Benefit Assessment of the Integrated Demand Management Concept for Multiple New York Metroplex Airports

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Benefits of the Integrated Demand Management (IDM) concept were assessed utilizing a newly developed automated simulation capability called 'Traffic Management Initiative Automated Simulation (TMIAutoSim).' The IDM concept focuses on improving traffic flow management (TFM) by coordinating the FAA's strategic Traffic Flow Management System (TFMS) with its more tactical Time-Based Flow Management (TBFM) system. The IDM concept leverages a new TFMS capability called Collaborative Trajectory Options Program (CTOP) to strategically pre-condition traffic demand flowing into a TBFM-managed arrival environment, where TBFM is responsible for tactically managing traffic by generating precise arrival schedules. The IDM concept was developed over a multi-year effort, focusing on solving New York metroplex airport arrival problems. TMIAutoSim closely mimics NASA's high-fidelity simulation capabilities while enabling more data to be collected at higher speed. Using this new capability, the IDM concept was evaluated using realistic traffic across various weather scenarios. Six representative weather days were selected after clustering three-months of historical data. For those selected six days, Newark Liberty International Airport (EWR) and LaGuardia Airport (LGA) arrival traffic scenarios were developed. For each selected day, the historical data were analyzed to accurately simulate actual operations and the weather impact of the day. The current day operations and the IDM concept operations were simulated for the same weather scenarios and the results were compared. The selected six days were categorized into two groups: 'clear weather' for days without Ground Delay Programs (GDP) and 'convective weather' for days with GDP and significant weather around New York metroplex airports. For the clear weather scenarios, IDM operations reduced last-minute, unanticipated departure delays for short-haul flights within TBFM control boundaries with minimal to no impact on throughput and total delay. For the convective weather scenarios, IDM significantly reduced delays and increased throughput to the destination airports.

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Nomenclature

AAR = Airport Acceptance Rate
AC = Adjusted Cost
AFP = Airspace Flow Program
ATCSCC = Air Traffic Control System Command Center
CFR = Call-For-Release
CTOP = Collaborative Trajectory Option Program
EDCT = Estimated Departure Clearance Time
ETA = Estimated Time of Arrival
EWR = Newark Liberty International Airport
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
IDM = Integrated Demand Management
LGA = LaGuardia Airport
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
RBS = Ration-by-Schedule
RMNT = Reroute Minimum Notification Time
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
TMI = Traffic Management Initiative
TVET = Trajectory Valid End Time
TVST = Trajectory Valid Start Time
TOS = Trajectory Options Set
ZBW = Boston Center
ZDC = Washington Center
ZNY = New York Center
ZOA = Oakland Center
ZOB = Cleveland Center

I. Introduction

Integrated Demand Management (IDM) is a near- to mid-term NASA concept that is intended to improve Traffic Flow Management (TFM) operations by coordinating strategic Traffic Flow Management System (TFMS) operations with more tactical Time-Based Flow Management (TBFM) operations. The goal of TFM is to regulate the traffic demand to avoid exceeding airport or airspace constraints while ensuring the available capacity is used efficiently [1]. In the IDM concept, the coordination between two systems is enabled by allowing TFMS to strategically regulate ("pre-condition") the traffic demand that is flowing into and departing within TBFM environment. This strategic regulation of the traffic demand was performed, in order to help support tactical traffic management operations within TBFM regions. In this paper, the IDM concept was tested in the Newark (EWR) and

LaGuardia (LGA) arrival traffic environment because it routinely experiences some of the highest arrival delays in the National Airspace System (NAS). In current day operations, traffic demand is commonly managed using pre-determined Miles-In-Trail (MIT) spacing to feed traffic into TBFM, which then creates arrival schedules to manage demand into the Terminal Radar Approach Control (TRACON). However, this technique does not necessarily produce either an efficient flow, or equity for close-in departures near the destination that may find themselves experiencing last-minute ground delay assigned by TBFM (known as "double-penalty") when the overhead arrival flow is saturated [2].

IDM utilizes Collaborative Trajectory Options Program (CTOP) as a part of the TFMS system to strategically pre-condition the traffic demand. CTOP is selected as the strategic traffic management tool for the IDM concept because there are several functions that may allow CTOP to pre-condition traffic more effectively than other Traffic Management Initiatives (TMIs), such as Ground Delay Program (GDP). First, CTOP has a capability of handling a multiple demand/capacity mismatch problem within a single program. CTOP uses both ground delay and reroute capability simultaneously to come up with the optimal solution to handle the resource-constrained problem across multiple Flow Constrained Areas (FCAs). Because of uncertainties in both demand and capacity (e.g., due to weather), adhering to the strategic traffic plan can be challenging. Unlike other TMIs, CTOP has the ability to continuously monitor the traffic demand and "automatically" revise the program when there is a discrepancy between the planned schedule and the actual traffic demand. This capability can help ensure a proper delivery of the traffic demand. Extending the current CTOP capabilities, the FCA-Balance-Algorithm (FBA) was developed at NASA to handle airport and upstream gate capacities simultaneously [3]. FBA calculates the available capacity across multiple arrival flow gates based on the scheduled demand per flow, while ensuring that the total traffic demand across the gates meets the desired throughput at the destination airport.

A central component of CTOP is its capability for incorporating the user-negotiated routing of aircraft, called Trajectory Option Set (TOS). It provides a mechanism for flight operators to submit a set of cost-weighted trajectory options instead of a single flight plan. Each trajectory option is accompanied by a Relative Trajectory Cost (RTC), which expresses the preferences of flight operators for the amount of assigned ground delay that they would take in the current flight plan before triggering an alternate route. During the slot assignment process, each flight's preference for TOS options is accounted for by placing the flight on the TOS option with the least Adjusted Cost, which is the sum of RTC and potential ground delay that could be assigned by taking each associated TOS option.

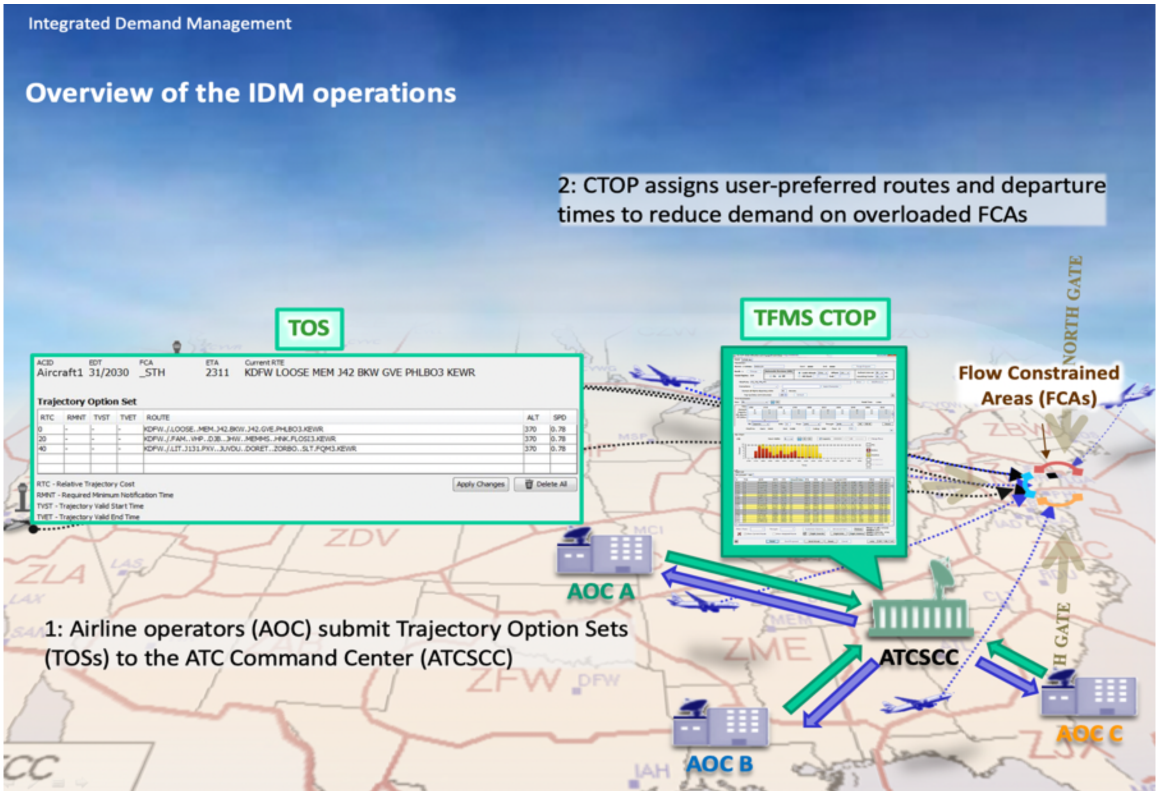
Once the flight enters the TBFM region, it is scheduled on a 'first-come, first-served' basis to the destination airport by the TBFM scheduler. Traffic is typically managed according to an arrival schedule that is frozen nearly 400 nm from the airport's TRACON boundary for NY metroplex airports. Unlike current operations, TBFM in the IDM concept is set up to allow the departures taking-off within TBFM regions to have schedule priority over the airborne flights. Although this setup has a potential for excessive airborne delays in current operations, the IDM concept uses CTOP to precondition the incoming airborne traffic to manage the overall demand, resulting in manageable airborne delays in the TBFM region. In the IDM concept, airport arrival rates, CTOP FCA capacity/rates, and TBFM inter-arrival spacing/rates are coordinated to complement each other without a direct linkage between the actual scheduling systems. In this setup, CTOP is a tool to strategically precondition the traffic demand at a coarse level due to high uncertainties, leaving TBFM to have the authority to manage the final schedule of the aircraft more tactically.

A detailed IDM concept of operations is described in Ref. 4. The concept has been explored in a series of human-in-the-loop (HITL) simulation studies in the NASA Ames Airspace Operations Laboratory (AOL), suggesting benefits of IDM concept in both clear and convective weather scenarios by providing more schedule predictability and better delay distribution in all cases, as well as increased throughput and reduced overall delays in convective weather scenarios [1, 3, 4, 5, 6]. While these studies produced promising results, each HITL simulation run to evaluate the IDM concept required 5+ hours of real-time simulation with human participants. The run length limited the number of experimental conditions that could be tested, as well as the overall number of HITL simulations that could be conducted. To conduct a more robust IDM benefit study, we needed to expand our capability to run of a broader range of possible weather and traffic conditions for multiple airports beyond what could be accomplished in the HITL evaluations. In support of these requirements, an automated simulation capability, called TMIAutoSim, was developed to closely mimic the high fidelity HITL simulation capabilities [7, 8] but with capabilities to automate human operators' inputs and to speed up the HITL simulation time. With utilization of this new capability, the benefit of the IDM concept was assessed for six different weather situations for two airports and three experimental conditions within a very short amount of time. The rest of the paper will describe the IDM benefit assessment for EWR and LGA arrival traffic flow management problems using this capability.

II. IDM Setup, Procedures and Tools for Newark and LaGuardia Airport Benefit Assessment

The IDM setup, procedures and tools, specifically for managing arrival traffic to EWR and LGA airports in the benefit assessment study, are described in this section. For strategic flow management, IDM used CTOP as the main TFMS tool to create multiple, interdependent constraints using Flow Constrained Areas (FCAs), which are segments of airspace where capacity-demand imbalance is projected. For Newark and LaGuardia airports, three FCAs per airport, associated with the traffic demand from the north, south, and west arrival gates/traffic flows, were placed at the runway threshold of each airport and filtered to allow only the north, south, or west arrival flows for each of the FCAs. The FBA tool evaluated the predicted demand and available capacities at the three FCAs and the destination airport for EWR and LGA airports. FBA calculated the capacity limits at the FCAs that would ensure that the sum of the traffic demand from the north, south, and west arrival gates did not exceed the target throughput at the destination airport.

