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Evaluation of Integrated Demand Mangement looking into Strategic & Tactical Flow Management

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***Abstract* - The motivation behind Integrated Demand Management (IDM) research is to explore possible improvements to United States National Airspace System (NAS) performance that could be realized through procedural integration of strategic traffic flow management capabilities, such as the Collaborative Trajectory Options Program (CTOP), and tactical capabilities, such as Time Based Flow Management (TBFM). An initial IDM concept for clear weather operations was developed and evaluated for potential benefits, including efficiency, delay reduction, predictability and throughput, and to identify any major issues that might represent a showstopper for a fielded application. Newark Liberty International Airport (EWR) arrival operations provided a use case for concept development. EWR uses miles-in-trail (MIT) metering to regulate demand into TBFM during high volume operations, and short-haul flights are often penalized with excessive, last-minute ground delays when the overhead stream is saturated. IDM addresses this problem by replacing MIT conditioning with CTOP to better manage the demand delivery to the TBFM entry points. A "quasi-real time" high-fidelity simulation that would normally involve participants was conducted using heuristic-based procedures that mimicked operators' behaviors instead. Five total conditions were compared: two baseline conditions with MIT delivery to TBFM entry points using two different TBFM settings; and three IDM conditions: one with airborne speed control using an Required Time of Arrival (RTA) capability, a second without RTA, and a third with no wind forecast errors. Results suggest that the IDM concept can deliver traffic more efficiently by shifting the delays from airborne to ground for both RTA and non-RTA conditions, while maintaining a target throughput rate. The results also suggest that with good predictability of airport capacity, excessive TBFM ground delay can be minimized by applying more strategic CTOP delay, increasing predictability for the airline operators. Overall, the results indicate that the implementation of an IDM concept under clear weather conditions can improve NAS system performance. Future IDM research aims to expand the concept to address demand/capacity imbalance d severe weather.**

Keywords - Flow management, Time-Based Flow Management (TBFM), Collaborative Trajectory Option Program (CTOP), ground delay, airborne delay, throughput, airline operators

I. INTRODUCTION

Traffic flow management in the U.S. is supported mainly by two separate systems: TFMS (Traffic Flow Management System) and TBFM (Time-Based Flow Management). TFMS is a more "strategic" NAS-wide system operated out of the Command Center and is used to manage traffic flows when airport or airspace capacity is insufficient to the expected demand. Its planning horizons range from 45 minutes to several hours or more. In contrast, TBFM represents a more local and "tactical" capability that is used to schedule and manage inbound arrival traffic to a destination airport. TBFM has a 30 – 90 minute time horizon and is operated from the traffic management units in applicable En route Center facilities [1, 2].

Traffic volume problems, resulting from a mismatch of demand and capacity at the arrival runway are mainly addressed today using miles-in-trails (MIT) and TBFM metering. In contrast to other research [3], Integrated Demand Management (IDM) [1] explores procedural ways to integrate different traffic flow management tools to streamline and improve overall NAS system performance. Specifically, IDM leverages CTOP (Collaborative Trajectory Options Program), a recently introduced NextGen TFMS planning tool, and new TBFM capabilities that support Extended Metering and Couple Scheduling capabilities, e.g. [4, 5].

A. Traffic Flow Management System (TFMS) with CTOP

The CTOP operation is a strategic traffic management initiative (TMI), which takes place well in advance of flights getting scheduled in TBFM. CTOP uses "expect departure clearance times" (EDCTs) to manage the scheduled traffic demand departures with the airport capacity constraints.

Under CTOP, a TMI uses multiple Flow Constraints Areas (FCAs) and Flow Evaluation Areas (FEAs) to address capacity constraints. A major advantage of CTOP is its ability to use these multiple FCAs and FEAs within a single program to handle more complex demand-capacity balancing problems. Another significant, new capability within CTOP allows airline operators to submit a preference-weighted set of route

alternatives called a Trajectory Option Set (TOS), a feature that will be utilized in later versions of the IDM concept. Figure 1 is a schematic representation of CTOP FCAs and FEAs that were used for initial IDM concept development. As shown in the figure, a small "inner ring" FCA was constructed roughly 40 miles from EWR; this FCA was used to build an initial arrival schedule that provided unique slot times for all inbound flights. Three upstream Flow Evaluation Areas (FEAs), one for each major traffic flow, were placed immediately outside the TBFM region: these were used to monitor and control conformance to the (downstream) FCA schedule before the flights entered the TBFM control region.

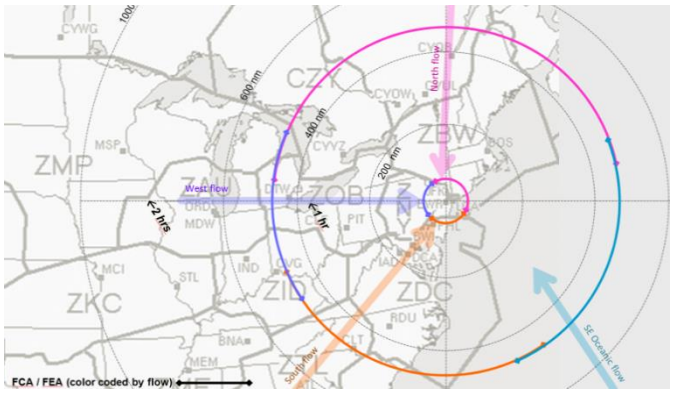

Figure 1. Schematic representation of CTOP Flow Control Arcs (FCAs): Upstream FEAs (outer arcs) and schedule to an airport (inner ring)

B. *Time-Based Flow Management*

While CTOP uses FCAs as constraint points for demand management, TBFM uses meter fixes and the runway threshold as "constraint satisfaction points" when building an arrival schedule. After an aircraft cross the TBFM freeze horizon, first-come first-served rationing logic is used to assign it a scheduled time of arrival (STA) at the crossing, based on the aircraft's estimated time of arrival (ETA). TBFM also provides the option of defining other layers of TBFM constraint satisfaction points and freeze for demand management further upstream. Figure 2 is a schematic representation of the TBFM adaptation that was used in initial IDM concept development. As shown in the figure, two layers of TBFM, one for the meter fixes and freeze horizon and another for the Extended Metering (XM) meter points and freeze horizon.

