MANAGEMENT BY TRAJECTORY: IMPROVING PREDICTABILITY FOR AIRSPACE OPERATIONS

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Abstract

In the present-day National Airspace System, the air traffic management system attempts to predict the trajectory for each flight based on the flight plan and scheduled or controlled departure time. However, gaps in trajectory data and models, coupled with tactical control actions that are not communicated to automation systems or other stakeholders, lead to trajectory predictions that are less accurate than they could be. This affects traffic flow management performance.

Management by Trajectory (MBT) is a NASA concept for air traffic management in which every flight operates in accordance with a 4D trajectory that is negotiated between the airspace user and the FAA to account for the airspace user's goals while complying with NAS constraints. The primary benefit of MBT is an improvement in system performance due to increased trajectory predictability and stability, which result from managing traffic in all four dimensions (2D route, vertical, and time), ensuring that changes to the flight's trajectory are incorporated into the assigned trajectory, and utilizing improved time or arrival control standards. Importantly, the performance improvements support increasing efficiency without increasing collision risk.

This paper provides an overview of MBT and describes fast-time simulation results evaluating the safety, performance, and efficiency effects of MBT.

Introduction

In the present-day National Airspace System (NAS), the air traffic management (ATM) system attempts to predict the trajectory for each flight based on the flight plan and scheduled or controlled departure time. However, gaps in trajectory data and models, coupled with tactical control actions that are not communicated to automation systems or other stakeholders, lead to trajectory predictions that are less accurate than they could be. This affects traffic flow management performance. Current practices and automated system capabilities are insufficient to support the Federal Aviation Administration's (FAA's) desired transition to Trajectory Based Operations (TBO).

MBT Concept Overview

Management by Trajectory (MBT) is a NASA concept for taking TBO to the next level of maturity. MBT looks beyond enabling technologies to articulate the operational concept at a lower level of detail and look at how TBO changes the ways in which participants interact. In MBT, each aircraft has an assigned trajectory that is negotiated between the FAA and airspace users, and complies with all National Airspace System (NAS) constraints. Any deviation from the assigned trajectory must be negotiated. By considering both airspace user and FAA objectives, and utilizing negotiated 4-dimensional trajectories (4DTs), MBT is able to seamlessly integrate different types of airspace users and trajectory characteristics into the traffic management plan. As a result, MBT accommodates a broad and expanding spectrum of current and anticipated airspace operations, ranging from traditional commercial aviation to emerging users such as unmanned aircraft systems, space vehicles, and on-demand air transportation vehicles.

Pilots and air traffic controllers use automation to keep the aircraft on its assigned trajectory, which includes complying with temporal or speed constraints. Equipped aircraft have substantial responsibility for complying with the assigned trajectory without controller intervention. Where uncertainty or disruptions occur, resolutions are handled through trajectory modifications as far in advance as possible. This allows MBT to eliminate most local, reactive control actions – which cannot be predicted in advance and have impacts on the downstream trajectory that cannot be known until they occur. MBT does this by inserting the impact of all NAS constraints into the assigned trajectory in the form of trajectory constraints. Where uncertainty remains, necessary adjustments to the trajectory constraints are made proactively, maximizing trajectory predictability and delivering associated benefits.

In MBT, each aircraft's 4DT is composed of a series of trajectory constraints and a trajectory description. *Trajectory constraints* are imposed to help ensure safe and expeditious flows of traffic. A goal of MBT is to minimize the constraints on the trajectory in order to provide the airspace user maximum flexibility. To ensure that the assigned 4DT is a complete description from the aircraft's current state to the destination, MBT also includes the notion of a *trajectory description* that completes the 4DT description when few trajectory constraints are required (see Figure 1). All aircraft are required to follow their 4DTs, complying with all trajectory constraints and the trajectory description, unless first negotiating a revision.

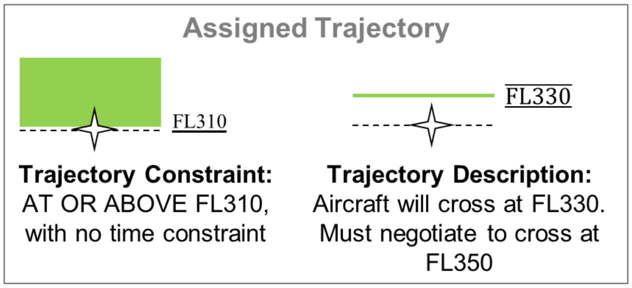

Figure 1. Trajectory Constraint vs. Trajectory Description

The primary benefit of MBT is an improvement in system performance due to increased trajectory predictability and stability, which result from managing traffic in all four dimensions (2D route, vertical, and time) and ensuring that changes to the flight's trajectory are incorporated into the assigned trajectory. This enables ground-based automation to schedule flights further ahead of time, which in turn allows more flights to use their time of arrival control (TOAC) capabilities than is currently feasible.