CTOP was used to allow airlines to submit a user preferred set of alternative routes via a TOS mechanism with an indication of their preference of the route option in a form of RTC. RTC can be computed by considering various factors and expressed as the minutes of ground delay that a departure may be willing to receive longer than the airborne reroute. The CTOP TOS allocation algorithm, using a Ration-By-Schedule (RBS) approach, resolved the demand/capacity mismatch problems by delaying the departures and/or selecting the alternative trajectories submitted by the airlines [9]. For the IDM setup in the benefits study, RTC was calculated to leave the flights on the original flight plan until its assigned ground delay exceeded 1.5 times the extra flight time plus the ground delay incured on the alternate route. Figure 1 illustrates the interactions between and Airline Operations Center (AOC) and the Command Center, as well as the depictions of the TOS and CTOP interfaces shown on TFMS to the air navigation service providers at the Command Center.


Integrated Demand Management

Overview of the IDM operations

2: CTOP assigns user-preferred routes and departure times to reduce demand on overloaded FCAs

1: Airline operators (AOC) submit Trajectory Option Sets (TOSs) to the ATC Command Center (ATCSCC)

ACID	EDT	FCA	ETA	Current RTE
Aircraft1	31/2030	_STH	2311	KDFW LOOSE MEM J42 BKW GVE PHLBO3 KEWR

Trajectory Option Set

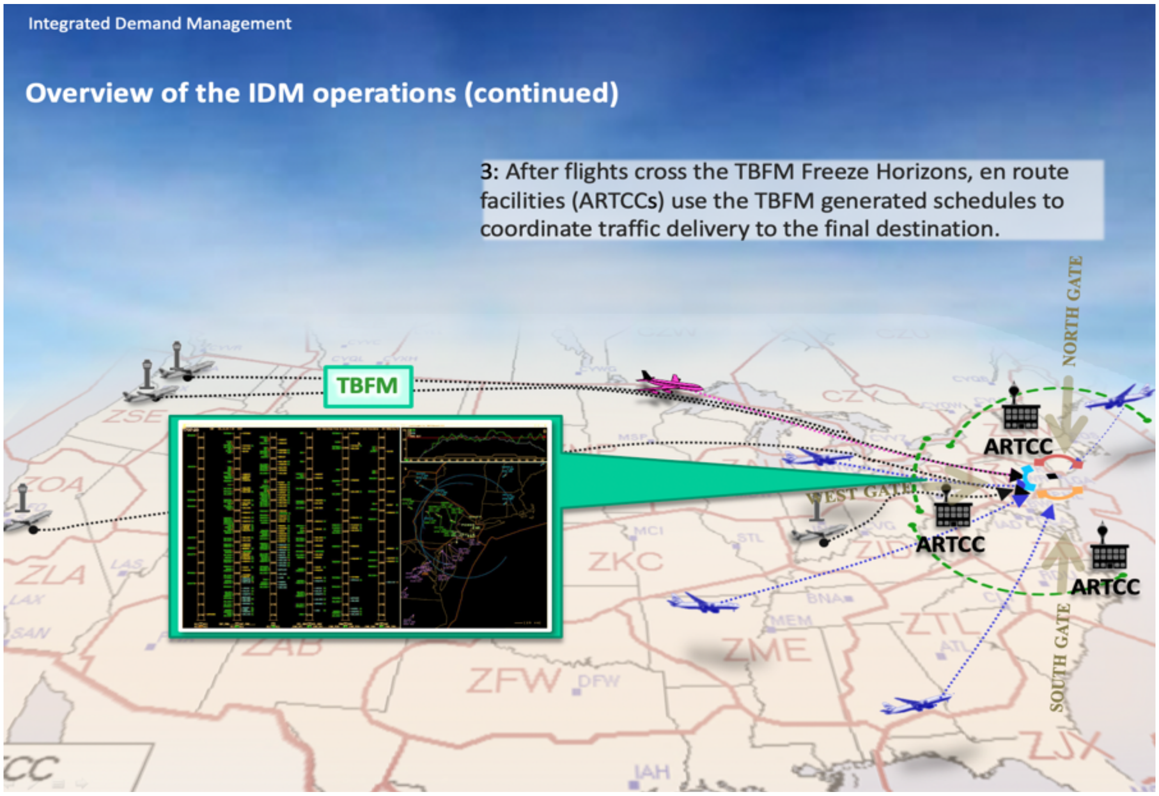
RTC	RMNT	TVST	TVET	ROUTE	ALT	SPD
0	-	-	-	KDFW./.LOOSE..MEM.J42.BKW.J42.GVE.PHLBO3.KEWR	370	0.78
20	-	-	-	KDFW./.FAM..VHP..DJB..JHW..MEMMS..HNK.FLOSI3.KEWR	370	0.78
40	-	-	-	KDFW./.LIT.J131.PXV..JUVDU..DORET..ZORBO..SLT.FQM3.KEWR	370	0.78

RTC - Relative Trajectory Cost
RMNT - Required Minimum Notification Time
TVST - Trajectory Valid Start Time
TVET - Trajectory Valid End Time

Figure 1: Schematic overview of tested IDM CTOP operations

For tactical flow management, IDM used TBFM to improve traffic delivery into capacity-constrained airports. TBFM is generally used to schedule flights arriving into a constrained airspace or airport. TBFM creates a schedule for all inbound flights which provides a scheduled time of arrival for each flight at the runway threshold. A scheduled time of arrival is then assigned to each flight to satisfy the required inter-arrival spacing for a sequence of fixes through to the runway threshold. The arrival sequence and assigned scheduled time of arrival for each flight continue to change as the flight's estimated time of arrival changes, up until the flight crosses a specified TBFM freeze horizon (FH).

In the overall IDM concept development, TBFM was set up to utilize the latest capability to cascade multiple TBFM scheduler, first using the Extended Metering (XM) scheduler from roughly 400 nmi to 140 nmi, followed by Meter Fix Arrival scheduler from 140 nmi to the meter fixes. However, due to the limitations of the emulated TBFM tool capability used in the benefits study, a single TBFM scheduler without XM capability, set roughly 400 nautical miles (nmi) upstream of the meter fixes, was used for Newark and LaGuardia airports. At that point, the flight's scheduled time of arrival "froze" and the target arrival time at the runway threshold was fixed. Air traffic controllers were then responsible for managing aircraft to absorb delay in the air using delay vectors and speed clearances to meet these assigned scheduled times of arrival. Figure 2 illustrates the TBFM interface and a schematic location where the TBFM schedules take place relative to the destination airport. In this benefit assessment study, those controllers' actions were mimicked and automated.



Integrated Demand Management

Overview of the IDM operations (continued)

3: After flights cross the TBFM Freeze Horizons, en route facilities (ARTCCs) use the TBFM generated schedules to coordinate traffic delivery to the final destination.

Figure 2: Schematic overview of tested IDM TBFM operations

III. Benefit Assessment of IDM Operations using TMIAutoSim Capability

A. Overview

This study was conducted to evaluate the benefits of IDM concept using realistic traffic under various weather scenarios. This section describes experiment design, method, and results of the study. The study focused on assessing the benefit of the IDM concept in terms of improvement in throughput and delay distribution. The benefit of the concept was tested under six different weather situations representing three months. The airport throughput, ground delays, airborne delays, and flight time change associated with the CTOP, TBFM and MIT operations were the major metrics of the study.

B. Method

B.1. Experimental Design

Three experimental conditions (i.e. *Baseline*, *Partial IDM,* and *Full IDM*) were evaluated for two airports (EWR and LGA) across six weather scenarios, total 36 simulation runs. Each simulation run lasted 12 hours, capturing peak traffic hours during each day. The following describes the three experimental conditions:

1. *Baseline*: In this condition, the CTOP was setup to act like a GDP by setting a single arrival rate at the destination airport to mimic the current day operations where there is no active use of the CTOP. The same

GDP rates that were used in the actual operations for the selected days were used in the Baseline simulation runs. In addition to GDP assigned delays, Miles-in-Trail (MIT) that was used in the actual operations for the selected days to thin out the arrival traffic further was also applied in the *Baseline* runs. MIT was only applied to the aircraft flying into the TBFM region. The TBFM was set-up to simulate its current-day operations, where current-day's TBFM FHs are located about 400 nm away from the EWR and LGA airports. One of the functions of the TBFM departure scheduling capability is that it has an algorithm that finds a slot in the overhead stream within the TBFM airspace for a short-haul departure by delaying non-frozen airborne flights. When this function is disabled, the short-haul departures are delayed until the first *full* slot in the overhead stream becomes available. In this condition, such function for the departure scheduling capability was disabled to mimic the current day operations that prioritizes airborne flights over the short-haul departures within the TBFM region.

2. *Partial IDM:* This condition was envisioned as an intermediary step between *Baseline* and the *Full IDM*, in which some IDM capabilities were enabled but others were limited. In this condition, CTOP was used instead of the GDP to pre-condition the traffic demand into the TBFM region. CTOP set the gate capacities at the North, South, and West gates based on calculated capacity estimation at the gate based on Weather Impacted Traffic Index (*WITI*) values, which will be described in the following section. The FBA function was used for the CTOP operations to automatically resolve constrained problems at the multiple FCAs mapped to the three gates. However, no TOSs were available for the CTOP operations, thereby minimizing the impact of FBA and resulting in strategic traffic management by CTOP to be similar to a GDP at the destination airport but using weather-based calculated capacities at the gates instead of operational GDP rates. For this condition, the TBFM was set up in the same way as the *Baseline* condition to prioritize airborne flights over short-haul departures for scheduling.
3. *Full IDM*: In this condition, full IDM functionalities were used. In addition to weather-based capacity calculations and FBA functions, Full IDM made TOS available for all aircraft managed by the CTOP program. In addition, the scheduling priority for the short-haul flights was elevated above the airborne flights so that they can be scheduled in TBFM to takeoff ahead of non-frozen airborne aircraft in the overhead stream.

B.2. Scenarios

B.2.1. Weather Scenarios and Capacity Estimation

The benefit assessment of the IDM concept required a representative set of weather scenarios to be identified from a realistic data set. To meet this goal, *WITI* values of upstream sectors mapped to the North, South, and West gates for the LGA and EWR arrivals were collected from the NASA SHERLOCK data warehouse. The hourly sector WITIs indicated how the air traffic was affected by the weather within a sector each hour [10].

Three months (June – August in 2016) of the hourly sector *WITI* data were collected. Based on the *WITI* values for each day, the days were clustered using K-means clustering techniques into six representative weather groups. From each clustered group, we chose one day with the same Airport Acceptance Rate (40 aircraft per hour for both LGA and EWR) for a 12-hour period (GMT 12 – 23Z) to represent that weather group in our simulations.

The following table summarizes the number of other days that were grouped to closely match with the six selected days, representing how frequently the similar weather situations occurred during the analyzed three-month period. Unfortunately, there were days with missing *WITI* values so the total number of days only added up to 78 days.

Table 1. Clustered six represented groups

Cluster	Selected Day	# of days	%
1	6/25/16	15	19.0%
2	6/28/16	3	4.0%
3	7/13/16	11	14.0%
4	7/18/16	7	9.0%
5	7/19/16	36	46.0%
6	8/11/16	6	8.0%
	Sum	78	100.0%

Figure 3 shows the screen captures of the Consolidated Storm Prediction for Aviation (CoSPA) image of the selected days (6/25/2016, 6/28/2016, 7/13/2016, 7/18/2016, 7/19/2016, and 8/11/2016 at 20Z). Since the clusters based on the weather were solely determined using the *WITI* values of the sectors directly related to the gates, the weather impacts are most visually noticeable around the New York airspace (indicated by blue circles). The scenarios included two relatively clear weather scenarios (6/25/2016 and 7/19/2016). On these days, there were no GDPs for NY metroplex airports, indicating that there was little to no severe convective weather present near the NY airspace blocking the gates. In other scenarios (6/28/2016, 7/13/2016, 7/18/2016, and 8/11/2016), GDPs were imposed during the parts of the day and different severity levels of the convective weather situation were impacting the gates near the airport.

