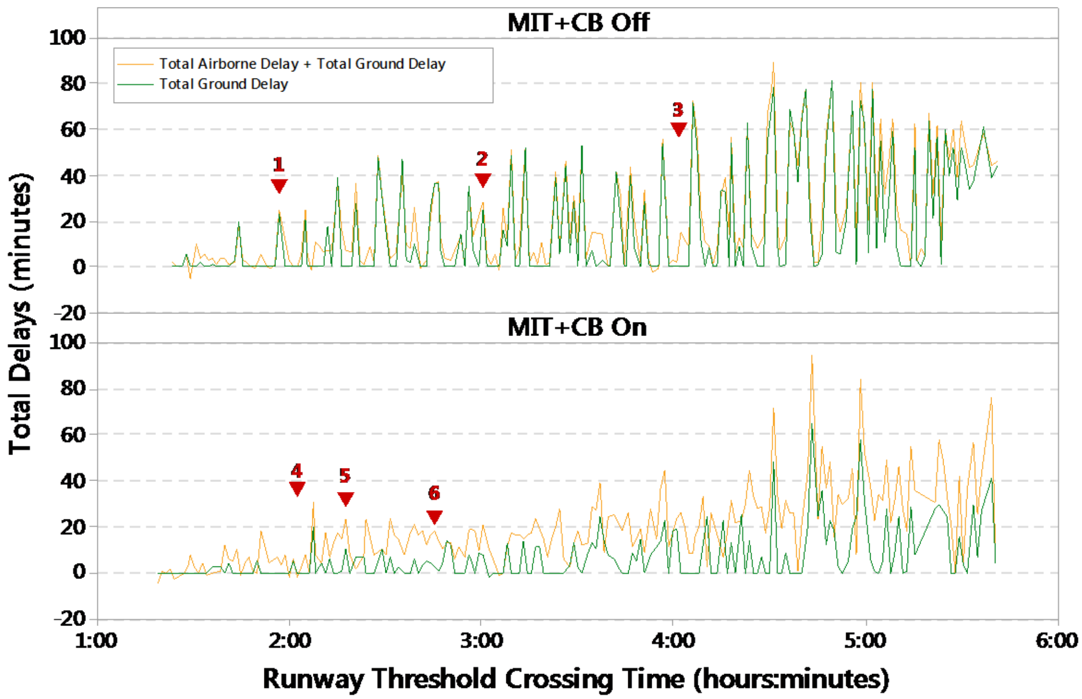

Fig. 16 Triggering events for possible different TMIs (gaggle scenario).

Table 9 Description of triggering event and possible TMIs (gaggle scenario)

Triggering Event	Event Description	Techniques
1	Acceptable airborne delays (< 2 minutes), Short-hauls with large ground delays (> 20 minutes)	Turn *Checkbox On*
2	Acceptable airborne delays (< 2 minutes), Ground delays started increasing for short-hauls (> 20 minutes)	Increase MIT
3	Short-hauls received ground delays (> 60 minutes), airborne delays (>5 minutes)	Full Ground Stop
4	Airborne delays started to build up (> 5 minutes)	Turn *Checkbox Off*
5	Airborne delays started increasing (> 5 minutes)	Increase MIT, possible airborne holding
6	Incursion of unacceptable airborne delays (> 10 minutes)	Full Ground Stop

In the Baseline MIT tool conditions (*MIT + CB Off* and *MIT + CB On*), the mismatch between the traffic demand and the capacity could have resulted in full ground stop, which is the strictest form of TMI that holds all aircraft within the scope at their departure airport.

E. Discussion

In the current phase of IDM concept development, no rerouting capabilities of CTOP were explored. The evaluation was conducted in an environment where no other constrained area in the en route airspace was presented. Hence, each flight had only one flight plan option submitted, and IDM CTOP used initial estimated arrival time of each flight to strategically plan the traffic demand based on a FSFS scheme. In the evaluation of the initial development of the IDM concept, the IDM CTOP was found to strategically provide equitable treatment in ground delay assignments across all flights regardless of origins of the departing airports (short-hauls vs long-hauls). Such results match the findings from past work that support the FSFS principle as a generally accepted standard for equitable resource allocation.