With more flights able to use TOAC, and improvements in aircraft performance capabilities relative to TOAC, ground-based automation systems can schedule flights with smaller buffers for uncertainty without increasing collision risk probability or tactical interventions, as shown in the simulation results discussed in this paper. Removal of excess separation leads directly to increased throughput and efficiency of the NAS.

Deployment of MBT involves changes to both the NAS Enterprise Architecture and to the roles of human operators. Some of these changes are already planned, while others would be new. For the MBT architecture, additions to data exchange standards and new trajectory negotiation automation software are required. For ATM participants, changes include requirements for:

- Airspace users to provide aircraft intent;
- Controllers and airspace users to engage in trajectory negotiation; and
- All participants to conform to assigned trajectories.

The MBT concept is a framework that fully supports integration of emergent operations, and this effort identified requirements for incorporating such operations into the MBT environment [1, 2, 3]. For example, airspace users are required to provide their aircraft's capabilities to the system, because the characteristics of autonomous and non-conventional vehicles may vary greatly from typical fixed-wing aircraft. FAA systems must be able to process vehicles with new operational profiles. There will be new negotiation automation associated with autonomous aircraft, including logic for when the human operator must be involved. These are enhancements that do not require changes to the MBT concept.

Research Questions

This paper describes a fast-time simulation evaluation of the safety, performance, and efficiency of MBT. The key research questions guiding the analyses described in this document included:

1. How does MBT influence safety risk?
2. How does MBT influence performance in the following areas:
    a. Trajectory prediction accuracy?
    b. Trajectory prediction stability?
3. How does MBT influence efficiency in terms of airspace throughput?

Note that additional questions and metrics were evaluated [4] but for brevity are not reported here.

Method

The analysis was carried out using Mosaic ATM's Metroplex Simulation Environment (MSE), a fast-time simulation environment for evaluating algorithms and operational concepts in the NAS [5]. The simulation used a condition involving en route sequencing and separation of arrivals into Atlanta Hartsfield-Jackson International Airport (KATL), and collected metrics to answer the research questions above. The simulated traffic used actual flight plans for July 7, 2017, archived from the TFMData SWIM feed. This section describes the simulation cases, metrics, and fast-time simulation capability.

Experiment Design

Six simulation environments and three conditions were defined, as discussed in this section.

Simulation Environments

The MBT simulation consisted of six different environments that built on each other. In the *Baseline* environment, aircraft departed at the scheduled time (or according to the Expect Departure Clearance Time [EDCT] in the Ground Delay Program [GDP] condition), and no adjustments were made to their trajectories to ensure spacing.

The *Baseline with Metering* environment added arrival fix metering to the Baseline environment. The metering schedule was developed according to the process described below. Aircraft did not have knowledge of their Scheduled Times of Arrival (STAs), mimicking the current approach to arrival metering in the NAS. In particular, the aircraft flight plan was not updated to reflect the metering STA. Therefore, trajectory predictions were based solely on observed data and the current-day flight plan. ATAs at the meter fix were governed by the current expectation that controllers deliver aircraft within +/- 1 min of their STA while, above all, maintaining at least 5 nm of separation. Aircraft always crossed the fix with at least 5 nm of separation.

In the *MBT* environment, aircraft departed at their scheduled times and had their trajectories adjusted to ensure appropriate spacing at the arrival fix. Assigned trajectories were updated to reflect metering STAs. As in the *Baseline with Metering* environment, ATAs were governed by the current expectation that controllers manage aircraft to meet the STAs within +/- 1 min while maintaining at least 5 nm of separation. The metering schedule was built using the same approach as in the *Baseline with Metering* environment, mimicking a near term implementation in which a distance-based separation standard was used. Any changes to the aircraft trajectories to achieve the metering schedule were in the form of closed trajectories that were known to the automation.