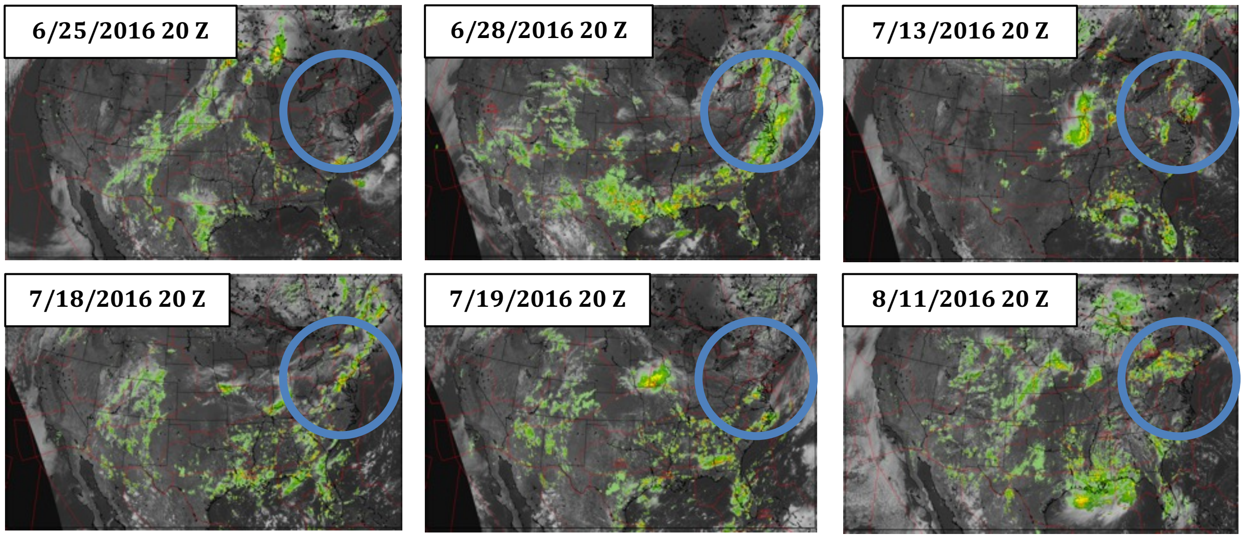


Figure 3: Weather depictions from the six representative weather days (from Collaborative Storm Prediction for Aviation, CoSPA by MIT-LL)

From Aviation System Performance Metrics (ASPM), the actual-implemented GDP during the selected days were collected to be used during the *Baseline* conditions. Figure 4 and 5 show the actual GDP rate and the duration that were executed during the six selected days. It can be observed that the different levels of the GDP rate and the duration were implemented to accommodate the various weather situations. There was no convective weather near the airport and no GDP on 6/25/2016 and 7/19/2016, which represented the "clear weather" days in the simulation runs.

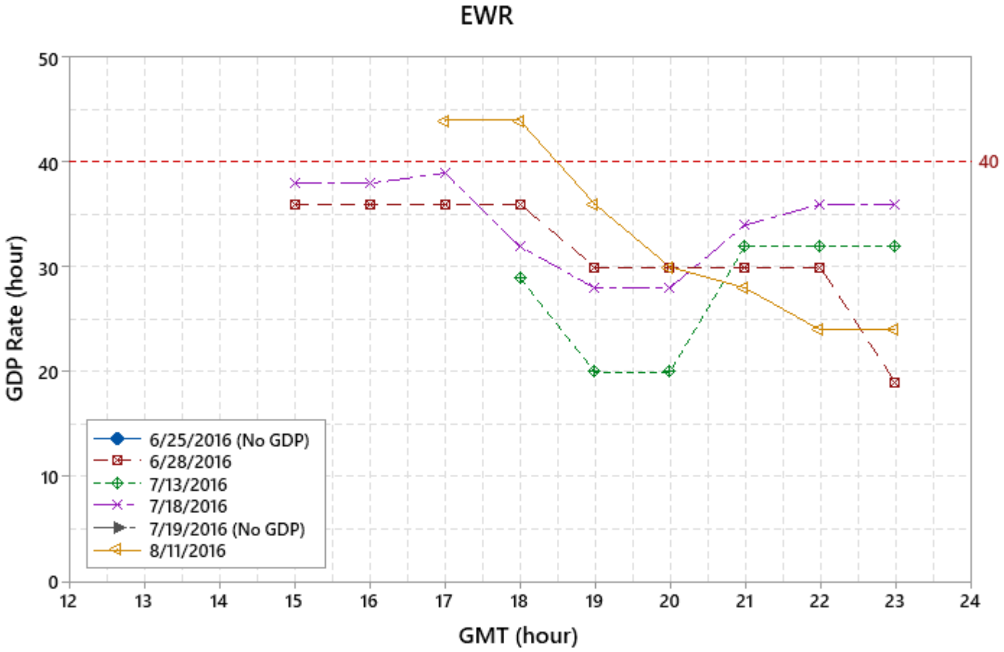


Figure 4: GDP rate used for the six representative weather days for EWR

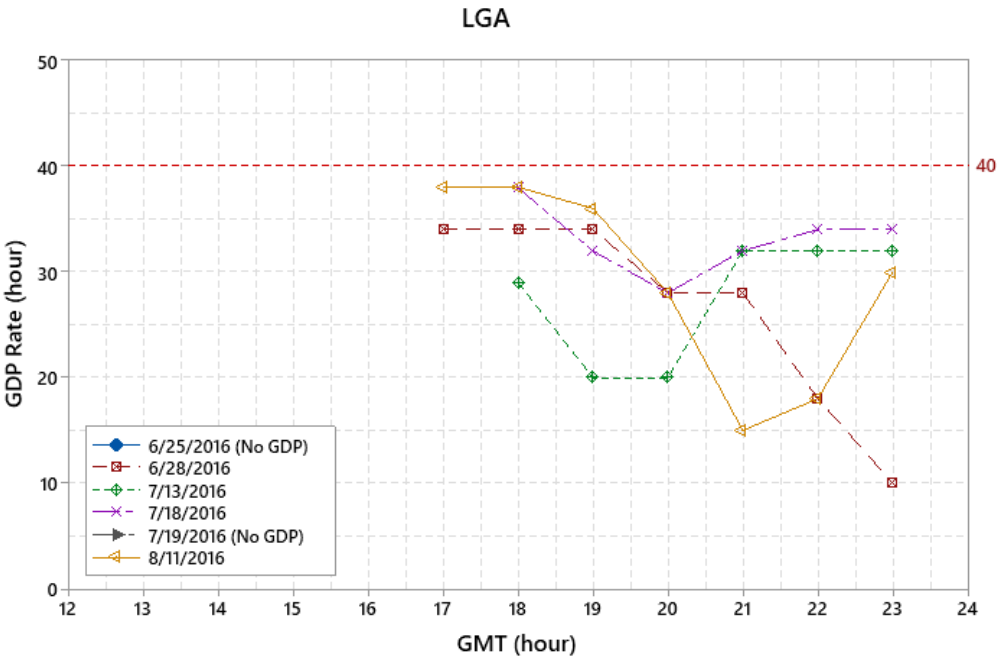


Figure 5: GDP rate used for the six representative weather days for LGA

For the *Baseline* condition, TFM data was analyzed to identify MITs used for six major traffic flows flowing into each gate (North, South, and West) during 12-hour of operations for each selected scenario day. The identified MITs were validated by comparing to one day's National Traffic Management Log (NTML) and receiving feedback from Subject Matter Experts (SMEs). The identified MITs varied from 0 to 40 MIT depending on the flow and the time of the operations.

For the *IDM* conditions, the maximum available capacity for each sector (x_{sector}) mapped to the gate was determined using the following equation:

$$x_{sector} = \min\left((1 - pWITI_{sector}) \cdot C_{sector}, x_{upstream\ sector}\right)$$

In this equation, $pWITI_{sector}$ refers to the normalized hourly percentage *WITI* value for the sector that is mapped to the sector. $pWITI_{sector}$ value ranges from 0 to 1, where 0 indicates that there was no weather impact and 1 indicates there was a severe weather that impacted the traffic flow entirely. C_{sector} indicates the estimated maximum sector capacity that was computed by the 99th percentile of the historical achieved throughput for the sector (from April 2014 to September 2014). For the first term, C_{sector}, was multiplied by $(1 - pWITI_{sector})$, in order to compute what portion of the historically achieved throughput could fly through under the weather-impacted sector.

Next, the value computed for the first term is compared to the second term, $x_{upstream\ sector}$. The second term was obtained by comparing the weather impacted throughput of the "upstream" sector and the available capacity in relation to the scheduled traffic demand of the selected day. The following equation describes how $x_{upstream\ sector}$ is computed, when there are one or more upstream sector(s) ($x_{upstream\ sector_i}$) that are linked to the sector ($x_{upstream\ sector}$):

$$x_{upstream\ sector} = \min\left((1 - pWITI_{upstream\ sector}) \cdot C_{upstream\ sector}, \left(\sum_{i=1}^{no.\ upstream\ sectors} x_{upstream\ sector_i}\right) \cdot \frac{d_{sector}}{\sum_{i=1}^{no.\ upstream\ sectors} d_{upstream\ sector_i}}\right)$$

In the equation above, the weather impacted throughput of the "upstream" sector is computed by "$(1 - pWITI_{upstream\ sector}) \cdot C_{upstream\ sector}$." The available capacity in relation to the scheduled traffic demand of the selected day is computed by multiplying the observed maximum historically flown traffic through all the "upstream" sectors ("$\sum_{i=1}^{no.\ upstream\ sectors} x_{upstream\ sector_i}$") to the proportion of the scheduled traffic demand ("d_{sector}") that were to fly through the "downstream" sector over the scheduled demand through the "upstream" sector(s) of the day that we were to simulate ("$\sum_{i=1}^{no.\ upstream\ sectors} d_{upstream\ sector_i}$"). The historically observed traffic throughput at the "upstream" sector (s) may also include the aircraft that were destined to land the other airports. Hence, such multiplication to the proportion of the scheduled traffic demand to the downstream gate were to estimate only the traffic capacity for the demand that were meant to land at the final destinations we were investigating. The capacity of all the associated upstream sectors, i.e. determined based on the feedback from the SMEs, were estimated using the same approach.

The described iterations of the comparison were to choose the minimum of estimated capacity, computed using the *pWITI* value or the proportion of the scheduled demand, among the series of the associated sectors that the aircraft fly through to cross the gate and land at the final destination. This is because when the multiple sectors are connected in a serial manner, only the sector with the least available capacity becomes the bottleneck, which works as a constraint that determines the maximum amount of the traffic that can fly through the sequence of the sectors.

The estimated maximum capacity for each gate varied and there were periods where a particular gate's maximum capacity showed relatively less availability than the other gates (see Figure 6). However, it was observed that total sum of the maximum capacity was mostly greater than the total available capacity at the airport (i.e., 40 aircraft per hour) throughout the 12-hour period.