The airborne delay assigned by TBFM during IDM condition (*CTOP+CB On*) showed delays that were more acceptable by controllers in comparison to the baseline conditions (*MIT+CB Off* and *MIT+CB On*), indicating that the strategic demand planning using IDM CTOP allowed more manageable long-haul traffic demand to flow into TBFM area.

The effect of *CB On* or *CB Off* function within TBFM was clearly noticeable in the results from the TBFM-assigned airborne and ground delay analysis. The results indicated that *CTOP+CB On* had less last-minute ground delay assigned by TBFM, compared to both *MIT+CB Off* and *MIT+CB On* conditions. Both CTOP and TBFM acted on the short-haul departures in the *CTOP+CB On* condition. Although the short-haul departures received ground delays from two sources, the very minimal last-minute delays assigned by TBFM ensured that last minute double penalty was reduced and equity was maintained in total ground delay assignment between short- and long-haul departures.

It was observed that the total ground delays assigned to the short-haul departures in the *CTOP+CB On* condition were less than the ground delays that the short-hauls received from only TBFM in the *MIT+CB Off* condition on average. Having *CB On* allowed the TBFM to find slots in the overhead stream for a short-haul departure by delaying the non-frozen flights. In the *CTOP+CB On* condition, the traffic demand fed into TBFM had effectively reserved slots in the overhead stream through the process of equitably assigning ground delays between short- and long-hauls at the strategic level using CTOP. Hence, such practice of inserting short-haul departures into the overhead flow had no substantial impact on the overhead stream.

However, in the *MIT+CB On* condition, having *CB On* impacted the heavy traffic demand flowing into TBFM and resulted in very high unacceptable airborne delays, although the function allowed the short-haul departures to be scheduled mostly on-time. Thus, it was observed that the total ground delays assigned to the short-hauls departures in the *CTOP+CB On* condition was slightly higher than the ground delay assigned to the short-hauls in the *MIT+CB On* condition. Nevertheless, such consequence was a result of trading reduced ground delays of short-haul departures for increased airborne delays. Airborne delays are considered to be much more expensive than ground delays. Hence, it was observed that the total delay cost induced in the *CTOP+CB On* condition was found to be the least out of three conditions, in terms of overall applied relative cost.

Moreover, in a real-world situation where such high airborne delays accrue in TBFM, as was the case in the *MIT + CB Off* and *MIT + CB On*, a more restrictive form of TMI (like a ground stop) could have been placed, possibly resulting in much higher ground delays. The 30 MIT TMI—that was in operation during both *MIT + CB Off* and *MIT + CB On* conditions—was not enough to solve the mismatch. However, due to the limited procedural actions in the study, the SMEs were not allowed to take additional actions. The SMEs indicated that the MIT problems as they played out would not have been workable in the real field, whereas, they indicated that there were no further actions that needed to be introduced during the *CTOP+CB On* condition.

Some unacceptable airborne delay cases were observed in MFX region during the *CTOP+CB On* operations. This was mainly due to the technical challenges that were faced using *CB On* function with XM capabilities. The *CB On* function involved running an algorithm to find a slot in the overhead stream within the MFX region for a short-haul departure by delaying the non-frozen airborne flights, which may have been already frozen in the XM schedules. Hence, no projected excess delay beyond the delay absorption ability of the MFX schedules could have been transferred to its directly linked XMP by 'Passback Delay.'

It is important to note the IDM concept is not built to improve efficiency by sacrificing throughput. In this study, the AAR at EWR airport was given and was used as the target throughput. In IDM (*CTOP+CB On*) condition, CTOP and TBFM were tuned accordingly to deliver the demand matching the estimated capacity and the results showed that the target throughput was achieved. However in reality, projecting a target throughput of an airport for a specific planning horizon is very challenging due to the uncertain nature of the projection. Using a poorly estimated capacity at an airport to strategically manage traffic demand can lead to various undesirable outcomes, such as overfeeding TBFM with high traffic demand, or vice versa, inducing unnecessary ground delays and underfeeding TBFM leaving the airport underutilized.