In the *RTP-25* environment, aircraft departed at their scheduled times and had their trajectories adjusted to ensure appropriate spacing at the arrival fix. Assigned trajectories were updated to reflect metering STAs. Aircraft were assigned a required time of arrival (RTA) to meet the STA according to the time interval required to ensure an acceptable collision risk probability associated with their Required Time Performance (RTP) capability (+/- 25 seconds). All aircraft were assumed to have the same RTP value (RTP-25).

To mimic improvements to aircraft capability to achieve greater RTP, two additional environments were used: *RTP-15* and *RTP-10*, in which all aircraft were capable of achieving +/- 15 and +/- 10 seconds, respectively. In both environments, aircraft departed at their scheduled times and had their trajectories adjusted to ensure appropriate spacing at the arrival fix. Assigned trajectories were updated to reflect metering STAs.

Simulation Conditions

Each of the simulation environments was evaluated in 2 weather and 2 GDP conditions.

In the *Clear Weather* condition, aircraft encountered some unpredictability in ground speed due to winds but this was a random effect.

In the *Disruptive Weather* condition, a weather system disrupted flights from the northwest between 11:30 and 13:30, requiring deviations. Flights departing from airports whose departure routes were blocked by the weather were delayed on the ground until the weather cleared.

In addition, some simulation cases included a *GDP* for KATL between 12:00 and 15:00. While the GDP was in place, the average arrival rate (AAR) for Atlanta was reduced from 130 aircraft per hour to 80. The typical AAR of 130 was based on the maximum actual hourly arrivals recorded in ASPM for Atlanta in 2017,[1] and the AAR of 80 during the GDP reduced the capacity enough to introduce delays. Aircraft were

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[1] https://aspm.faa.gov/

assigned an EDCT to reduce demand so it would not exceed the AAR. Affected aircraft departed at their EDCTs; aircraft without EDCTs departed at their scheduled departure time. For brevity, results for the GDP condition are largely omitted from this text; refer to the MBT Preliminary Operational Performance Assessment (pOPA) [4].

Metroplex Simulation Environment (MSE)

MSE provides a software framework for evaluating air traffic concepts and algorithms. MSE supports common aviation data and simulation operations. It uses components called Planners and Executors to perform simulations. Planners create an optimized plan as defined by users in custom plugins. A plan may be as simple as an airport configuration schedule, or as complex as detailed 4DTs for each flight. Planners use aircraft models to generate surface and airborne trajectories. Planners also create metrics for analysis and output display data for future playback.

Executors carry out the optimized plan. Custom executors are defined in plugins. Executors use the MSE Aircraft Model to generate surface and airborne trajectories if necessary. Executors create metrics for analysis and output display data for future playback.

MSE simulations typically consist of planning and execution performed in iterative cycles.

Specific aspects of MSE used to evaluate the benefits of MBT included the implementation of arrival metering for the different simulation environments, as well as implementation of the GDP and the weather and associated reroutes. They also involved the trajectory predictions relative to the flown trajectories.

Trajectories

MSE simulates aircraft movement via trajectories computed according to the algorithms provided in the planners discussed in the previous section. A key piece of information for the MBT simulation was the predicted trajectory at various points in time and the data available to the simulated automated systems to compute the predicted trajectory in each simulation environment. This most directly affected the estimated time of arrival (ETA) prediction accuracy.

At simulation start, all predicted trajectories were based on a 4DT expansion of the flight plan route and scheduled departure time. Predicted departure times were shifted for aircraft that received an EDCT.

As the aircraft traversed its trajectory, its observed position might vary from the predicted position due to wind and other conditions that were modeled as a random disturbance in the ground speed. This was in addition to disturbances associated with metering and weather discussed below.

In the *Baseline* and *Baseline with Metering* environments, trajectory predictions were based on the aircraft's observed position and speed and the flight plan, similar to the current NAS. Except when deviating around weather, the prediction assumed the aircraft would proceed directly to the next fix in the flight plan.

In *MBT* environments, aircraft were kept on closed trajectories. This was particularly important during metering and weather deviation operations, in which the metering STA and/or weather deviation route were incorporated into the assigned trajectory (flight plan). Therefore, these data were available to the system to use in trajectory predictions.

Metering Implementation

In the simulation, speed alone was used to absorb metering delay, even if the required speed was unreasonably low for the aircraft. This served as a proxy for controllers applying vectors to meet the metering time. The amount of time for which the aircraft operated at an unreasonably low speed was considered time spent on an open trajectory.