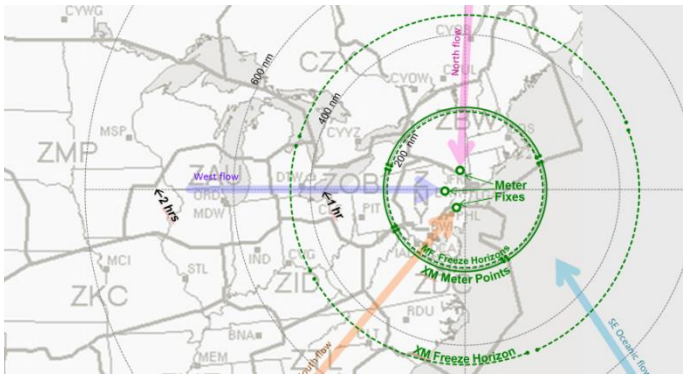

Figure 2. Schematic representation of TBFM Meter Fixes and Freeze Horizons (Meter Fix Freeze Horizon & Extended Metering Freeze Horizon)

One of the major issues with TBFM under current operations is that it has limits on how much excess demand it can handle before overloading controllers with absorbing untenable airborne delays; TBFM becomes useless under those conditions. However, the strength of TBFM is that when traffic volume is delivered with acceptable delays, it can deliver traffic to the target airport much more efficiently with less delay than an operation without TBFM. Historically EWR has not been able to utilize TBFM to its full potential. IDM hopes to utilize the newest features of TBFM with a strong delivery of pre-managed traffic demand.

C. *Challenge to Harmonize TFMS and TBFM configurations*

For harmonizing TFMS and TBFM tool, we need a good prediction about the rate settings for the TBFM, well in advance (e.g. 3 - 6 hours out) in order to adapt the FCA settings in CTOP accordingly. One of the assumptions in harmonizing the demand across the two systems is that robust demand prediction can be made strategically in clear weather days. We recognize that it would be more challenging to make such an assumption in changing weather conditions due to difficulty in strategic demand predictions. For now, weather scenarios are beyond the scope of this paper and will be addressed in later studies.

D. *IDM Concept Description*

The basic idea of IDM is to coordinate demand management across CTOP and TBFM by setting capacity limits in CTOP that will provide appropriate demand into TBFM. This coordinates the two systems, although they are not directly coupled. Even though CTOP creates a demand schedule to an FCA location within the TBFM control region, TBFM will build its own arrival schedule, independent from CTOP, after aircraft cross the TBFM freeze horizon. Figure 3 overlays the CTOP setup in Figure 1 with the TBFM setup in Figure 2 to illustrate how the two adaptations are coordinated, with the CTOP FEAs placed just upstream of the TBFM XM freeze horizon.

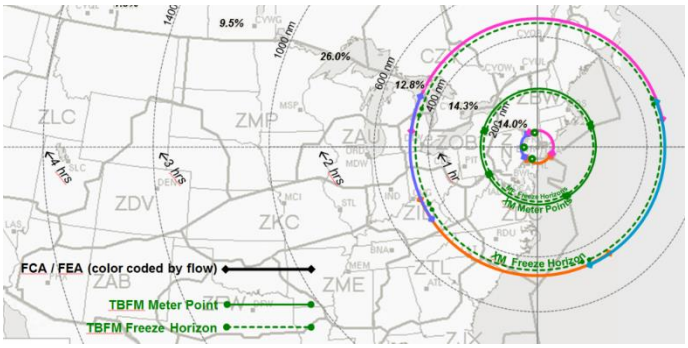

Figure 3. Integrated Demand Management Concept

This coordinated but independent scheduling means that the initial strategic CTOP arrival schedule constructed many hours in advance can be replaced by a TBFM schedule that is based on more current information. The initial CTOP arrival schedule will manage the demand into TBFM, but does not require the same precision as the final arrival schedule. This feature was considered to be important in building a robust and flexible

system that does not overburden controllers and traffic managers with excessive and unnecessary schedule management.

The IDM-concept addresses a solution for the United States National Airspace System (NAS) focusing on current and Next Gen tools and technologies. Similar research for Europe can be found with keywords like 4D-trajectory management, or time-based arrival management [6, 7, 8].

E. Different Types of IDM Operations

As a part of an initial IDM concept exploration and evaluation, two instantiations of IDM that used different capabilities were tested during simulated clear weather arrival operations. The goal for this and subsequent future studies is, to identify and evaluate the efficacy of different technologies that could fit into the IDM framework and add or subtract them from the final concept based on the outcome.

In addition to CTOP and TBFM systems, we examined the impact of assigning Required Times of Arrival (RTAs) to airborne arrivals in the CTOP-controlled region as a method for improving CTOP schedule conformance after the aircraft takes off to improve the delivery accuracy into TBFM. While Jones et al. [9] looked into speed delays up to 500 miles out from the final destination (~TBFM region), aircraft needed to be in level flight and at least 600 miles from the airport to be RTA-eligible under IDM. The concept was tested with and without RTA assignment in two test conditions (called "EDCT+RTA" and "EDCT only", respectively) in order to measure the impact of RTAs into the TBFM region.