IV. Exploratory Study

A. Overview

In the initial IDM concept, CTOP is meant to control take-off times of departures during strategic demand management. However, once aircraft take-off according to their scheduled departure times, the aircraft are no longer actively controlled to ensure their planned schedule flying into TBFM. Hence, the RTA exploratory study was conducted: 1) to explore RTA as a control mechanism to improve delivery of strategically planned long-haul en route traffic demand entering TBFM, and to determine if using RTA is shown to improve delivery accuracy, then 2) to evaluate the impact of such improvement in delivery accuracy on overall TFM operations under the initial IDM concept, and 3) to identify if RTA assigned aircraft gained benefit from achieving better delivery accuracy, and finally 4) to ensure that the throughput would meet the desired target using the RTA capability.

B. Hypotheses

The first hypothesis was constructed to determine whether use of RTA improves the delivery accuracy at the TBFM entry point.

Hypothesis 1: assigning RTA to long-haul aircraft will improve delivery accuracy at TBFM entry points.

The second hypothesis was examined to identify whether improving delivery accuracy of long-hauls to the TBFM entry points has a positive impact on the IDM operations in terms of delays incurred within TBFM.

Hypothesis 2: improving delivery accuracy of long-hauls will decrease both airborne and ground delay induced within TBFM during the IDM operation.

The third hypothesis was constructed to test whether aircraft could gain any benefit by flying RTA to improve delivery accuracy when they enter TBFM.

Hypothesis 3: RTA assigned aircraft will receive less airborne delay when they entered TBFM.

Finally, the last hypothesis was assessed to verify that target throughput could be achieved in the initial IDM concept, even with the use of RTA.

Hypothesis 4: the initial IDM operation with use of RTA will deliver target demand to the final destination.

C. Method

C.1. Participants

The same eight participants from the evaluation of initial development of IDM participated in this exploratory study.

C.2. Procedures

The procedure stayed the same for all participants, except that one of the participants at the TFMS planner stations was asked to directly send RTA advisories to aircraft that were in level flight and at least 600 miles from the airport, bypassing the sector controller. The eligibility of RTA based on meeting such criteria was indicated by automation aids on their TFMS ERAM display. Aircraft that were within 600 nm by the time they reach their cruise altitude were excluded from RTA eligibility. This was 1) to allow sufficient flight distance to make changes using speed control, and 2) to avoid effect of climb uncertainties.

C.3. Experimental Apparatus

The simulation was conducted on the same set-up as used in the evaluation of the initial IDM concept. However, in order to achieve the objectives of the exploratory study, a few more functions were added. On the customized MACS ERAM display provided to the participants at the TFMS planner stations, there was an automation aid that indicated which aircraft were eligible for receiving RTA assignment using the flight data block (see figure 17).

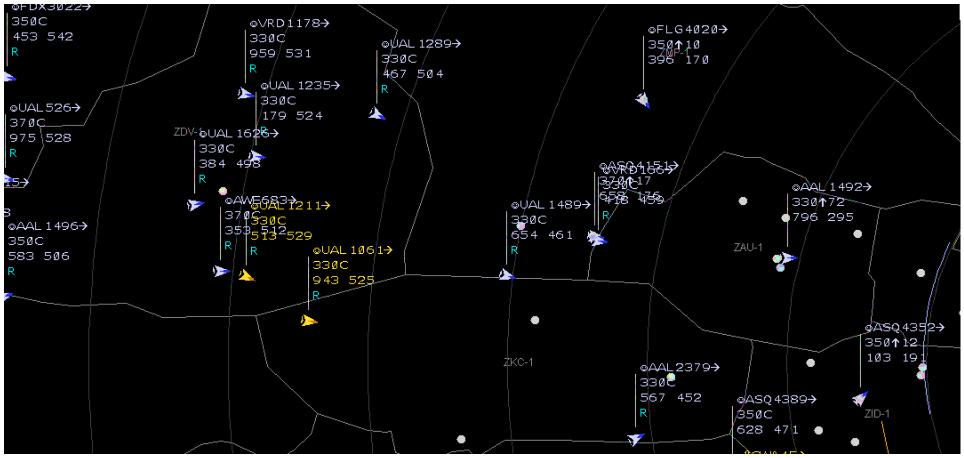

Fig. 17 RTA eligibility indicated by “R” symbol in flight data block.