For each arrival fix, each flight's STA must meet the scheduling restrictions of both the airport/runway schedule and the specific arrival fix schedule. When a flight crossed the freeze horizon (time T_F), the flight's planned trajectory was used to find the planned arrival fix time (T_{SF}) and corresponding runway time (T_{SR}). MSE then attempted to place the flight into the runway schedule at time T_{SR} and into the arrival fix schedule at time T_{SF}. If the runway schedule did not contain an open slot, the time delta (Δ) to the next open slot was computed and added to both T_{SR} and T_{SF}. The arrival fix schedule was then checked for an available slot at $T_{SF} + \Delta$; if not available, the delta was increased to the next available arrival fix schedule opening. This was repeated until open slots were found in the runway schedule (at time T_{SR}') and the arrival fix (at time T_{SF}'). Once satisfied, T_{SF}' became the STA for the flight.

The required time interval in the runway schedule between the current flight looking for a slot and the previous flight in the schedule is based on the airport capacity. The time interval between flights in the arrival fix schedule was computed according to the simulation case (see below); this produced the actual time of arrival (ATA) at the fix.

Once the STA and actual arrival fix crossing time were computed, MSE modified the flight's speeds from the freeze horizon to the arrival fix in order to hit the actual crossing time. In the *Baseline* and *Baseline with Metering* environments, the flight plan trajectory speeds were not modified. In the *MBT* environments, it was assumed that the STA was available for the trajectory prediction and any slow portions of the flight path were assumed to be accounted for to mimic the use of closed trajectory control instructions. Note that incorporating information about the metering STA into the flight plan trajectory did not eliminate all uncertainty, as discussed below.

<u>Computing the Time Interval Between Flights</u>

To simulate controller delivery of aircraft to the meter fix without use of TOAC, flights in the *Baseline*, *Baseline with Metering*, and *MBT* environments maintained a desired separation distance of D_D = 7.5 nmi, a minimum separation distance of D_M = 3.3 nmi[2], with a controller reliability for maintaining that minimum separation of CR = 0.9999 and a ground speed of S_G (computed from the indicated airspeed [IAS] required at the arrival fix and accounting for winds). With these values, a mean time interval and standard deviation were computed. The mean time interval was used for arrival fix scheduling, and the actual time the aircraft reached the arrival fix was pulled from a normal distribution created from the mean time interval and the standard deviation. To simulate a controller prioritizing maintaining safe separation over meeting the metering STA, the arrival slot for the flight was specified using the actual time of arrival rather than the scheduled time, so that subsequent flights followed the actual traffic flow rather than the scheduled traffic flow through the fix.

For the *RTP-10*, *RTP-15*, and *RTP-25* environment, the collision risk probability required that the arrival fix time interval between flights was 45 seconds for RTP-10, 68 seconds for RTP-15, and 108 seconds for RTP-25. This time interval was used to set the STA, and the actual time of arrival at the fix was the STA plus a random value from a normal distribution with a mean of 0 and standard deviation of 5, 10, or 15 s for RTP-10, 15, and 25, respectively.

Weather Implementation and Reroutes

Obstructive weather was simulated as a stationary polygon with a start and end time. Enroute flights inside the weather polygon at the time of activation were considered "unaffected" and could continue normally. Flights on the ground scheduled to depart from an airport within the active weather polygon, whose trajectories traversed the polygon, were delayed until the end of the weather event. Flights enroute with trajectories through the active weather polygon were rerouted around the polygon following the shortest path. The rerouted path started at the last fix before entering the weather polygon (or the flight's current position if it happened to be closer to the polygon than the fix) and finish at the first fix outside and past the weather polygon. Aircraft that had not departed whose trajectories traversed the weather polygon that could be rerouted around the weather were given a reroute and allowed to depart. These reroutes were treated as “closed” trajectory flight plan amendments in all simulated environments.

In the *Baseline* and *Baseline with Metering* environments, the portions of the re-route that were moving away from or tangential to the original flight path were marked as "open" trajectory sections, with the remaining portions heading back to the original flight path being marked as "closed". In the *MBT* environments, all portions of the reroute were considered to be known and marked as "closed."

Simulation Metrics

The metrics used in this assessment fell into three inter-related categories: safety, performance, and efficiency. The acceptable probability of collision risk was held constant [6], ensuring that safety was not jeopardized by changes in performance and efficiency.