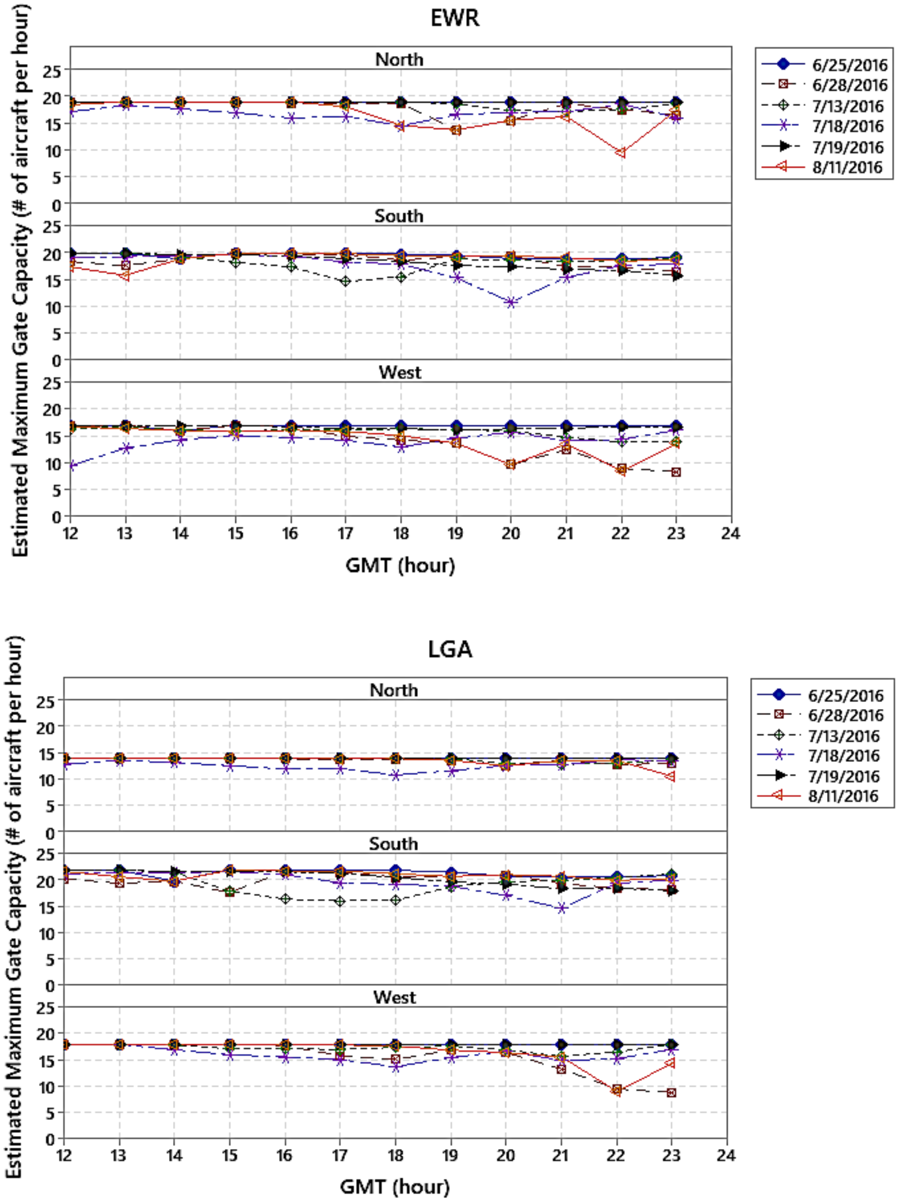
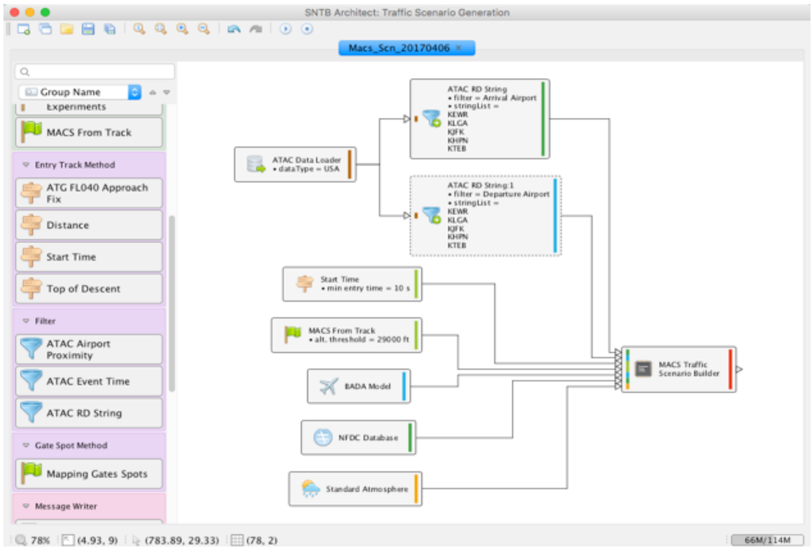


Figure 6: Estimated maximum capacity (hour) for each gate of the six representative weather days

B.2.2. Traffic Scenario and Demand Estimation

The weather impact on the arrival traffic delivery to the airport is highly dependent on the location and the timing of the weather cells, reducing the available resources within the airport, in relation to the traffic demand. A traffic scenario was built based on historically flown data using a NASA's Testbed scenario generator tool [11], as shown in Figure 7. This tool has the capability to take a snapshot of live traffic demand and their flight plans and generate traffic scenarios that could be used for target generation within our simulation environment.



ATAC RD String
• filter = Arrival Airport
• stringList =
KEWR
KLGA
KJFK
KHPN
KTEB

ATAC Data Loader
• dataType = USA

ATAC RD String:1
• filter = Departure Airport
• stringList =
KEWR
KLGA
KJFK
KHPN
KTEB

Start Time
• min entry time = 10 s

MACS From Track
• alt. threshold = 29000 ft

Figure 7: A snapshot of SMART-NAS testbed scenario generator tool

In order to evaluate the impact of the different levels of the convective weather situations, the scenario was modified to represent the nominal scheduled traffic demand throughout the year for the 12-hour period (GMT 12 – 23Z) we are testing. Figure 8 represents the traffic scenario that was built for simulating the EWR and LGA arrival traffic. The weather impact on the target airport throughput is highly dependent on the location and the timing of the weather cells in relation to the traffic demand. Hence, in order to clearly see the impact of the convective weather in the different scenarios, the same traffic scenario was used during all six different weather scenarios. The first hour of the traffic scenario had lighter demand than the actual traffic demand (see Figure 9). The scenario was built this way intentionally (ramping up after two hours) because it would be unrealistic to have too many inflight aircraft close to landing at the beginning of the simulation. Also, having too many close-in airborne aircraft affects the TBFM operations.

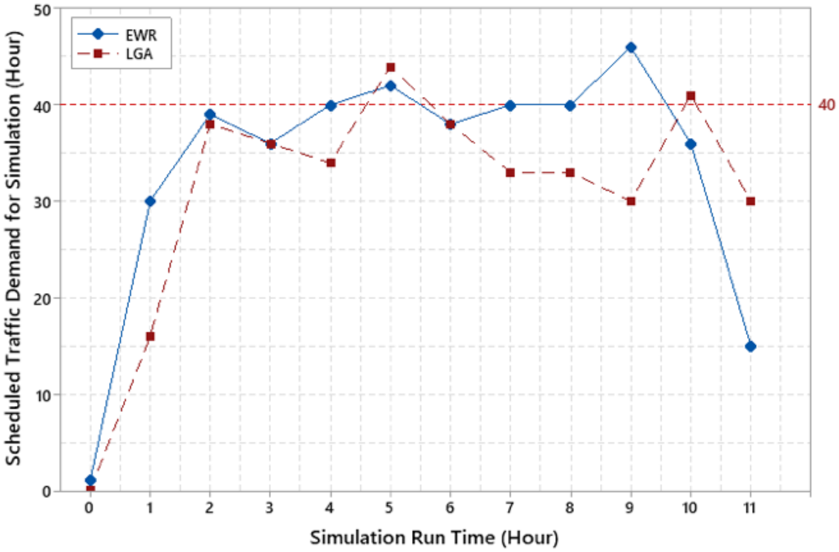


Figure 8: Hourly traffic demand of the nominal traffic scenario built for EWR and LGA for the study

Figure 9 represents the boxplots of the actual scheduled traffic demand for the 12-hour period in 2016 for EWR and LGA, obtained from ASPM. As shown in Figure 9, EWR scheduled traffic demand gradually ramped up to its peak during the latter part of the 12-hour period. LGA scheduled traffic demand was more sustained throughout the day but its peak traffic was generally less than EWR.

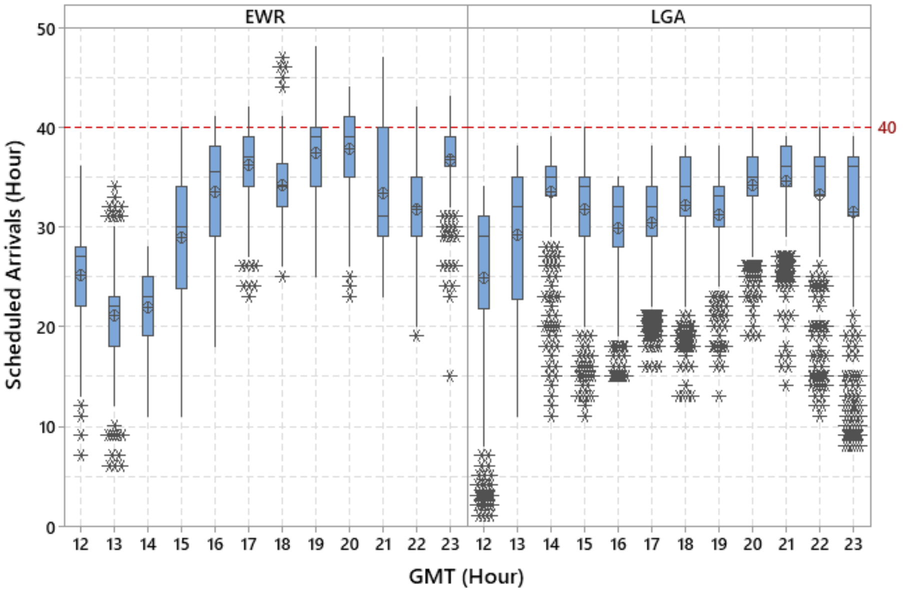


Figure 9: Boxplots of actual scheduled traffic demand (GMT 12 – 23Z) in 2016 from ASPM

Figure 10 illustrates the flown trajectories of the EWR and LGA traffic scenario that was used in the simulation runs. The traffic scenario was built while maintaining the realistic characteristics of the actual traffic flowing into EWR and LGA. The scenario had a total 403 aircraft scheduled to land at the single runway EWR 22L, and 373 aircraft were scheduled to land at LGA 22L over a 12-hour period. The scenario was comprised of 147 (36.5%) short-haul departures taking-off within the TBFM region for EWR arrivals and 177 (43.5%) short-haul departures for LGA—these approximately match the short-haul departures' proportion in the current day operation. For EWR, the heaviest flow (153 out of 403 aircraft) arrived from the south through Washington Center (ZDC). The north flow had the second heaviest traffic demand (138 aircraft out of 403) through Boston Center (ZBW). The west had the least traffic demand (112 aircraft out of 403) and included international arrivals through Cleveland Center (ZOB). For LGA, the south flow had 186 aircraft, the west flow had 121 aircraft, and north flow had the 66 aircraft.

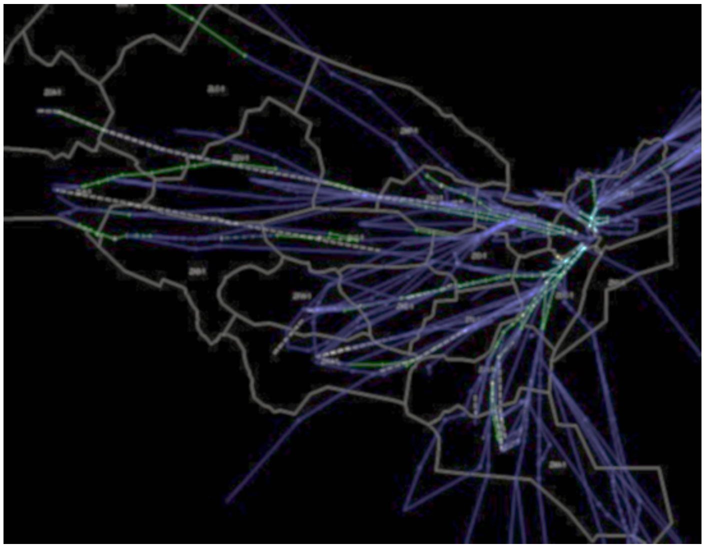


Figure 10: Flown trajectories of the EWR and LGA traffic scenario used in the study

For *Full IDM* condition, Trajectory Option Set (TOS) were generated and utilized during the CTOP operations. The TOSs were initially generated by applying clustering techniques on three months of flown flight plan routes (June to August 2015) and reviewed by three SMEs— retired air traffic managers from Cleveland Center, Washington Center, and Air Traffic Control System Command Center (ATCSCC)—for operational and procedural acceptability. In the scenario, 213 aircraft for EWR and 292 aircraft for LGA were found to be eligible for having multiple route options and used for this study. Due to the nature of the flows into EWR and LGA, mostly west flow flights had the alternative trajectory options for all three gates.