In addition, the aircraft that were assigned with an RTA were specified to assist the situation awareness of the controllers. Once an aircraft was assigned with RTA, RTA information was displayed in the fourth line of the full data block (see figure 18). The information shows the fix just outside of the TBFM entry point and the specified time it needs to meet. The scheduled time to the fix near the TBFM entry point is anchored to the CTOP generated schedule at the FCA. There was a gap of approximately 5 nm between the scheduled fix and the TBFM region to allow the RTA assigned speed to resume back to nominal speed before entering TBFM. The color-coded RTA indicates the conformance level of the aircraft actually making the RTA within the desired +/- 1 minute parameter.

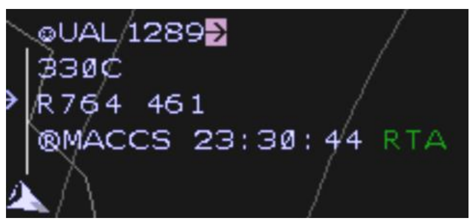

Fig. 18 RTA information displayed in full flight data block.

The full data block could be minimized to just show the RTA conformance level represented by different colors (see figure 19). The RTA target times were generated to the nearest waypoint on the aircraft’s flight plan prior to entering TBFM regions. RTA conformance was the difference between RTA assigned time to cross the fix and ETA to the fix. Green indicated RTA conformance was within +/- 1 minute, and if it deviated from that range, it was indicated by yellow color to bring attention to the controllers. RTA was data linked to the aircraft flight deck and automatically input into the Flight Management System (FMS). The pseudo-pilots were responsible for monitoring RTA conformance and would inform the controllers at the TFMS planner station when they could not make their assigned time. In such events, the controllers were provided with the capability to mark the aircraft with a red color.

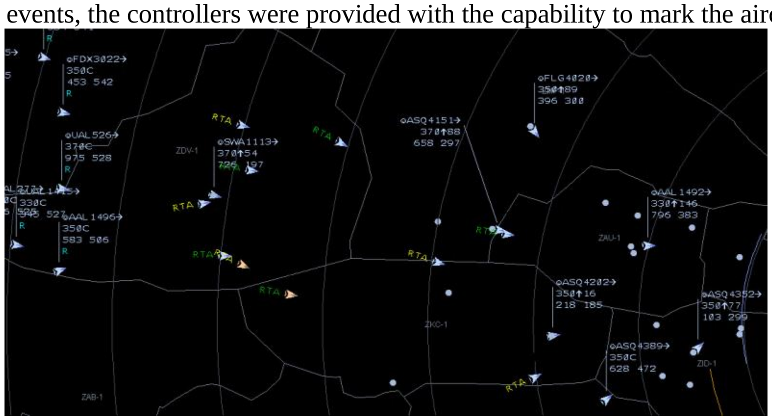

Fig. 19 RTA conformance indicated by different color codes.

MACS flight deck FMS software that emulates the general characteristics of a Honeywell "Black Label" FMS (B757/HW BL) was used for the experiment (see figure 20).

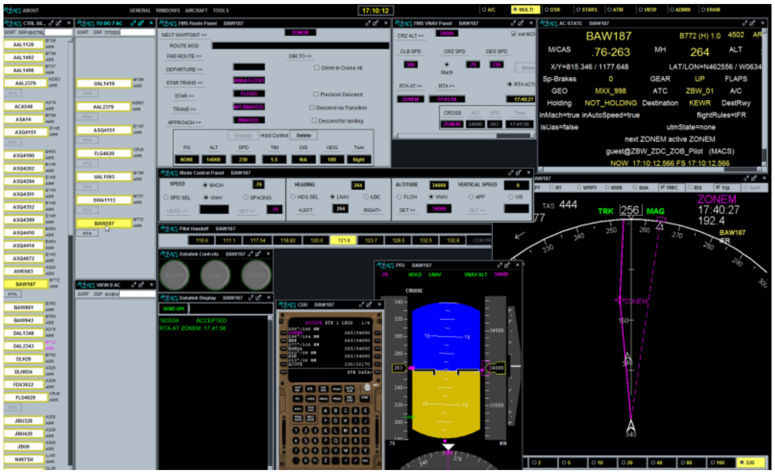

Fig. 20 MACS FMS software.

MACS FMS emulation allowed a user-adjustable RTA tolerance setting, which re-computed the flying speed so that aircraft crossed the target fixes at the closest time to assigned RTA time, when the difference between the assigned RTA time and Estimated Time of Arrival (ETA) became greater than an user-adjustable parameter, in which this parameter's value was set to be +/- 60 seconds in this study.