1) IDM operations based on 'EDCT Only'

In IDM, an initial arrival schedule is built by CTOP to a target airport by assigning an FCA slot to every aircraft to that airport (See Figure 1, inner ring), which in turn generates EDCTs for all pre-departures. In "EDCT Only" operations, there are no further adjustments to meet the CTOP FCA schedule after takeoff. After the aircraft enters the TBFM region by crossing the XM freeze horizon, TBFM takes over the scheduling task and builds a new arrival schedule that is "first-come, first served" and independent from the initial CTOP arrival schedule.

Although the aircraft are supposed to take off within +/- 5 minutes of their EDCTs to be in conformance, departure time errors – i.e., the difference between assigned and actual departure times – routinely fall outside these conformance windows during today's operations. Departure errors and/or other disruptive factors (e.g. wind error forecast) may result in an aircraft failing to arrive at its FCA slot time unless actions are taking to bring it back into conformance.

2) IDM operations based on 'EDCT and RTAs'

In contrast to the 'EDCT Only' operations, 'EDCT and RTA' adds an inflight control loop to manage the CTOP FCA schedule after the aircraft are airborne in order to arrive as closely as possible to their assigned FCA slot times. The operations are identical to the 'EDCT Only' operations until after departure, with a CTOP arrival schedule providing an FCA slot and EDCT to each eligible pre-departure. In this condition, however, aircraft that reach cruise altitude at least 600 nm out from the destination airport are assigned RTAs to the outer FEAs based on their CTOP-assigned slot times (see Figure 1, outer arcs). Aircraft that are RTA eligible can change their speeds inflight to increase their schedule conformance to their original FCA slot times; reducing, for example, the impact of departure errors. After the aircraft cross the Extended Meter Fix (XM) freeze horizon operations once again become identical to the 'EDCT Only' condition, , with TBFM building a new "first come, first served" arrival schedule that is not linked to the CTOP schedule.

F. Previous IDM Studies

From a first IDM concept evaluation study [1] that was completed in January 2016 the authors reported that CTOP-pre-conditioning of demand into TBFM appeared to provide benefit. However, due to various simulation shortcomings, such as short simulation runs, too few RTA eligible aircraft in the EDCT+RTA condition, very mild winds, and other factors, the results from the study were inconclusive. In this paper, the January 2016 study is replicated but with corrections to the prior study to produce clearer and better results which will be detailed in the Results section.

During both studies, two alternative TBFM settings for scheduling departures from origin airports located within the TBFM freeze horizon were used and evaluated. One setting, referred to as "Checkbox On", allowed the pre-departure aircraft to be scheduled ahead of airborne flights that were not yet frozen on the TBFM arrival schedule. The other setting, known as "Checkbox Off", prioritized the unfrozen airborne arrivals, forcing the pre-departures to wait for the first available full slot to avoid affecting any of the overhead traffic. Results from the January study, reported in [2], suggest that the settings shifted the ratio of airborne to ground delays within the TBFM region, but had similar overall delay cost. In today's operations at EWR the TBFM setting "Checkbox Off" is used to ensure that the system does not accidently assign excessive airborne delays that the controllers cannot handle. For EWR this is quite important as it brings together traffic flows from four different Centres. Without an IDM-concept it is hard for the local controllers to judge whether TBFM "Checkbox On" causes strong delays on traffic flows of the other Centres.

As a precursor to the study in this paper, an additional study [10] was conducted to vary wind strengths and wind errors and to assess whether assigning an RTA can increase the delivery performance into TBFM under these varying conditions. The study indicated that RTA assignment can increase the number of aircraft entering TBFM with an accuracy of +/-1 minute. However, as long as the accuracy doesn't need to be better than +/-5 minutes, there appears to be no added benefit with RTA assignments.

The study in this paper uses "Checkbox on" in all IDM conditions. Only the two Baseline conditions are done both ways, with Checkbox on and off. The study also includes both IDM conditions EDCT and EDCT+RTA.

G. Research Questions

For the simulation study at hand, key metrics such as ground delay, airborne delay, total delay and throughput are evaluated for the IDM concept.

The study consists of three main experimental conditions (BASELINE, EDCT and EDCT+RTA) with TBFM Checkbox On. A fourth condition, a Baseline with TBFM Checkbox Off, was added to provide a closer approximation of today's operations. Finally, a separate EDCT+RTA condition with "perfect" conditions for CTOP operations was added. In this condition there were no wind forecast errors and no departure errors for traffic located outside the TBFM region. This allowed us to establish the upper limits of the system performance under ideal conditions.

Following are some of the key research questions and metrics examined in this study:

- the target throughput rate of the IDM conditions in comparison to the Baseline conditions
- the effect on airborne delay in the TBFM region, caused by forcing short-haul aircraft into the arrival stream; in particular, IDM should result in acceptable assigned airborne delay in the TBFM metering region as this is a sensitive metric for operator workload
- the distribution of strategic (CTOP assigned) versus tactical (TBFM assigned) ground delay in the IDM conditions in comparison to the Baseline conditions
- the ratio of airborne and ground delay, as well as the total delay under different conditions

In addition, comparisons between EDCT Only and EDCT+RTA will assess whether the inflight control loop (RTA assignments) is necessary to provide satisfying delivery into TBFM.

II. METHOD

A. Simulation Environment

The simulation setup included the Multi-Aircraft Control System (MACS) software [11], a CTOP emulator (called "nCTOP") and a fielded TBFM system (version 4.2.3). MACS provided a high fidelity air traffic control simulation environment and engine that provided the simulated traffic and traffic situation displays for traffic managers, controllers, and pilots. For this study, MACS also provided the underlying logic for the CTOP schedules and the FCA placements, ability to set the scheduled departure times, as well as the ability to issue and monitor the RTA assignments.

A CTOP emulator (nCTOP) was developed to emulate the "look and feel" and the basic functionalities of the operational CTOP to provide a front-end user interface for the participants. Through nCTOP, the participants could access different FCAs and FEAs in the system, view the predicted traffic demand for the FCAs/FEAs, and set their capacities at a 15-minute granularity. In this simulation environment, nCTOP exchanged the demand and capacity information with MACS, which generated the underlying schedules for the CTOP FCAs. In the study, nCTOP was used to set the capacity for the inner FCA (called FR for "Flow Ring"), which was set 40 nm around the RWY).