Finally, the traffic scenarios included realistic departure errors, generated by gathering nine days of the historical data (7/03, 7/04, 7/05, 7/10, 7/11, 7/12, 7/15, 7/18 and 7/20 in 2018) from System Wide Information Management (SWIM) data obtained from NASA SHERLOCK data warehouse. In order to obtain the departure error data set for short-haul departures, actual take-off time and call-for-release times that were assigned during those nine days were compared. For the aircraft departing outside of the TBFM region (referred to as "long-haul" departures in this paper), Expect Departure Clearance Times (EDCT) assigned to the long-haul departures during those nine days were gathered and compared to their actual take-off time. From the short-haul departure error dataset, any departure errors that were greater than +/- 5 minutes (+: late departures, -: early departures) were considered outliers and removed from the dataset. From the long-haul departure error dataset, departure errors greater than +/- 20 minutes were considered outliers, therefore, they were filtered as well. From these two departure errors datasets, subsets of the departure errors were randomly sampled and inserted into the traffic scenario with respect to their departure origins (some tweaking of the departure errors were done by considering the general characteristics of the departure error distribution of the origin airport as some airports have skewness in their departure error distribution). Figure 11 shows the histogram of the departure errors that were inserted into the traffic scenario. 57.9% and 53.8% of the long-hauls departures for EWR and LGA, respectively, conformed to the EDCT conformance (+/5 minutes). 57.8% and 60.7% of the short-hauls departures for EWR and LGA, respectively, conformed to the call-for-release conformance (2-minute early and 1-minute late).

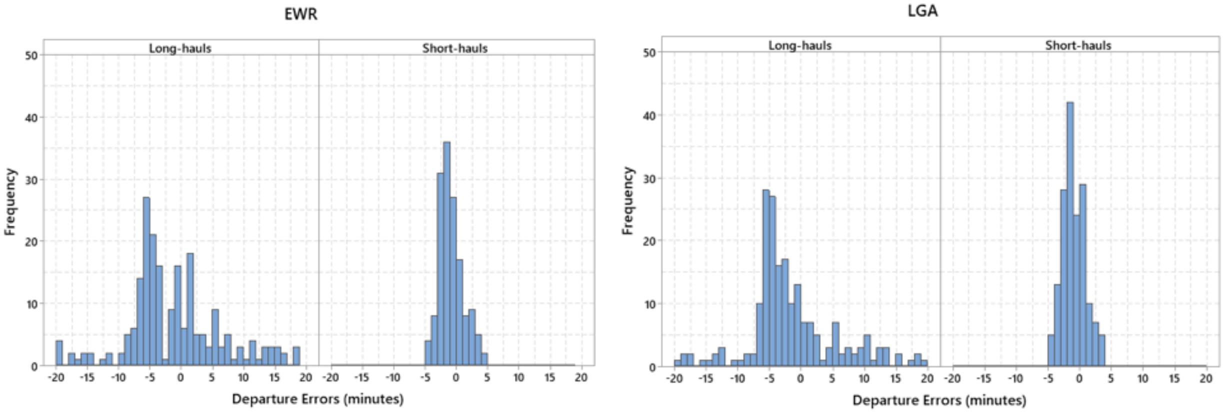


Figure 11: Histograms of the departure errors used in the study

B.3. Apparatus

The TMIAutoSim capability was developed to overcome some of the limitations of conducting the real-time HITL simulations [7, 8] but it was also developed to leverage the existing HITL simulation capabilities while automating the observed human operator inputs from the past HITL simulations. Moreover, the software development was made to enable the simulation to run in much faster (5X) speed and also allowing many simulations to be conducted by automatically loading various parameters without any manual interruption.

The TMIAutoSim capability consisted of five major components: 1) Multi-Aircraft Control System (MACS), 2) nCTOP (NASA developed CTOP emulator), 3) Automated Simulation Manager, 4) eTBFM (TBFM emulator that can run fast-time), and 5) MIT scheduling algorithm. MACS is a high-fidelity air traffic control simulation capability that was developed for prototyping scheduling systems and simulating air traffic. MACS loaded the traffic scenario and computed the aircrafts' trajectories to calculate their Estimated Time of Arrivals (ETAs) to a fix that experimenters specified. Such computed ETAs for the trajectories were used by nCTOP, eTBFM, and MIT scheduling algorithm to generate various schedules to the assigned fixes.

The communication among MACS, nCTOP and Automated Simulator manager were done via TCP/IP protocol, where eTBFM and MIT scheduling algorithm are placed within the Automated Simulation Manager. The major function of the Automated Simulation Manager was to synchronize all the components (see Figure 12). The performance of the TMIAutoSim has been validated by comparing to the results collected from the past HITL studies. Also, the detailed information about the capability is previously documented in [7].

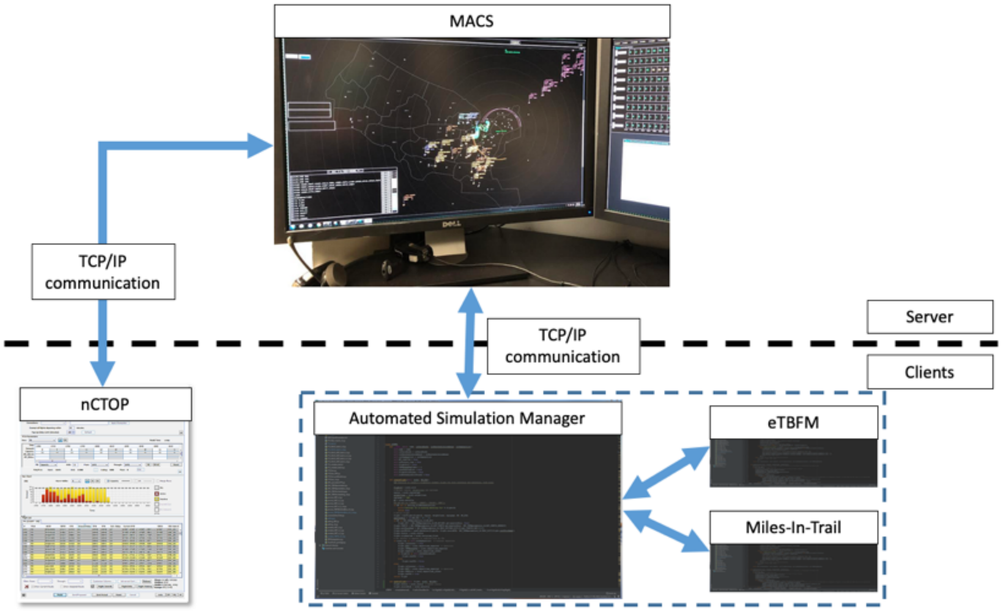


Figure 12: System architecture of automated simulation capability (TMIAutoSim)

B.4. Automated Operating Procedures

There were a few major operating procedures that were automated for each component of the TMIAutoSim. CTOP is an interactive TMI tool, designed for a user to monitor/evaluate the mismatch between traffic demand and available capacity at the FCAs and set the capacity limits accordingly. For the simulation study, the forecasted demand and capacity mismatch were evaluated at the beginning for the duration of the day and the FCA capacities were set based on historical data or computed gate capacities, depending on the experimental condition. For *Baseline* condition, the aforementioned GDP rates from the historical data were automatically loaded to nCTOP, then nCTOP performed like a GDP by setting a single-FCA at the airport and assigned ground delays to the aircraft accordingly. For the *IDM* conditions, the estimated maximum capacity per gate information was automatically loaded into nCTOP. Then, the nCTOP utilized the FBA algorithm to distribute the available resource at the airport (i.e., 40 aircraft per hour) to each gate in proportion to the predicted traffic demand per gate while considering the loaded maximum gate capacity information.

In the study, nCTOP provided a mechanism for airline flight operators to submit TOSs in *Full IDM* condition. TOSs were generated ahead of time and were available for the aircraft during this condition. nCTOP accessed these route options and the preference information when resolving imbalances between demand and capacity. There are several ways to provide the preference of the route options. One way was by providing information in terms of the cost of the route option using RTCs. In addition, there are other preference fields in CTOP capability that the flight operators could use to further provide their preferences: Trajectory Valid Start Time (TVST), Trajectory Valid End Time (TVET), and Reroute Minimum Notification Time (RMNT). The flight operators could use RMNT to indicate when they are willing to or not willing to receive reroute assignment. Also, the flight operators may choose to provide a TVST on a reroute option that prevents the reroute option from being assigned earlier than the user specified time. This is useful when the flight operator forecast that airspace of such route option is going to be blocked by the weather for a certain duration of the time. However, for this study, only the RTC among all the user-settable fields was used as a mechanism for the user to provide their preference for the TOS submitted.

The RTC values used in the study used a very simple model, across all aircraft in the simulation regardless of airline preferences. The RTC values were automatically calculated using the MACS trajectory computations. The following equation represents the RTC computation equation we used:

$$\begin{aligned} RTC = 1.5 \times (&flight\ time\ of\ the\ alternative\ trajectory\ options \\ &- flight\ time\ of\ the\ current\ trajectory\ option\ as\ indicated\ as\ the\ most\ prefered\ option) \\ &+ minimum\ cost \end{aligned}$$

CTOP identifies the earliest arrival time at any of a CTOP's FCAs among any submitted TOS options called, Initial Arrival Time (IAT). Using the IAT information, CTOP assigns aircraft to the slots based on the FSFS-scheme. First, "exempt" aircraft are treated with the priority in the slot assignment. Next, "non-exempt" flight fills the remaining slots according to their IAT order. The flights that are airborne when the program is initiated and flights that are too close to departure time to take updates to their departure time or to their trajectories (i.e., 30 minutes prior to take-off time is used as a rule for this study). During this slot allocation process, CTOP computes Adjusted Cost (AC), (i.e., the sum of RTC and potential ground delay assigned by taking the first available slot by flying TOS options). This is computed to assign TOS option with the least AC value to the aircraft (i.e., assuming the TOS with the least AC value is the most preferred option for the aircraft).

During the study, most preferred TOS route had 'zero' as the RTC value, then nCTOP used the equation above to compute the RTC for the alternative TOS routes. In the equation, the multiplication of 1.5 times the flight time difference was to reflect cost of the additional flight time in relation to the additional ground delay. The flight time difference between the most preferred route and the other routes were often found to be very small, especially for the aircraft flying from the far distances. This could have led to a situation of aircraft receiving an alternative TOS route, even though the benefit in terms of saving ground delay is negligible for taking such reroute. Hence, in order to avoid this situation, we added additional *minimum cost* to the RTC values for the alternative TOS options. The *minimum cost* was set to be 10 for the study.

In order to mimic the TBFM call-for-release procedures, the short-haul departures were automatically scheduled 20-minutes before the scheduled take-off times that were assigned either by the GDP or nCTOP. Once eTBFM assigned Scheduled Time of Arrivals (STAs) to the aircraft to the meter-fix, such information was automatically sent to MACS and the aircraft were assigned with the Required Time of Arrivals (RTAs) to meet the schedule. This process provided a fast-time simulation method to mimic "speed control" that controller would have applied to deliver the aircraft to meet the STAs at the meter-fix. MACS flight deck FMS allowed a user-adjustable RTA tolerance setting. This tolerance conformance range was set to be +/- one minute in this study, matching current day operational tolerances when the controllers are asked to work of times. When the difference between the assigned RTA time and ETA at the crossing fix became greater than the specified parameter, the appropriate speed adjustments were applied. This RTA set-up was applied to the aircraft with MIT assigned times to the TBFM entry crossing point as well.

During the Baseline operations, MITs were applied to the long-haul aircraft automatically after GDP implementation. For the scenarios without GDP, MITs were still applied to the long-haul aircraft. Specific MITs were automatically applied for each scenario differently based on the historical information. Target time of arrival at the TBFM entry fixes were generated by the required spacing for MITs. That target time of arrivals were assigned to the long-hauls as the RTA time, as soon as the aircraft reach the cruise phase, mimicking the speed control that would be done by the air traffic controllers

IV. Results

The results for the benefits study are presented in two-fold: 1) the IDM operations during the clear weather scenarios, and 2) the IDM operations during the convective weather scenarios. The characteristics of the results differed qualitatively between the clear and convective weather conditions, creating a rationale for describing these results separately. There were six scenarios that were simulated to evaluate the concept under different weather situations. Among the scenarios, two scenarios (06/25/2016 and 7/19/2016) had relatively clearer weather situations near the airports with no GDPs in the operational data. As those two days had different tool condition than other days for the Baseline condition (no GDP operations), the first part of the results section will focus on reporting those two simulated day's results under three different tool conditions (*Baseline*, *Partial IDM* and *Full IDM*). The second part of the section will present the results of assessing the IDM concept during the rest of the four simulated convective weather days' operations (06/28/2016, 07/13/2016, 07/18/2016 and 08/11/2016). The last part of this section will also elaborate on the impact of the TOS submission during the IDM operations across the tested weather scenarios.