To implement the constraint on how fast or slow a RTA assigned aircraft could fly at a reasonable level, flight operators' cost index preferences, i.e. the ratio of the time-related cost of a flight operation and the cost of fuel, was used in the study. The speeds relevant to the cost index values used by several airlines were gathered and used in the study. Based on the collected information, the speed range for the 'heavy' weight class aircraft was restricted to be between Mach 0.76-0.85. And the speed range for 'large' weight class aircraft was set to stay within Mach 0.74-0.84.

C.4. Independent Variables

One tool condition was tested under the two traffic scenarios (distributed and gaggle) that were previously used. The results of the new tool condition was compared to the results of the *CTOP+CB On* tool condition obtained in the evaluation of initial development of the IDM. The following describes the new tool condition that was created to test RTA capabilities within the initial IDM concept:

CTOP + Checkbox On + RTA (CTOP+CB On+RTA): In this condition, the same tools and the procedures from the *CTOP+CB On* tool condition were used. The only difference was that the controllers at the TFMS planner stations were asked to assign RTA to the aircraft that were identified as RTA eligible.

The same departure errors, wind severity and the associated wind forecast errors from the initial IDM concept evaluation study were used.

C.5. Dependent Variables

The same three dependent variables used in the IDM evaluation study, throughput, airborne delay, and ground delay, were collected. In addition to those measures, Crossing Time (CT) performance to the TBFM entry point was obtained. CT performance was considered to be the difference between the actual CT and the scheduled CT time of an aircraft crossing a TBFM entry point. TBFM entry points were identified as arcs located approximately 5 nm outside of XM FHs (the most outer part of TBFM regions) of each XMP. Scheduled CTs to the TBFM entry points were generated based on the CTOP scheduling algorithm. CTOP planned the STAs of both short- and long-haul aircraft to the ring-shaped FCA in order to balance the demand and the capacity of the FCA. The STA information was used to determine when the long-haul aircrafts should enter the TBFM entry points.

CT performance was categorized into the target tolerance range and the marginal tolerance range. The target tolerance range was +/-1 minute, also matching the value entered in the RTA tolerance setting. The marginal tolerance range was +/-5 minutes. These values were established according to SME input which indicated that +/-5 minute conformance was operationally workable for the TBFM system to manage the arrival flow into EWR.

D. Results

D.1. Overview of Results

This section provides the results from conducting the RTA exploratory study. According to results of the hypotheses testing, assigning RTA to long-hauls improved the delivery accuracy at TBFM entry points. However, such improvement did not lead to reduction in airborne and ground delays induced within TBFM operations, nor did it benefit the RTA assigned aircraft in terms of delays received from TBFM.

D.2. Results of Hypothesis 1: assigning RTA to long-haul aircraft improved delivery accuracy at TBFM entry points.

The first hypothesis was tested by comparing CT performance of RTA assigned aircraft during *CTOP+CB On+RTA* condition to the results obtained from *CTOP+CB On* condition in the initial IDM evaluation. There were 73 aircraft that received RTA assignment in the distributed scenario and 69 aircraft received RTAs in the gaggle scenario. The figure 21 shows the CT performance of those aircraft observed in the IDM tool conditions (*CTOP+CB On+RTA* and *CTOP+CB On*). In the figure, green reference lines indicate the target tolerance range and the orange reference lines represent the marginal tolerance range.