The nCTOP interface uses MACS' ETA calculations to generate and show the predicted demand. nCTOP can also show various delay information, such as how much ground delay aircraft got assigned from the initial scheduled time and the time when the new schedule was initiated (CTOP ground delay).

Once aircraft entered the TBFM region, their arrival times were managed referencing the TBFM schedules, first in the XM followed by the MF regions. TBFM scheduling was accomplished using a custom adaptation of a fielded TBFM version. XM freeze horizons were placed approximately 400 nm from Newark airport and approximately two nm inside of the three outer FEAs, and were designed to capture the traffic flows heading to the North, West and South gate meter fixes (SHAFF, PENNS, and RBV/DYLIN, respectively). The MF freeze horizons were set up approximately five nm inside the Extended Metering Points/Arcs (XMPs). The TBFM adaptation was configured to absorb two minutes of delay in the MF region, with remaining delays "passed back" if possible into the XM region. For the XM region, the distances between the freeze horizons and XMPs differed for each flow, so the absorbable delay varied between three to six minutes. TBFM flexible scheduling was turned on, which allows shifting scheduled time of arrivals (STAs) up to one minute early.

TBFM schedulers were set up to provide standard wake vortex spacing to the runway threshold, plus an additional separation buffer of 0.4 nm. This setting was expected to deliver an average rate of 44 aircraft/hour, although the actual delivery rate depended on the actual aircraft fleet mix.

Figure 4 shows the configuration for the Traffic Planner participant position, which consisted of the 'MACS' ERAM Planning Station that displayed the traffic flows, FCAs/FEAs and their schedules, and RTA assignments, nCTOP interface to show traffic demand and capacity for the FCAs/FEAs, and TBFM schedules for the XM and the MF regions. The nCTOP elements (FCA/FEAs) and TBFM elements (freeze horizons and meter fixes) were configured in this study in a way to support a procedural integration of these tools.

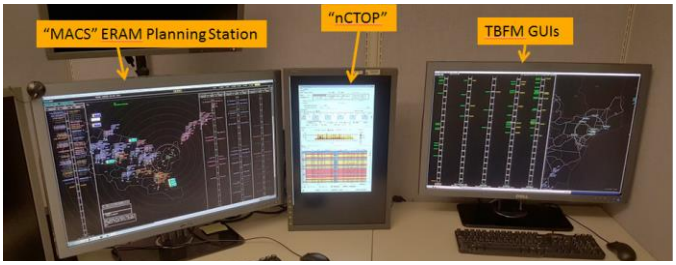

Figure 4. Simulation Infrastructure to research into strategic demand management at Airspace Operation Lab (AOL), NASA Ames

B. Experimental Design

A 5*2 factor experimental design consisted of the Factor (CONDITION) with five operational conditions: Baseline Checkbox Off, Baseline Checkbox On, EDCT, EDCT+RTA,

and EDCT+RTA*. In the EDCT+RTA* condition, departure and wind forecast errors were eliminated for all aircraft outside of the TBFM region. The second Factor (SCENARIO) varied the distribution of heavy aircraft within the simulation runs to be more "distributed" across the run or more concentrated as a "gaggle" near the end of the run. The experimental design is summarized in Table I.

TABLE I. EXPERIMENTAL DESIGN

Experimental Design		Baseline		Integrated Demand Management		
CONDITION		BL Off	BL ON	EDCT	EDCT+ RTA	EDCT+ RTA*
SCENARIO	Distri-buted	Check Box OFF	Check Box ON	Check Box ON	Check Box ON	CBox ON No errors outside TBFM
	Gaggle	Check Box OFF	Check Box ON	Check Box ON	Check Box ON	CBox ON No errors outside TBFM

The three core conditions from the experiment design are BASELINE Checkbox On, EDCT, EDCT+RTA. In all three conditions, TBFM operations remained constant and the only difference was in how the traffic was managed prior to TBFM entry.

In the Baseline conditions, CTOP FCAs/FEAs were replaced with MIT spacing for pre-conditioning the traffic into TBFM, analogous to today's operations. Based on inputs from subject matter experts (SMEs), a number of fixes associated with north, west, and south flows into Newark were identified and delivered to 30 MIT for the given fixes. In the EDCT condition, nCTOP was used to build an initial CTOP-schedule to a 40 mile ring around the RWY to deliver traffic at a 44 aircraft/hour rate. The EDCT+RTA condition was identical to the EDCT condition but RTAs assignments were added to all airborne aircraft that reached its top-of-climb and the remaining flight distance is more than 600 nm to EWR.

Since IDM builds a CTOP FCA schedule that takes into account internal TBFM departures and manages the traffic demand entering TBFM to match the capacity that TBFM can handle, the TBFM Checkbox On setting that prioritizes the internal departures should not result in excessive airborne delays for the overhead stream in TBFM while allowing the internal departures to take off with minimal delays. Therefore, all IDM conditions with and without RTAs were run with TBFM Checkbox On and compared with a Baseline Checkbox On.

A second Baseline condition that prioritized airborne flights over departures during TBFM departure scheduling (Checkbox Off) was added to increase external validity reference today's operations. Finally, a 5th condition, eliminated departure errors and wind prediction errors outside the TBFM region to assess IDM performance with the best possible conditioning of demand into TBFM. .