A. IDM during the Clear Weather Scenarios

The IDM concept was first evaluated by comparing its operations to the current-day TFM operations for managing the EWR and LGA arrivals during the clear weather day (06/25/2016 and 07/19/2016). These clear days represented 65% of the three-month period of the data that we applied the clustering techniques. For these two days, no GDPs were implemented but MITs were applied to the long-hauls for the *Baseline* condition to mimic the TMIs in the operational data. In clear weather days, the historical data suggested high throughput rates at the airport already, so we did not expect throughput to increase under the *IDM* conditions. However, in the past IDM HITL study [4], the IDM concept in clear weather showed benefits of shifting the last-minute excessive ground delay for the short-hauls departures within the TBFM region to more strategic and predictable ground delays, distributed across all flights. More specifically, today's clear weather operations often experience large ground delays for the short-haul flights within the TBFM region as well as significant airborne delays in certain peak traffic situations. Under IDM, all flights take strategic ground delays that are relatively equitable across all flights. In this study, we expected to replicate the results from the past HITL study but with a more realistic traffic scenarios and closely mimicked baseline condition using the newly-developed TMIAutoSim capability.

Figures 13 and 14 show the equity of ground delays between short-hauls and long-hauls departures in the *IDM* conditions. They display the ground delays assigned by CTOP to the non-exempt short-haul and long-haul departures in relation to the runway threshold crossing time during the tested in *Partial* and *Full IDM* conditions for two clear weather days for EWR and LGA, respectively. For these two days, the CTOP program was implemented after the first 120 minutes for 10 hour-duration (up to 720 minutes in the simulation run time) as the traffic demand was designed to ramp-up after first two hours and dissipate after 12 hours. In Figure 13 and 14, the red "o" represents the total amount of the CTOP ground delay assigned to the short-hauls in minutes. The blue "x" represents CTOP delay assigned to the long-hauls. In general, the delays can build up over run time when the demand consistently exceeds capacity, as shown in EWR traffic (Figure 13) but not in LGA traffic (Figure 14). However, examination of any given runway crossing time show relatively even distribution of red "o" and blue "x", suggesting that the ground delays assigned by CTOP were fairly distributed between the non-exempt short- and long-haul departures.

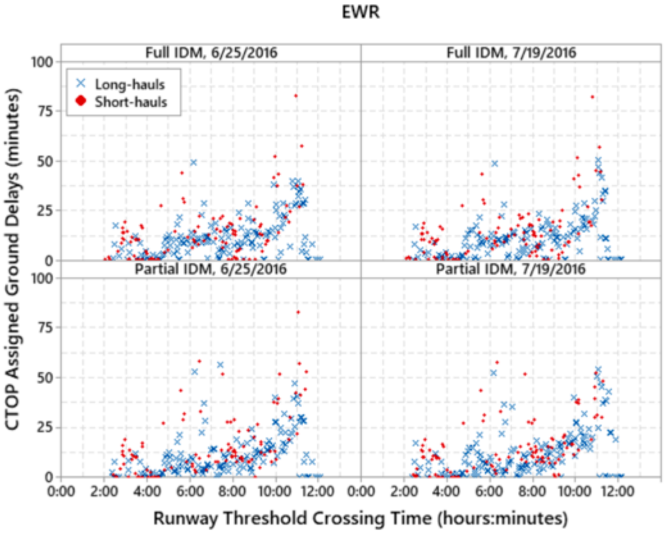


Figure 13: CTOP assigned ground delays (minutes) as a function of runway threshold crossing time (hours:minutes) for the two clear weather days (06/25/2016 and 07/19/2016) for EWR airport

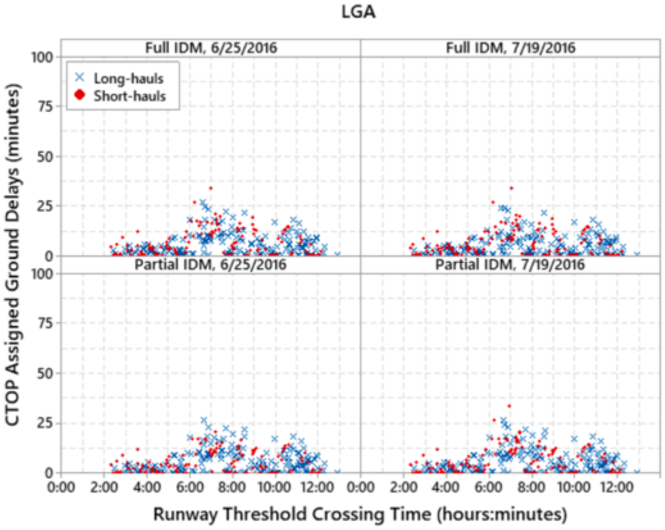


Figure 14: CTOP assigned ground delays (minutes) as a function of runway threshold crossing time (hours:minutes) for the two clear weather days (06/25/2016 and 07/19/2016) for LGA airport

Tables 2 and 3 summarize the ground delay assigned by the CTOP to the non-exempt short-haul and long-haul departures during the tested IDM conditions for two clear weather days. The results in the table support that the CTOP provided fair treatment between short-hauls and long-hauls, as suggested by similar median delays between them for both airports. There was an exception case, in which a short-haul departure in the EWR scenario received a large ground delay. The aircraft was departing from one of the airports within ZBW center and it was initially scheduled to take-off when a gaggle of international heavy jets arrived into ZBW via the north gate. Hence, it frequently received very large ground delays. This case illustrates the impact of unscheduled long-haul flights on the ability for the short-haul flights to take off.

Table 2. Ground delay assigned by CTOP to the short vs. long-hauls in *Partial IDM* (hours:minutes)

Scenario	Airport	Short- vs. Long-hauls	Average	SD	Median	Max	N
6/25/16	EWR	*Short-hauls*	00:16	00:16	00:11	01:23	104
		Long-hauls	00:11	00:11	00:08	00:57	154
	LGA	*Short-hauls*	00:05	00:05	00:03	00:21	126
		Long-hauls	00:05	00:06	00:04	00:26	184
7/19/16	EWR	*Short-hauls*	00:14	00:13	00:11	00:58	104
		Long-hauls	00:12	00:12	00:08	00:54	154
	LGA	*Short-hauls*	00:06	00:07	00:03	00:34	126
		Long-hauls	00:05	00:05	00:03	00:24	184

Table 3. Ground delay assigned by CTOP to the short vs. long-hauls in *Full IDM* (hours:minutes)

Scenario	Airport	Short- vs. Long-hauls	Average	SD	Median	Max	N
6/25/16	EWR	*Short-hauls*	00:14	00:14	00:11	01:23	104
		Long-hauls	00:11	00:10	00:09	00:49	154
	LGA	*Short-hauls*	00:06	00:07	00:04	00:34	126
		Long-hauls	00:05	00:06	00:03	00:26	184
7/19/16	EWR	*Short-hauls*	00:14	00:14	00:11	01:22	104
		Long-hauls	00:11	00:10	00:10	00:50	154
	LGA	*Short-hauls*	00:06	00:06	00:03	00:34	126
		Long-hauls	00:05	00:05	00:03	00:24	184

During the *Baseline* conditions, there were no CTOP ground delays. Instead, MITs were applied once the aircraft were airborne to manage some of the long-haul traffic flowing into the TBFM regions. Table 4 presents the summary statistics of the delays produced by applying MITs to the long-hauls during the *Baseline* conditions. These MITs were the ones present in the NTML and not the MITs used nominally for each gate to manage the arrival traffic when TBFM is not used. Table 4 shows that relatively less delays assigned to the long-hauls during *Baseline* in comparison to the delays assigned by CTOP during the *IDM* conditions. This created more traffic demand pressure flowing into the TBFM region during the *Baseline* condition with intention to deliver high traffic throughput, but with possible impact on the short-haul departures.

Table 4 Miles-In-Trail delays assigned to the long-haul in the Baseline conditions (hours:minutes)

Scenarios	Airport	Average	SD	Sum	N
6/25/16	EWR	00:02	00:03	02:10	80
	LGA	00:01	00:01	00:27	49
7/19/16	EWR	00:01	00:02	01:08	69
	LGA	00:01	00:02	01:31	117

Table 5 contains the airborne delays induced by the TBFM scheduler from each tested condition for the same aircraft that were captured by the 10-hour program period. The results show that more TBFM airborne delays were produced during the *Baseline* condition than the *Partial IDM* condition. Both *Baseline* and *Partial IDM* disabled the TBFM departure scheduling function for prioritizing the short-haul departures over the airborne aircraft. During the

Full IDM condition, the TBFM departure scheduling function was enabled, therefore, relatively larger accumulated airborne delays were observed.

Table 5 Summary statistics of the airborne delays assigned by TBFM (hours:minutes)

Airport	Scenario	Condition	Average	SD	Sum	N
EWR	6/25/16	*Baseline*	00:02	00:02	12:05	372
		Partial IDM	00:02	00:02	10:11	372
		Full IDM	00:02	00:03	15:07	372
	7/19/16	*Baseline*	00:02	00:03	13:41	372
		Partial IDM	00:02	00:02	10:19	372
		Full IDM	00:03	00:03	18:04	372
LGA	6/25/16	*Baseline*	00:01	00:02	08:41	357
		Partial IDM	00:01	00:01	07:22	357
		Full IDM	00:02	00:02	10:14	357
	7/19/16	*Baseline*	00:02	00:02	13:12	357
		Partial IDM	00:02	00:02	09:23	357
		Full IDM	00:02	00:02	11:22	357

Figure 15 and Table 6 illustrates the TBFM assigned ground delays for the three conditions. As expected, *Baseline* condition resulted in the greatest last-minute TBFM ground delays for the short-haul flights, followed by the *Partial* and then the *Full IDM* condition. The strategic ground delays by CTOP reduced the TBFM departure delays in *Partial IDM*, but with the airborne priority given during the departure scheduling, the ground delays were still larger than in *Full IDM*, where the priority was given to the departure scheduling.

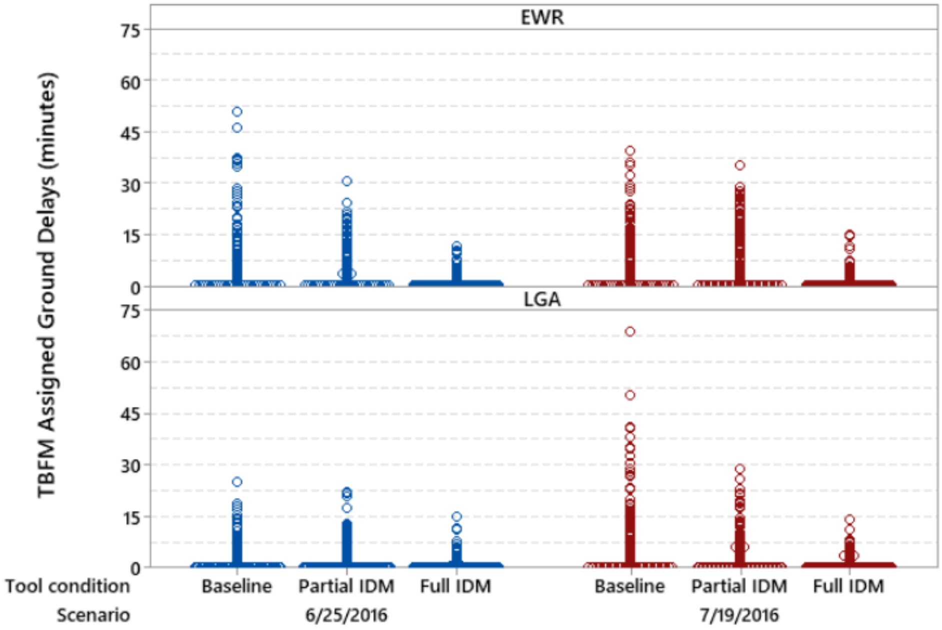


Figure 15: TBFM ground delays (minutes) assigned to each aircraft in both clear weather scenarios (06/25/2016 and 07/19/2016) in all three tool conditions

Table 6 summarizes the ground delays assigned by TBFM departure scheduler during each tool condition. In the table, we observed the *Partial IDM* condition produced less ground delay than the *Baseline* condition. Also, *Full IDM* condition produced the least ground delay as this condition had the short-haul departures priority function over the airborne aircraft enabled.