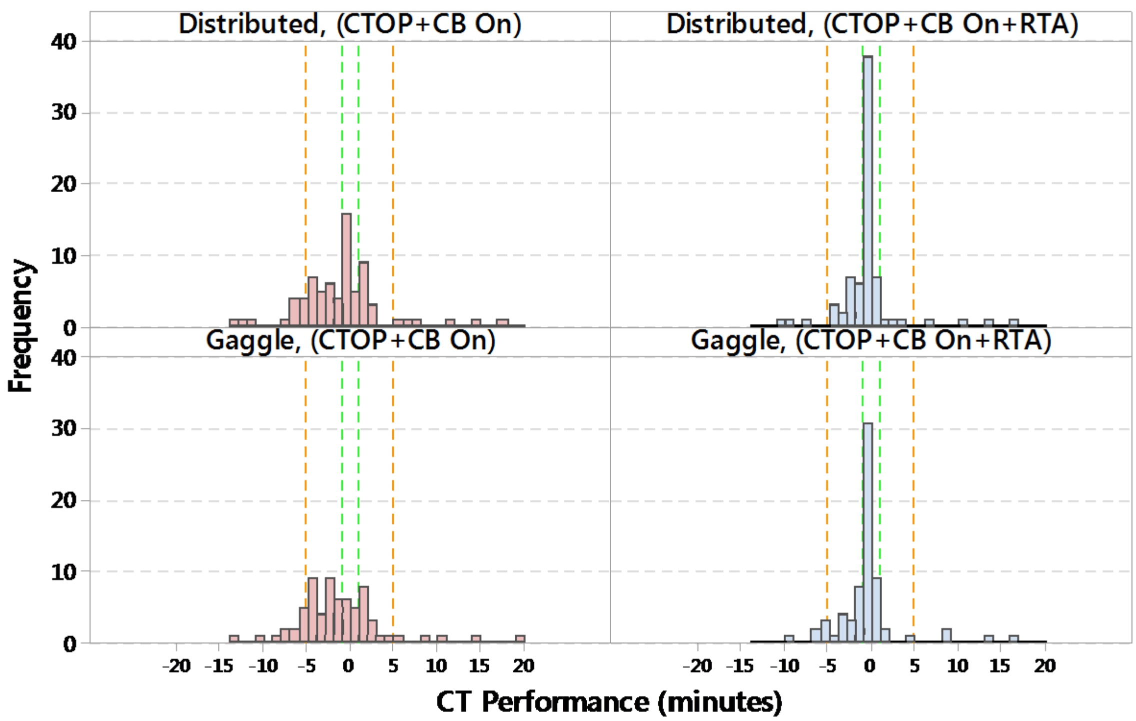

Fig. 21 CT performance in the IDM conditions (*CTOP+CB On+RTA and CTOP+CB On*).

Table 10 provides the CT performance in relation to the tolerance ranges. It is found that RTA improved delivery accuracy, indicated by the percentage of aircraft that met the target and marginal tolerance range criteria.

Table 10 CT performance based on tolerance range (marginal and target), in minutes

Scenarios	Tool Conditions	Out of Tolerance	Marginal	Target	Marginal	Out of Tolerance
		[-∞,-5)	[-5,-1)	[-1,1]	(1,5]	(5,+∞]
Distributed	*CTOP + CB On*	16.4 %	30.1 %	28.8 %	16.4 %	8.2 %
	CTOP + CB On + RTA	4.1 %	24.7 %	61.6 %	4.1 %	5.5 %
Gaggle	*CTOP + CB On*	17.3 %	40.5 %	15.9 %	18.8 %	7.5 %
	CTOP + CB On + RTA	8.7 %	23.2 %	60.0 %	4.3 %	3.8 %

D.3. Results of Hypothesis 2: improving delivery accuracy of long-haul had no obvious impact on decrease in delays induced within TBFM during IDM operation

As the results from *hypothesis 1* were found to support the hypothesis, the assessment of hypothesis 2 followed to examine whether such observed improvement in delivery accuracy helped reduce the overall delays incurred within TBFM regions. Table 11 presents the ground delays that were assigned during both *CTOP+CB On+RTA* and *CTOP+CB On* conditions. The results indicate that there was no additional benefit achieved in terms of minimizing the last-minute ground delay that TBFM assigned.

Table 11 Ground delay assigned by TBFM (hours:minutes:seconds)

Tool Conditions	Scenarios	TBFM Regions	Mean	SD	Median	Maximum	N
CTOP + CB On	Distributed	XM	0:00:24	0:01:01	0:00:00	0:05:00	45
		MFX	0:01:16	0:01:23	0:01:00	0:04:00	22
	Gaggle	XM	0:00:10	0:00:29	0:00:00	0:02:00	47
		MFX	0:02:00	0:01:44	0:03:00	0:05:00	23
CTOP + CB On + RTA	Distributed	XM	0:00:14	0:00:42	0:00:00	0:03:00	47
		MFX	0:01:08	0:01:29	0:00:30	0:05:00	22
	Gaggle	XM	0:00:15	0:00:43	0:00:00	0:03:00	45
		MFX	0:01:57	0:01:57	0:02:00	0:06:00	23

Additional was analyses were conducted to determine whether the improvement in delivery accuracy decreased the airborne delay incurred within TBFM regions. Tables 12 and 13 provide the airborne delay assigned by TBFM XM and MFX schedulers. Again, for both traffic scenarios (distributed and gaggle), no additional reduction of airborne delays within TBFM was observed due to use of RTA.