C. Traffic Scenario

The traffic scenarios (Gaggle and Distributed) included 196 aircraft each, going into Newark Airport (EWR22L, 1 RWY). Gaggle stands for the fact that the north flow with heavies comes in as a gaggle, while in the distributed scenario they were spread out. Traffic was started with 43 aircraft already in flight, 86 pre-departures outside TBFM and 67 pre-departures in the TBFM region. The traffic mix included 19 Heavy Jets, 7 B57s, 6 Turbos and 164 Light Jets with respect to weight class. The average uncontrolled traffic demand in the scenarios largely exceeded the 44 aircraft/hour rate set in the study, creating a demand/capacity mismatch that required delay absorption, either in the air or on the ground.

D. Departure Error

Departure errors were grouped into four categories. TBFM internal departures that were "in-conformance," departed within their [2 min early; 1 min late] 'call for release' (CFR) conformance window; 85% of the TBFM departures met this criteria. TBFM departure errors were classified as "not-in-conformance" if the departure error was outside the CFR conformance window; most of this cohort was within a range of [3 min early, 4 min late]. For aircraft departing outside the TBFM region (non-TBFM departures), the EDCT conformance window was defined as [5 min early; 5 min late]. About 69% of the non-TBFM departures were in-conformance with their assigned EDCT, and most of the remaining 31% remained between within [16 min early; 20 min late]. The distribution of departure errors for both CFR and EDCT scheduled departures were obtained from historical data.

E. Procedure

In general the study was conducted as a 'quasi-real time' operation involving high fidelity tools that would normally be used by participants in a human-in-the-loop simulation. In this study, however, participant decisions related to tool usage were replaced with a set of heuristic-based procedures derived from the January 2016 study. This provided greater consistency in task performance across conditions and participants, making it easier for us to interpret our results.

One downside to this approach was that we eliminated the use of controller-initiated mitigation strategies (e.g., additional ground delays, ground stops or airborne holding) that would normally be used when the airborne delays become excessive or unworkable. Controllers did use some of these techniques in the January study, resulting in a more realistic Baseline that mimicked today's operations. Unfortunately, this meant that the Baseline results related to throughput and delays were difficult to compare with the corresponding IDM conditions, when these techniques were not used.

Initial CTOP-assigned arrival schedule: At the start of the simulation run, most aircraft were pre-departures that would cause demand to exceed EWR's arrival capacity if they took off on their originally schedule departure times. In the Baseline condition these initial departure times were only modified when the flight could not fit into the 30 MIT overhead arrival flow. When that occurred the departure was delayed until there

was room in the overhead flow, as is done across the country in today's operations. During the IDM conditions, the Command Center 'TFMS' Planner first exempted all airborne flights and pre-departures that were within 30 minutes of their departure times from receiving nCTOP delays, then used the nCTOP interface to set FCA capacity to 11 aircraft per 15 minute bin for the duration of the program. The planner then sent the new capacity entries to the MACS simulator which used them to revise the nCTOP FCA schedule and change departure times of non-exempt flights as needed to conform to the new schedule.

CTOP / Pre-TBFM Region (>~400 miles to destination): For the Baseline Condition a MACS sector controller position was setup to manage the departure aircraft into EWR and the airborne delays required for 30 MIT in the CTOP region. MACS automation for sequencing and spacing was running to enable one controller to manage 30 MIT for 5 EWR flows in parallel. Schedule conformance was the controller's main task and separation management was not a concern. For the IDM conditions, this working position was not staffed and aircraft where flying according to their FMS flight plans.

RTA assignment: For the IDM EDCT+RTA conditions, RTA target times generated for the three FEAs located outside of the TBFM XM freeze horizons were based on the FEA crossing times associated with the inner FCA schedule. These RTAs referenced the nearest waypoint on the aircraft's flight plan prior to the FEA, and were issued after the aircraft reached cruise altitude. During the simulation, RTA assignment was simplified by having the clearances sent directly to the pilots from the Planner station, bypassing the sector controller. Aircraft that were within 600 nm of Newark airport by the time they reach their cruise altitude were excluded from RTA eligibility since the distance to the FEAs were too short to change the crossing times effectively using speed control.

MF and XM Region: Departures in these regions were scheduled with reference to the TBFM schedule. The internal TBFM departure option was set to Checkbox On for all conditions except for the Baseline Checkbox Off condition. A "Traffic Management Coordinator" (TMC) was staffed to schedule the internal departures for both XM and MF schedules. In order to provide consistent departure scheduling and to minimize workload, the TMC followed a consistent procedure for the 'call for release' (CFR) departure scheduling.

After aircraft were frozen in the XM region, a controller in the XM region used speed and lateral path clearances to deliver the arrivals on their XM scheduled times. Any delays that could not be absorbed in the XM region were passed on to the MF region. Based on SMEs' inputs, the XM region was assumed to be capable of absorbing delays of +/- 5 minutes with reasonable workload, while in the MF region a delay of +/- 2 minutes was considered acceptable, and delays that exceeded these values were considered to be beyond the acceptable workload. The MF and TRACON regions did not have controllers during the simulation to work off the delay in order to minimizing staffing requirements. It was assumed, however, that controllers in the these regions would have been able to meet the assigned Meter Fix and Threshold STAs; therefore, MF-STAs and Threshold STAs were used to represent actual arrival times for the data analysis.