Table 6. Ground delays assigned by TBFM departure scheduler (hours:minutes)

Airport	Scenarios	Tool Conditions	Mean	SD	Sum	N
EWR	6/25/16	*Baseline*	00:09	00:11	19:41	129
		Partial IDM	00:06	00:07	13:08	129
		Full IDM	00:01	00:02	03:10	129
	7/19/16	*Baseline*	00:08	00:09	17:41	129
		Partial IDM	00:08	00:08	16:15	129
		Full IDM	00:02	00:03	03:18	129
LGA	6/25/16	*Baseline*	00:03	00:04	09:01	157
		Partial IDM	00:03	00:04	08:12	157
		Full IDM	00:01	00:02	02:41	157
	7/19/16	*Baseline*	00:09	00:11	23:46	157
		Partial IDM	00:04	00:06	11:38	157
		Full IDM	00:01	00:02	02:45	157

Finally, Table 7 presents the summary statistics of the number of aircraft landed (throughput) during the 10-hour period where the CTOP program was implemented. For the tested two clear weather days, the *IDM* conditions introduced the CTOP as an alternative to MIT for pre-conditioning traffic demand into TBFM. Unlike MITs operations (managing only the long-hauls) during the Baseline conditions, the IDM CTOP strategically pre-conditioned both the long-hauls and short-hauls aircraft. Although more aircraft were controlled by the strategic TMIs during the IDM conditions, we observed similar throughput was achieved across all tested three tool conditions (*Baseline*, *Partial IDM*, and *Full IDM*), as expected. It was also observed that reduction in the excessive last-minute ground delays assigned by TBFM was achieved, particularly, in the *Full IDM* condition.

Table 7. Runway throughput based on total number of flights in the 10-hour period (2 – 12 hours)

Scenarios	Scenarios	Tool Conditions	Avg. Hourly Rate	SD	Median	Max.	Total number of flights landed during the 10-hour period
EWR	6/25/16	*Baseline*	37.1	8.0	39.0	44.0	371
		Partial IDM	37.1	4.9	38.0	41.0	371
		Full IDM	37.2	4.3	38.0	41.0	372
	7/19/16	*Baseline*	37.1	8.0	39.0	42.0	371
		Partial IDM	37.1	5.4	37.5	43.0	371
		Full IDM	37.2	4.1	38.0	41.0	372
LGA	6/25/16	*Baseline*	35.4	3.5	34.5	41.0	354
		Partial IDM	35.2	2.8	34.5	41.0	352
		Full IDM	35.2	3.8	33.5	43.0	352
	7/19/16	*Baseline*	35.0	3.7	34.5	42.0	350
		Partial IDM	35.0	2.9	34.0	40.0	350
		Full IDM	35.3	3.9	34.0	44.0	353

B. IDM during the Convective Weather Scenarios

The following presents the benefits of the IDM concept operations during convective weather, representing 35% of the three-month historical data set, and represented by four target weather scenarios from 06/28/2016, 07/13/2016, 07/18/2016, and 08/11/2016. When compared to *Baseline*, the *IDM* conditions were expected to achieve higher throughput at the destination airports when upstream gates were partially blocked by the convective weather because the IDM concept calculates weather-related gate and airport capacities and uses them to set FCA rates in CTOP. In addition, if one of the gates is blocked extensively for a significant amount of time, TOS capability in CTOP will enable the airline operators to circumvent the blocked gate by rerouting to the alternate gates. Since CTOP has the capability to handle multiple FCAs within the same program, CTOP can re-allocate and/or re-distribute resource to other FCAs even if one FCA is affected by the convective weather cell, allowing higher throughput to be achieved for the downstream airports

Table 8. Runway throughput based on total number of flights landed during the TFMS TMIs (EWR)

Scenarios	Scenarios	Period	Tool Conditions	Avg. Hourly Rate	SD	Median	Max.	Total number of flights landed
EWR	6/28/16	3 - 12 hour	*Baseline*	33.0	3.3	35.0	38.0	297
			Partial IDM	36.0	4.8	38.0	39.0	324
			Full IDM	37.0	5.5	38.0	42.0	333
	7/13/16	6 - 12 hour	*Baseline*	24.3	4.8	25.0	30.0	146
			Partial IDM	37.0	6.1	39.0	42.0	222
			Full IDM	36.5	7.5	38.5	43.0	219
	7/18/16	3 - 12 hour	*Baseline*	36.9	3.8	38.0	42.0	332
			Partial IDM	37.1	3.7	38.0	40.0	334
			Full IDM	37.1	4.0	37.0	42.0	334
	8/11/16	5.25 - 12 hour	*Baseline*	32.9	6.1	33.0	41.0	230
			Partial IDM	34.9	8.9	38.0	41.0	244
			Full IDM	35.6	9.9	39.0	43.0	249

Table 8 and 9 show the throughput achieved during each scenario under different tool conditions for EWR and LGA airports, respectively. The evaluation time period for each scenario was chosen based on when GDPs were issued as TFMS TMIs in NTML for the target dates. As shown in Table 8 and 9, the throughput improvement varied significantly based on the severity of the weather in different days and the weather impact on EWR and LGA airports. For EWR airport (see Table 8), the average throughput was significantly lower for *Baseline* (24.3) than *IDM* conditions (37.0 for *Partial IDM;* 36.5 for *Full IDM*) for one of the scenarios (7/13/16) but more muted in the other three scenarios. For *Partial* vs. *Full IDM,* there did not seem to be much throughput difference between the two conditions, suggesting that the TOS capabilities or TBFM airborne vs. departure priorities did not impact the ability to deliver the traffic demand to the available gate and airport capacities.

Table 9. Runway throughput based on total number of flights landed during the TFMS TMIs (LGA)

Scenarios	Scenarios	Period	Tool Conditions	Avg. Hourly Rate	SD	Median	Max.	Total number of flights landed
LGA	6/28/16	5 - 12 hour	*Baseline*	31.0	3.4	31.0	35.0	217
			Partial IDM	35.9	2.8	35.0	41.0	251
			Full IDM	36.4	3.5	36.0	42.0	255
	7/13/16	6 - 12 hour	*Baseline*	25.3	4.9	23.0	32.0	152
			Partial IDM	36.5	3.5	36.5	40.0	219
			Full IDM	36.7	3.8	36.5	43.0	220
	7/18/16	6 - 12 hour	*Baseline*	27.3	8.2	26.5	39.0	164
			Partial IDM	36.3	3.5	36.5	40.0	218
			Full IDM	36.7	3.3	36.5	42.0	220
	8/11/16	5 - 12 hour	*Baseline*	33.7	3.8	34.0	39.0	236
			Partial IDM	36.1	2.3	36.0	40.0	253
			Full IDM	36.4	3.2	35.0	42.0	255

For LGA airport (see Table 9), the average throughput on two of the scenarios was significantly lower for *Baseline* (25.3 for 7/13/16 and 27.3 for 7/18/16) than *IDM* conditions (36.5 for *Partial IDM;* 36.7 for *Full IDM* on 7/13/16; 36.3 for *Partial IDM;* 36.7 for *Full IDM* on 7/18/16). The results were more muted in the other two scenarios. For *Partial* vs. *Full IDM,* again there did not seem to be much difference between the two conditions in terms of throughput, suggesting that the TOS capabilities or TBFM airborne vs. departure priorities did not impact the ability to deliver the traffic demand to the available gate and airport capacities.

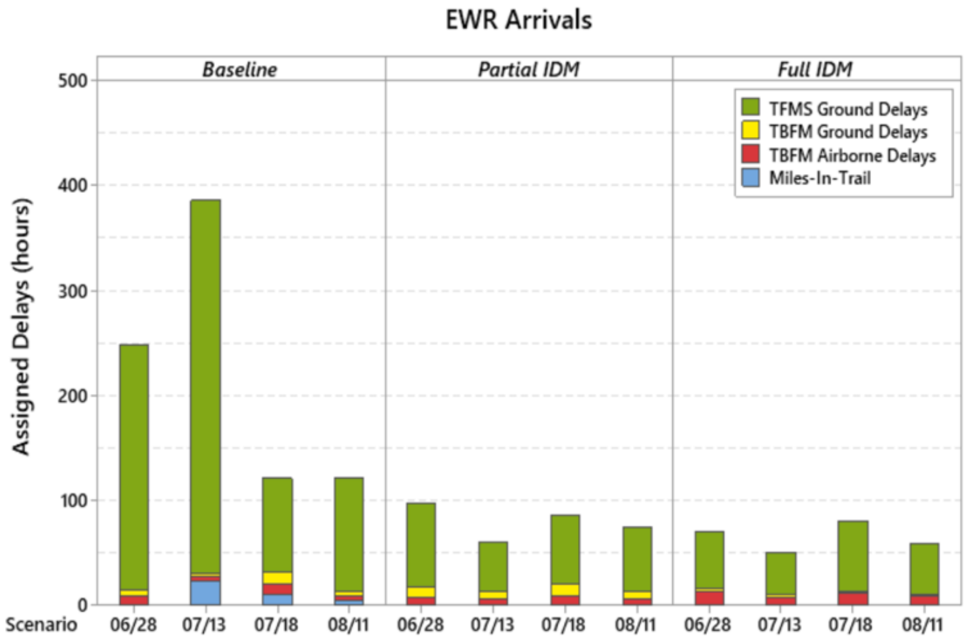


Figure 16: Total delays assigned by the different TMIs in all tool conditions during the convective weather scenarios for EWR airport

Figure 16 and 17 illustrate the total delays that were applied to arrival traffic from different TMIs (in hours). In the figure, *Baseline* created significantly more total delays than the two *IDM* conditions. A significant portion of the total delay in *Baseline* was due to TFMS ground delay from GDPs, which was reduced when CTOP was used in the *IDM* conditions. The total accumulated delay was similar between *Partial* and *Full IDM* conditions, with slightly increased delay for *Partial* over *Full IDM*. Furthermore, *Partial IDM* had more TBFM ground delay, likely due to the scheduling priority given to the airborne flights over short-haul departures within TBFM region. As expected, there was a strong negative correlation (ρ = -0.886) between the average hourly rate and the total delay assigned by the different TMIs, indicating more throughput could be achieved with reduced total delay.