Table 12 Airborne delays assigned by TBFM (XM scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-5, 5)	[5, 10)	[10, ∞]	
Distributed	*CTOP + CB On*	169	5	0	174
	CTOP + CB On + RTA	174	0	0	174
Gaggle	*CTOP + CB On*	168	3	0	171
	CTOP + CB On + RTA	173	0	0	173

Table 13 Airborne delays assigned by TBFM (MFX scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-2, 2)	[2, 4)	[4, ∞]	
Distributed	*CTOP + CB On*	100	70	22	192
	CTOP + CB On + RTA	124	61	7	192
Gaggle	*CTOP + CB On*	124	54	13	191
	CTOP + CB On + RTA	101	78	17	196

D.4. Results of Hypothesis 3: there was no indication of RTA assigned aircraft receiving less airborne delay when they entered TBFM.

To further verify the effect of the use of RTA on operations, TBFM assigned airborne delay for RTA aircraft was analyzed. Tables 14 and 15 present the airborne delay assigned to the RTA assigned aircraft by TBFM XM and MFX schedulers. The amount of TBFM assigned airborne delay of RTA assigned aircraft in the *CTOP + CB On + RTA* condition was compared to the amount of TBFM assigned delay in the *CTOP + CB On* condition, when no RTA was used. There was no significant indication showing that the aircraft flying the RTA gained further benefit in terms of reduction of TBFM assigned airborne delay in IDM operations.

Table 14 Airborne delays assigned by TBFM (XM scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-5, 5)	[5, 10)	[10, ∞]	
Distributed	*CTOP + CB On*	70	3	0	73
	CTOP + CB On + RTA	73	0	0	73
Gaggle	*CTOP + CB On*	67	2	0	69
	CTOP + CB On + RTA	69	0	0	69

Table 15 Airborne delays assigned by TBFM (MFX scheduler), in minutes

Scenarios	Tool Conditions	Acceptable	Marginal	Unacceptable	N
		[-2, 2)	[2, 4)	[4, ∞]	
Distributed	*CTOP + CB On*	34	30	9	73
	CTOP + CB On + RTA	42	29	2	73
Gaggle	*CTOP + CB On*	37	23	9	69
	CTOP + CB On + RTA	29	29	11	69

D.5. Results of Hypothesis 4: the initial IDM operation with use of RTA delivered target demand to the final destination.

Table 16 presents the total number of aircraft landed in last four hours of the simulation for each scenario under the RTA condition (*CTOP +CB on +RTA*). The results support that the target throughput (= 44 aircraft per hour) was achieved in the condition.

Table 16 Runway throughput based on total number of flights landed in last 4 hours (90 – 330 minutes)

Scenarios	Tool Conditions	Mean	SD	Total number of Flights Landed in last 4 hours (90 - 330 minutes)
Distributed	*CTOP + CB On + RTA*	43.5	1.67	174
Gaggle	*CTOP + CB On + RTA*	43.5	0.33	174