F. Metrics

The key metrics used in the study include:

- *Throughput* – the number of aircraft per hour that would have crossed the EWR22L threshold, based on the aircrafts' final STA threshold times
- *Assigned Airborne Delay* – the assigned airborne delays to the XMPs and meter fixes when the aircraft crossed the XM- and MF-freeze horizons
- *Assigned Airborne Delay Categories* – for a better understanding of the assigned airborne delays from an operational perspective, these delay values were classified into *acceptable*, *marginal* and *unacceptable* delays. In the XM region, +/-5 minutes delays were categorized as acceptable, 5-10 minutes as marginal and >10 minutes as unacceptable. In the MF region +/2 minutes were considered acceptable, 2-4 minutes as marginal and > 4 minutes as unacceptable.
- *TBFM assigned Ground Delay* – for the internal departures within the XM and MF region, this metric measures any TBFM induced ground delays for these departures due to the CFR procedures.
- *CTOP assigned Ground Delay* – for all departures, this metric measures the EDCT delays issued by nCTOP within the IDM conditions
- For a relative comparison between conditions total airborne delay, total ground delay and total delay the following three metrics were calculated:
    - *Total Airborne Delay* – to calculate the total airborne delays, additional open-loop runs without human interventions were completed for the two scenarios to calculate a reference flight time for each aircraft. The total airborne delays were then calculated for each aircraft by subtracting open-loop flight time from the actual flight time of the corresponding aircraft for each condition separately and aggregated over all aircraft
    - *Total Ground Delay* – the sum of nCTOP assigned and TBFM assigned ground delays, aggregated over all aircraft
    - *Total Delay* – the sum of total airborne delays and total grounds delay aggregated over all aircraft

III. RESULTS

This section describes the results from the study with respect to the throughput and different distributions of delays. Although the results were analysed separately for the two traffic scenarios (Distributed and Gaggle), the overall pattern of results and their conclusions were similar between them. Therefore in this paper, the results will only focus on reporting the Distributed scenario only so that there is minimal repetition of data in reaching the overall conclusions.

A. *Throughput*

For *throughput*, the target rate was set to 44 aircraft/hour. The simulation was designed aiming at comparable *throughput*, so that the variation caused by conditions becomes observable in the metrics such as Ground Delay, Airborne Delay and Total Delay. In this study, *throughput* has to be seen as a control variable that is held constant, rather than a dependent variable. The results show that we accomplished maintaining a relatively constant throughput across all conditions. Throughput values vary between 41 and 47 per hour across the different hours and conditions. It should be noted that the target rate is more a 'called out' rate that varied based on the fleet mix (weight class). TBFM achievable rate depended the wake vortex spacing based on the fleet mix (i.e. increased number of Heavy Jets increased the inter-arrival spacing and reduced the overall rate), resulting in actual rate ranging +/- 2 aircraft per hour of the target rate. On average over a 4 hour simulation runtime, the throughput for Baseline Checkbox On was 45.75 aircraft/hour (*SD*=1.58), 44 aircraft/hour for EDCT (*SD*=1.33), and 43.5 aircraft/hour for EDCT+RTA (*SD*=1.67). In addition, the throughput for Baseline Checkbox Off was 44.25 aircraft/hour (*SD*=2.92) and 44.25 aircraft/hour for EDCT+RTA* (*SD*=1.58).

B. *Assigned Airborne Delay*

For the airborne delay, the IDM conditions were expected to reduce airborne delays in general since nCTOP was used to shift the airborne delays in the CTOP region to EDCT ground delays. Airborne delay that was of greater interest, however, was how the assigned airborne delays in the TBFM region were impacted by the IDM conditions compared to Baseline. The assigned airborne delays in the TBFM region were compared to the two Baseline conditions, Checkbox On and Checkbox Off. The TBFM assigned airborne delays were categorized as *acceptable*, *marginal* and *unacceptable*. The number of delays in each category is summarized in Tables II and III.

XM Region: As shown in Table II, most aircraft in the three IDM conditions (i.e., EDCT, EDCT+RTA and EDCT+RTA*) resulted in *acceptable* delays while the two Baseline conditions had large number of aircraft in both *marginal* and *unacceptable* delay categories. For the EDCT+RTA conditions no aircraft were assigned *marginal* or *unacceptable* TBFM airborne delays. For the EDCT condition, only five aircraft had the *marginal* airborne delays.

TABLE II. EXTENDED METERING REGION AIRBORNE DELAY, IN MINUTES

Condition	'acceptable'		'marginal'	'unacceptable'	N
	[-5,0)	[0, 5)	[5,10)	[10, ∞]	N
Baseline CB Off	7	126	32	9	174
Baseline	3	68	65	38	174
EDCT	19	150	5	0	174
EDCT+RTA	17	157	0	0	174
EDCT+RTA*	19	154	0	0	173

*no wind prediction error, no Departure error for outside TBFM Departures

In contrast, the Baseline Checkbox Off condition resulted in n=32 in the category *marginal* and 0<n<10 *unacceptable* airborne delays. Checkbox On condition further increased the counts of *marginal* and *unacceptable* delays with only 71 aircraft classified as *acceptable* assigned airborne delay for this region.

MF Region: The delay results were more nuanced in the MF region. As shown in Table III, the three IDM conditions had greater number of *acceptable* delays and fewer *unacceptable* ones as the delivery precision increased from EDCT, EDCT+RTA to EDCT+RTA* (no errors in CTOP region). The three IDM conditions with Checkbox On result in 100, 124 and 132 *acceptable* airborne delays and 22, 7 and 5 *unacceptable* airborne delays, respectively. In contrast to the BASELINE Checkbox On condition resulted in 74 *unacceptable* delays. Interestingly, Baseline Checkbox Off condition shows similar number of aircraft with *acceptable* delays as the EDCT condition with Checkbox On. However, the ground delay results for the internal departures, reported in the following section, show the relevant difference between these two conditions.

TABLE III. METER FIX REGION ASSIGNED AIRBORNE DELAY, IN MINUTES

Condition	'acceptable'		'marginal'	'unacceptable'	N
	[-2, 0)	[0, 2)	[2, 4)	[4, ∞]	
Baseline CB Off	11	78	62	42	193
Baseline	11	45	62	74	192
EDCT	7	93	70	22	192
EDCT+RTA	12	112	61	7	192
EDCT+RTA*	10	122	55	5	192

*no wind prediction error, no Departure error for outside TBFM Departures

Summary for Assigned TBFM Airborne Delay: In Table IV, the categories are presented aggregated over XM and MF TBFM regions to carve out the major message for the IDM concept.