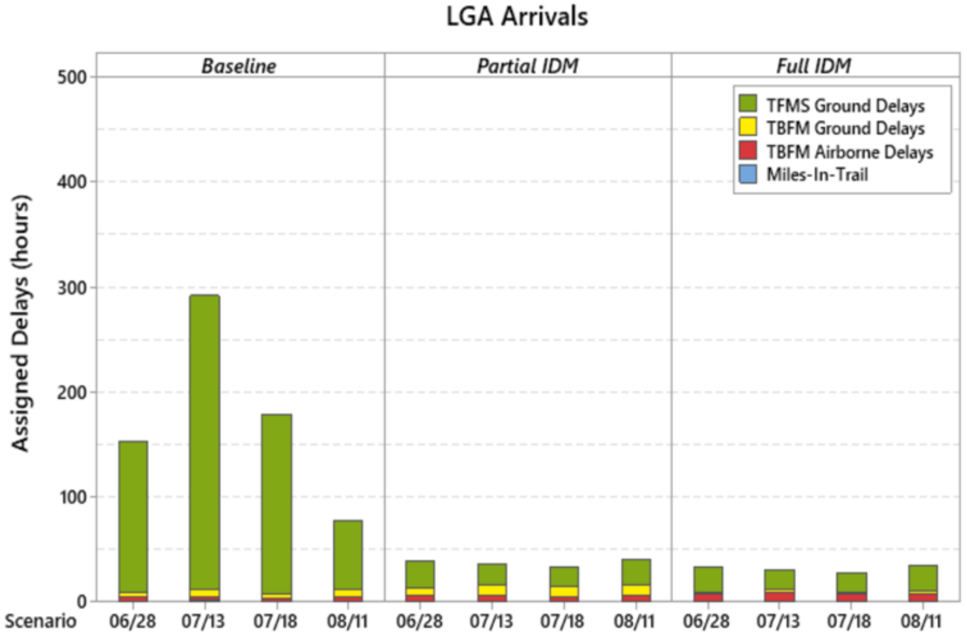


Figure 17: Total delays assigned by the different TMIs in all tool conditions during the convective weather scenarios for LGA airport

Table 10. Delays assigned by CTOP (*Partial IDM* vs. *Full IDM*) during the convective weather scenarios (06/28, 07/13, 07/18, and 08/11 in 2016) (hours:minutes)

Airport	Date	*Partial IDM*			*Full IDM*				n
		Total Ground Delays	Average [SD]	Median	Total Ground Delays	Average [SD]	Median	Additional Flight Time [# of TOS reroutes]	
EWR	6/28/16	79:51	00:20 [00:23]	00:11	53:53	00:14 [00:11]	00:11	2:49 [22]	236
	7/13/16	46:19	00:17 [00:14]	00:14	40:57	00:15 [00:13]	00:12	1:00 [10]	161
	7/18/16	65:37	00:17 [00:17]	00:11	66:30	00:17 [00:18]	00:11	2:12 [15]	236
	8/11/16	62:32	00:21 [00:19]	00:14	47:27	00:16 [00:13]	00:12	1:26 [10]	181
LGA	6/28/16	25:11	00:07 [00:06]	00:06	23:52	00:06 [00:06]	00:05	00:10 [1]	228
	7/13/16	20:05	00:06 [00:05]	00:06	19:12	00:06 [00:06]	00:06	00:21 [3]	186
	7/18/16	18:36	00:06 [00:06]	00:05	18:37	00:06 [00:06]	00:05	00:10 [1]	186
	8/11/16	24:32	00:06 [00:06]	00:05	24:01	00:06 [00:06]	00:05	00:10 [1]	228

For the comparison of TOS impact on the two *IDM* conditions, Table 10 summarizes the ground delays assigned by CTOP during the *Partial* and *Full IDM* conditions for the selected convective weather scenarios. The table contains the additional flight time that was produced by assigning reroutes, and the number of TOS reroutes occurred during the *Full IDM* conditions. For EWR airport, a small but significant percentage of flights were rerouted via TOS. For those reroutes, the additional flight time was modest, between 1 to 3 minutes. Correspondingly, there were reductions in total ground delays in three out of four weather scenarios in *Full IDM* relative to *Partial IDM.* In contrast, LGA airport showed very few TOS reroutes in *Full IDM* condition. Accordingly, there were no visible differences in the total ground delays between the two *IDM* conditions for LGA airport.

Finally, Figure 18 shows the ground delays assigned by the CTOP per flow (North, South, and West) for EWR. During the severe weather situations (06/28, 07/13, and 08/11 in 2016), TOS submission helped effectively re-allocate traffic demand to other gates, resulting in more balanced delay distribution among the flows, thereby replicating the HITL results in [5]. Scenarios from 6/28/2066 and 8/11/2016 showed more pronounced delay reduction from the West gate with TOS participation in the *Full IDM* condition, whereas the other two scenarios had much more muted impact. Most of the flights flying from the North or South gates had no geographically feasible trajectory options allowing them to fly to the other gates. Hence, if the West flow traffic were rerouted to the other gates, they were impacted as those aircraft took up the slots. The impact of those rerouted aircraft came out to be greater for the North departure aircraft as the majority of the slots were already taken by the heavy international traffic from Europe. In the 07/18/2016 *Full IDM* condition, there were some aircraft in the North flow that received large ground delays by CTOP, indicated as outliers (marked by asterisk sign '*' in the Figure 18). Those outliers were the departures with no TOS submission that were affected by other rerouted aircraft.

Figure 19 is the depiction of the ground delays assigned by the CTOP per flow (North, South, and West) for LGA. In general, LGA traffic demand was lighter than the available capacity at the gates. Therefore, the ground delays assigned by the CTOP per flow were observed to be less than what was observed in Figure 18 for EWR. There were only one to three aircraft receiving the TOS reroutes, creating little impact on the distribution of the delays. There was a small increase in delays for the north flow in the *Full IDM* condition, which was caused by originally west gate assigned aircraft getting TOS rerouted to the north gate and inducing delays to the other north flow aircraft.

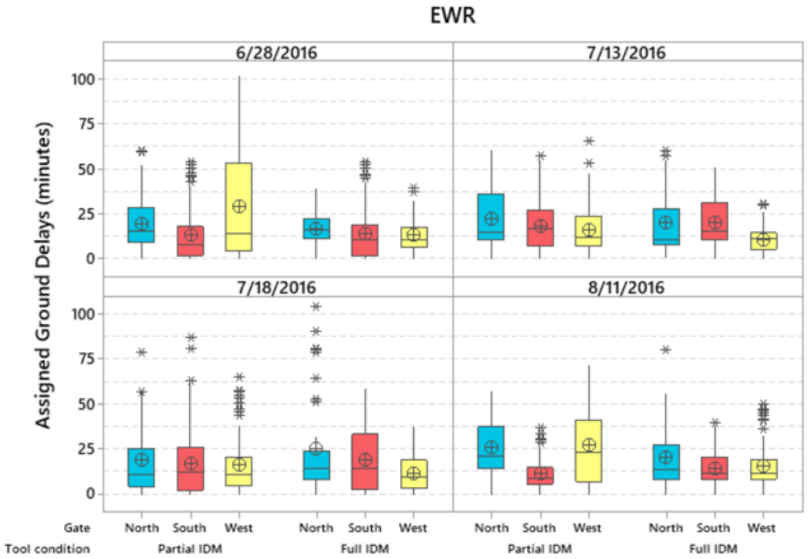


Figure 18: Boxplots of CTOP assigned ground delays (minutes) per flow (North, South, and West) for *Partial* and *Full IDM* Conditions during the convective weather scenarios for EWR (06/28, 07/13, 07/18, and 08/11 in 2016)

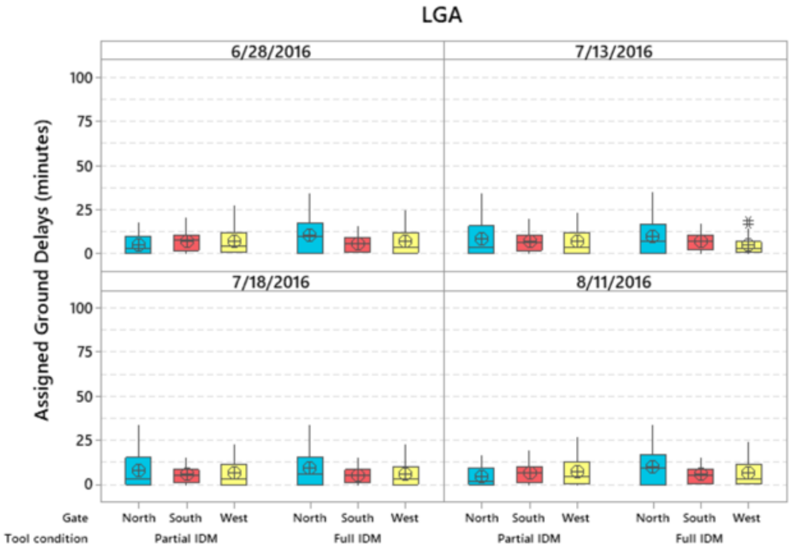


Figure 19: Boxplots of CTOP assigned ground delays (minutes) per flow (North, South, and West) for *Partial* and *Full IDM* Conditions during the convective weather scenarios for LGA (06/28, 07/13, 07/18, and 08/11 in 2016)

V. Discussion

The results of the IDM concept assessment confirmed that IDM brings benefit in both the clear and convective weather scenarios, where the different TMI tool sets were used to perform the TFM in the current operations. During the clear weather scenarios, it was observed that IDM operations achieved a more equitable distribution of the ground delays among the departures regardless of their origins. Such strategic traffic fow management using CTOP effectively reserved enough space for the short-haul departures within the TBFM region to be able to fit into the overhead stream. However, the available space created by pre-conditioning was more effectively utlized to reduce short-haul ground delays when *Full IDM* condition was used to prioritize short-haul departure scheduling over the airborne flights. When airborne flights entering the TBFM region had the schedule priority over short-haul departures, as assumed in *Partial IDM* condition, the short-haul departure delays were reduced compared to *Baseline,* but much less than in *Full IDM* condition.

In the *Baseline* condition during the clear weather, only MIT was utilized to pre-condition the long-haul traffic demand flowing into the TBFM region. This way of managing traffic created a constant heavy traffic demand pressure for achieving high throughput. Although the *IDM* conditions seemed to create more CTOP ground delays overall, such delays were mostly assigned well in advance of departure, which guaranteed more schedule predictability for the airlines compared to the *Baseline* condition, where short-haul departures received last-minute excessive ground delays from the TBFM departure scheduler. This was mainly due to unscheduled long-haul flights, feeding heavy traffic into the TBFM region, leaving fewer available slots in the overhead stream for the short-haul departures. The heavy traffic feed during the *Baseline* condition also caused more airborne delays to be produced within the TBFM areas, when compared to the *Partial IDM* operations with the same TBFM departure scheduling capability setup.

During the convective weather days, the beneift of IDM was noticeable, in terms of both throughput and delays. The IDM operations showed vast improvement in throughput due to setting up multiple FCAs to handle three major flows flying into two airports. The results showed that fewer delays were produced with more traffic delivered to the final destinations as well. The findings from this study also demonstrated that IDM operations could be more effective when the aircraft were submitting TOSs in re-allocating demand to the capacity-constrained areas.

In the results, performance improvement as measured by delays and throughput varied significantly during the four different scenarios. A potential direction for future research would be to characterize how these performance benefits depend on severity and location of weather in different weather scenarios. Moreover, due to the strategic nature of the planning time horizon of the IDM concept for pre-conditioning traffic demand, there may be challenges in terms of planning based on uncertain predictions. In the study, departure errors were introduced as one source of uncertainty in the accuracy of traffic demand delivery. However, various other sources may bring uncertainties to accurate delivery of the planned demand. Further exploration on how to account for the impact of such various sources on operations is another potential direction for the research.

VI. Conclusion

The IDM concept has been successfully expanded to handle multiple airspace constrained areas and airport constraints by using strategic and tactical traffic flow management tools, along with NASA's FBA algorithm. The IDM concept was evaluated for Newark and LaGuardia airports using realistic traffic and weather scenarios taken from the operational data over three-month period. Our simulation capabilities were adapted to set up the CTOP, TOS, FBA, and TBFM tools according to the IDM concept for the two target airports. Three 12-hour simulation runs were conducted across six weather scenarios and compared to the *Baseline* condition using traditional Ground Delay Program and Miles-in-Trail traffic initiatives. The results showed the benefit of the concept in both clear and convective weather scenarios. In the clear weather days, IDM's strategic method of pre-conditioning traffic demand was shown to: 1) demonstrate more efficient TBFM operations, 2) promise equity in NAS resource sharing, 3) resolve the notorious 'double-penalty' issue that short-hauls are experiencing in current-day operations, yet still 4) deliver to the target throughput. During convective weather, the results showed that IDM operations could achieve up to 52% more throughput than the Baseline operations, while producing fewer overall delays.

VII. Acknowledgments

The authors would like to thank all the subject matter experts who shared their invaluable inputs to the concept development. The authors would also like to thank Nancy Smith and Connie Brasil for numerous discussions about the IDM concept.

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