V. Discussion

In the RTA exploratory study, long-haul aircraft were actively controlled by assigning RTA to ensure their planned schedule flying into TBFM within the initial IDM concept, the *CTOP+CB On* condition, where traffic demand management was primarily controlled by assigning take-off times. In the initial IDM concept, the scheduled entry time into TBFM is anchored to the CTOP generated schedule to the FCA located near the airport. CTOP was designed to regulate the overall traffic demand flowing into TBFM; however, there was no coupling between the CTOP and TBFM schedulers. Once aircraft entered TBFM regions, TBFM re-scheduled flights for the final arrival schedules. Hence, RTA capabilities were used mainly to assist managing the long-haul traffic demand flowing into TBFM, rather than keeping the flight sequence or achieving high precision in delivery. Two sources of uncertainty in arrival traffic demand flying into TBFM were introduced; departure errors and wind forecast errors. The results from conducting the exploratory study support that assigning RTA to the long-hauls improved the delivery accuracy at TBFM entry points. However, no clear observation implying that such improvement in delivery precision had a positive impact on the overall airborne and ground delay induced within TBFM regions. Moreover, improved precision by flying RTA did not benefit the actual RTA aircraft in terms of receiving less airborne delay once they entered TBFM regions. These results were compared to IDM operations without the use of RTA in the *CTOP+CB On* condition, which had already performed effectively with the uncertainties introduced in the simulation. Hence, there was very little room for improvement in terms of reducing airborne and ground delay incurred within TBFM. Since assigning RTA has been shown to achieve accurate CT performance, RTA capabilities could be explored for use in airspaces (e.g., terminal areas) where more precision is required. In addition, there could be space for more use of RTA exploration with the introduction of more severe and various sources of uncertainties into the IDM operational environment.

VI. Overall Conclusions

After the evaluation of the initial IDM concept, the subsequent conclusions were made: 1) IDM operations provided equitable use of the constrained NAS resources indicated by the fairly assigned ground delays between short- and long-haul departures, 2) such equity in ground delay assignment led to delivering more manageable long-haul traffic demand into TBFM, preventing the incursion of unacceptable airborne delays, and 3) the regulated long-haul demand contained reserved slots for the short-haul departures within TBFM, which minimized the unexpected last-minute ground delays assigned by TBFM. Moreover, the results indicated that 4) the IDM enabled delivering target throughput to the final destination. In addition, 5) it was found that the IDM operation reduced overall expected cost associated with delays in arrival traffic management by transferring airborne delays into ground delays.

The following conclusions were determined by conducting the RTA exploratory study: 1) assigning RTA to long-haul aircraft improved delivery accuracy at TBFM entry points. However, 2) since the IDM operations without use of RTA under the introduced uncertainties performed effectively in terms of minimizing delays within TBFM, it was difficult to identify the benefit of using RTA within the context of the initial IDM concept.

Effective operations of the IDM concept heavily rely on accurate prediction of capacity available at the resource constrained areas. The initial IDM concept was evaluated in a condition where there was a single FCA located near the airport, and accurate capacity estimation of the FCA was provided and shared across the CTOP and TBFM systems. This allowed effective coordination between the systems for evaluating the validity of the concept.

Without accurate prediction of capacity at the FCA for a specific planning horizon, the illustrated conclusions may not be as promising. For instance, without clear coordination between CTOP and TBFM based on the accurate capacity prediction, CTOP may feed more traffic demand than what TBFM can handle, thus increasing airborne delay and giving additional excessive delays to the short-haul flights that have already been controlled by CTOP. Future work should investigate a way to estimate the capacity of constrained areas accurately with reasonable look-ahead time. Effective strategic demand planning using CTOP should synchronize with what can be handled within TBFM. Improving the capabilities of more accurate estimation will become more important with use of multiple FCAs within a single CTOP program.

In addition to placing effort into better capacity estimation, investigation on how to recover from the demand planning based on poor estimation or sudden changes in the plans could be explored. The system operators should be granted more tactical and defined ways of dynamically revising the demand planning. Also, there should be mechanisms for flight operators to provide more input. For example, flight operators could share their availability for potentially departing earlier than their assigned EDCT in the event of a cancelled TMI to assist the recovery process in ways that could benefit them.

Future IDM studies will introduce multiple FCAs within a CTOP, allowing the problem space for CTOP TOS capabilities to be explored. The results of the initial IDM concept evaluation showed promising outcomes pertaining to limited NAS resource utilization from the perspective of a system operator. TOS options are designed to incorporate input from flight operators into the system, where such inputs could lead to significantly different results in resource utilization. The focus of future evaluation could lie in investigation of how input from flight operators can lead to more efficient use of constrained airspace resource utilization and achieve more flexible, and less centralized system architecture in TFM operations. In addition, an exploration of handling capacity/demand balancing among the multiple FCAs within a single CTOP program could be performed.

Acknowledgments

The authors would like to thank all the subject matter experts who shared their invaluable inputs to the concept development. The authors would like to thank the lab personnel at the Airspace Operations Lab at NASA Ames Research Center.

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