TABLE IV. TBFM ASSIGNED AIRBORNE DELAY ACCEPTABILITY BY CONDITION (REGIONS AND RUNS COMBINED IN PERCENTAGE)

Condition	'acceptable'	'marginal'	'unacceptable'	%
Baseline CB Off	60%	26%	14%	100
Baseline	35%	35%	31%	100
EDCT	73%	20%	6%	100
EDCT+RTA	81%	17%	2%	100
EDCT+RTA*	84%	15%	1%	100

*no wind prediction error, no Departure error for outside TBFM Departures

The IDM concept pre-conditions traffic into TBFM with >73% of aircraft showing *acceptable* TBFM assigned airborne delays, in contrast to the Baseline condition that had 35% of aircraft with *acceptable* delays. The airborne delay of the Baseline Checkbox Off condition with 60% had more comparable airborne delays to the IDM conditions by shifting the delays to the internal departures which will be reported in the next section.

C. *Ground Delay*

Ground delay calculations were divided into two distinct categories of delays: CTOP-assigned and TBFM-assigned ground delays. As a consequence of the IDM concept, strategic CTOP-assigned ground delays were expected to reduce both airborne and more tactical (and less predictable) TBFM ground delays, ground delay is addressed as CTOP-assigned ground delay. In addition, CTOP-assigned ground delays for the aircraft that depart outside TBFM were also expected reduce the ground delays for the internal departures.

In order to make a direct comparison between TBFM and CTOP assigned delays for the same set of aircraft across the conditions, the ground delay results for the internal departures, which had both types of delays, were calculated and shown in Tables V, VI and VII. These tables distinguished the different departure regions, MF, XM and outside TBFM (i.e. CTOP region), respectively. The tables show the conditions, number of aircraft samples, median (Mdn) and maximum (Max) ground delays assigned by TBFM (applicable for internal departures only), assigned by CTOP and the combined total. As data are not normal distributed Mdn is reported instead of mean and standard deviation.

TABLE V. GROUND DELAY METER FIX REGION DEPARTURES, IN MINUTES

Ground delay		TBFM		CTOP		Total	
Condition	**N**	**Mdn**	**Max**	**Mdn**	**Max**	**Mdn**	**Max**
Baseline CB Off	22	48.5	81	0	0	48.5	81
Baseline	22	4.5	16	0	0	4.5	16
EDCT	22	1	4	26	42	27	44
EDCT+RTA	22	0.5	5	26	42	27	42
EDCT+RTA*	22	0	5	28	41	31	41

TABEL VI. GROUND DELAY EXTENDED METERING-DEPARTURES, IN MINUTES

Ground delay		TBFM		CTOP		Total	
Condition	**N**	**Mdn**	**Max**	**Mdn**	**Max**	**Mdn**	**Max**
Baseline CB Off	45	21	68	0	7	21	68
Baseline	45	4	13	0	5	4	13
EDCT	45	0	5	26	43	26	46
EDCT+RTA	45	0	3	26	43	26	43
EDCT+RTA*	45	0	3	27	44	28	44

TABLE VII. GROUND DELAY OUTSIDE TBFM DEPARTURES, IN MINUTES

Ground delay		TBFM		CTOP		Total	
Condition	**N**	**Mdn**	**Max**	**Mdn**	**Max**	**Mdn**	**Max**
Baseline CB Off	64	-	-	0	86	0	86
Baseline	64	-	-	0	69	0	69
EDCT	64	-	-	30	42	30	42
EDCT+RTA	64	-	-	30	42	30	42
EDCT+RTA*	64	-	-	32	45	32	45

Tables V and VI show that under IDM, tactical TBFM delays were minimized (less than one minute for the median delay) by assigning CTOP ground delays more strategically. In the meter fix region (Table V), the IDM conditions show maximum TBFM delays <=5 minutes in contrast to 16 minutes in the Baseline (Checkbox On) condition. In the XM region (Table VI), the maximum values were <=5 minutes for the IDM conditions and 13 in Baseline. In Baseline Checkbox Off condition which has closer resemblance to today's operational settings, TBFM-assigned ground delays were much worse, resulting in 81 minute maximum delay in MF region and 68 minute maximum in XM region.

The reduction in TBFM-assigned ground delays in IDM was due to strategically assigning CTOP delays instead. Tables V and VI show that the CTOP-assigned delay values for the IDM conditions go up to 42 minutes (MF) and 44 minutes (XM) as expected while they remain low in Baseline condition.

Finally the median for CTOP delay of the outside TBFM departures show that under IDM not only TBFM departures get the ground delay assigned. While the median ground delay is ~ 3 min in the Baseline condition, the median ranges between 30 and 40 min in the IDM conditions.

D. *Summarize Airborne, Ground and Total Delay*

To summarize the results, Figure 5 illustrates a visual representation of a plot of the actual total airborne delay, total ground delay and total delay ratios using Baseline Checkbox Off as reference. Each vertex of the pentagon represents a condition and each delay values were divided by corresponding values from Baseline Checkbox Off condition. Therefore, Baseline Check Off condition would be plotted as a pentagon with a value of 1.0.

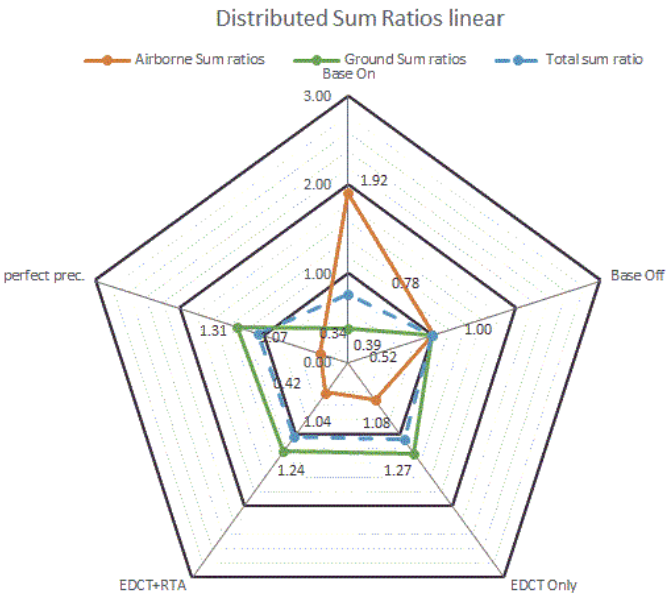

Figure 5. *Distributed Scenario:* Airborne, Ground and Total Delay

As shown in Figure 5, total airborne delay (orange) was almost doubled in the BASELINE Checkbox On versus Checkbox off condition while the IDM conditions show only

half or less total airborne delay. In contrast, total ground delay (green) show the opposite effect. The Baseline (On) condition shows less than half of the ground delay compared to Baseline (Off) but the IDM conditions show similar total ground delay ranging between [1.15, 1.23] compared to Baseline (Off). Finally, total airborne + ground delay (blue) suggest a slight decrease in total delay for Baseline (On) and similar delay for IDM conditions compared to Baseline (Off). Delay ratios were 1, 1.07 and 1.06 for EDCT, EDCT+RTA and EDCT+RTA*, respectively.

IV. Discussion

Within this quasi real time simulation study a concept for Integrated Demand Management was tested. From a system perspective the IDM concept addresses multiple goals that are of interest by different stakeholders and there is not one single optimal metric to evaluate the concept. In this paper we have been looking at Throughput, Ground Delay, Airborne Delay and Total Delay, as well as the impact of prioritizing inside TBFM departures (Checkbox On/Off) and impact of uncertainties like (departure error and wind prediction error). To evaluate the IDM concept, the key metrics are discussed with respect to the IDM expectations. For this paper we addressed six research questions to evaluate the concept.

Throughput: Although the new IDM-schedule strategically delays aircraft longer on the ground, the data indicate that there is enough demand to deliver to a target rate, in this case 44 aircraft / hour. As mentioned earlier, the goal is not to optimize the fit for this 'called out' rate, as this number also varies based on fleet mix. However, the message is that IDM does not result in a significant decrease in throughput under clear weather conditions.

Airborne Delay and Prioritizing Short-Haul Flights: IDM operations do not result in marginal or unacceptable airborne delays in the TBFM region, even with prioritizing the internal departure scheduling over the airborne flights. The manageable delays provide support for the IDM concept that reserves slots for the internal departures in the initial CTOP schedule to deliver the appropriate demand to TBFM. It is interesting to see that the number of acceptable delays even increases comparing the IDM conditions against the Baseline TBFM Checkbox Off while also eliminating the marginal and unacceptable delays. As mentioned earlier, to not end up with marginal and unacceptable delays is important as this is known to result in unacceptable workload for the controllers.

Ground Delay and Minimizing Tactical Delay by Applying More Strategic CTOP-assigned Ground Delay: The simulation results demonstrated that under clear weather conditions, the IDM approach used is able to minimize the last minute ground delay issued by TBFM, by applying more early strategic CTOP delay, which is of relevance for the airlines and passengers. As the CTOP-assigned early arrival schedule is reserving an FCA slot also for the internal departures, the IDM concept can also address the problem that close in departures do not get caught on the ground because the overhead stream is blocking the airspace.

Shift of Airborne to Ground Delay under the Umbrella of Total Delay: The IDM concept shows how a shift from airborne delay can be managed in a controlled manner with tools and functionalities under the scope of NextGen. The data gathered in the simulation further indicate that a major shift of airborne delay towards ground delay is possible. The simulation was setup in a way to keep total delay and throughput comparable between conditions. Due to these control variables, the effects of airborne and ground delay could be contrasted between conditions.

In addition we were interested in:

Uncertainties (Departure Error and Wind Prediction Error): The departure error and wind prediction error does not seem to be a critical factor of uncertainty. One possible explanation for that might be that its stochastic nature might even out over time. As we do not deliver to a fixed initial CTOP-schedule, but TBFM can re-sequence aircraft if they are late or early, the system performance seems to be robust to this source and magnitude of errors.

EDCT vs. EDCT+RTA: The results of the simulation support that using EDCT times to build a departure schedule allows feeding traffic for a target capacity. In this simulation and in line with [10], there was no major advantage of the IDM operation EDCT+RTA over EDCT only. Also supported by the experience of SMEs it is important not to overfeed TBFM, but TBFM is very robust in building a good final arrival schedule.

Quasi Real Time Simulation Approach: The current research presented a quasi-real time simulation approach that requires a sophisticated interpretation of the results. The limitations of operator interactions by a set of procedures and heuristics and a strict application of TBFM Checkbox On/Off) does limit a comparison to real operational data in the field. It must be said however, that in such a complex simulation environment, simulating air traffic within the whole NAS, does ask for reducing the variance of operator interactions to be able to interpret the data between the experimental conditions.

A. Conclusion and Future Work

The follow-up study, using longer simulations, more realistic winds and higher experimental control demonstrated more substantively that IDM is beneficial, as indicated by the initial IDM-study [1]. The increased number of data points, higher controllability and better external validity, increases the power that the IDM concept can deliver the traffic more efficiently. The delays can be shifted from airborne to ground for both RTA and non-RTA conditions and at the same time a target throughput rate can be satisfied. We also conclude that under good predictability of airport capacity, the last minute tactical TBFM ground delay can be minimized by applying more strategic CTOP delay, increasing predictability for the airline operators. Overall, it can be said that the implementation of an IDM concept can improve the NAS system performance under clear weather conditions. Future IDM research aims at incorporating convective weather solutions, e.g. suggested by [12]. An enhanced IDM concept should provide NAS performance benefits also when demand/capacity imbalances occur due to severe weather.

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