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[2] Based on an analysis identifying the separation that triggered an event.

Safety Metrics

Two metrics were used to quantify safety risk. The first was the number of loss of separation (LOS) events, and the second was the probability of a collision. Each metric evaluated events that represent potential effects at different levels of severity [7].

Loss of Separation (LOS) Events

The number of LOS events observed represented the number of times a controller would be expected to intervene, a proxy for the level of controller workload required to separate air traffic, and a common safety metric used in FAA safety assessments.

Collision Risk

Time-based collision risk models estimate the likelihood of a collision based on several relevant variables. When two aircraft are scheduled to cross the same three-dimensional point in space, the most sensitive variable influencing collision risk is the separation interval, defined as the amount of time scheduled between the two aircraft. The likelihood of the aircraft arriving at the same point at the same time (i.e., a collision event) when they are scheduled to arrive at discrete times is also dependent on how accurately the aircraft can achieve their assigned crossing times. The size of the aircraft and the speed at which the aircraft is traveling through the intersection are also variables that contribute to the probability of collision.

If the distribution of error in each aircraft's arrival time is known, then the likelihood of collision can be determined mathematically. Figure 2 depicts the problem, in which aircraft J and aircraft K are assigned crossing times at a common fix, with the amount of time between the two scheduled crossings identified as the separation interval. As aircraft time performance improves, the shape of the error distribution (i.e., variance) will narrow, lowering the probability of overlap between the two aircraft arrival times. Similarly, as the interval between the aircraft is increased, the probability of overlap is also reduced.

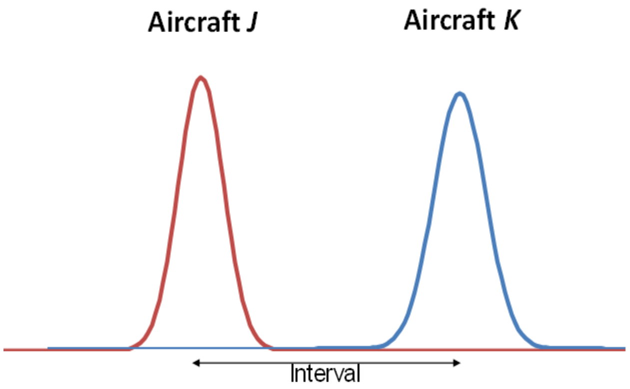

Figure 2. Collision Risk Probability

Performance Metrics

The performance metrics for the MBT simulation included both aircraft and air traffic control (ATC) automation system performance. Time on an open trajectory, ETA predictability, and ETA stability were measured. The aircraft RTP was a simulation input. See the MBT pOPA [4] for discussion of how time on an open trajectory was measured and results for that metric.

Estimated Time of Arrival (ETA) Predictability

One expectation is that MBT will improve trajectory predictability by keeping aircraft on closed trajectories that provide a complete trajectory prediction from the aircraft's current location to the destination. Improved trajectory predictability is a key MBT benefit mechanism that enables controllers to use strategic, closed clearances that involve more efficient adjustments to an aircraft's trajectory to achieve NAS objectives. Enhanced predictability also improves demand predictions used by traffic flow management (TFM) to manage demand relative to capacity and provide a more consistent flow of air traffic, reducing delay.

Trajectory predictability was measured using ETA prediction error, calculated as the absolute difference in minutes between the ETA and ATA, with the ETA measured at different points prior to crossing the arrival fix.

Estimated Time of Arrival (ETA) Stability

In the current NAS, represented in the simulation by the *Baseline* and *Baseline with Metering* environments, one might see ETA predictions incrementally shift closer to the actual time of arrival as a flight gets closer to the prediction location (in our case, the meter fix). Therefore, while the ETA might change significantly between the original and final predictions, there may not be large jumps in estimates from one prediction to the next. This metric investigated whether the additional information available in an MBT environment might lead to greater shifts in time estimates between consecutive predictions. ETA stability impacts the practical utility of MBT, because predictions that are highly volatile will be less useful to decision-makers.

We measured stability by calculating the average absolute value of change between consecutive ETA predictions for each flight, generating one value per simulated flight. Using the average ensured that flights were weighted equally regardless of the number of ETA predictions made.

Required Time Performance (RTP) Metric

The RTP metric establishes a convention for quantifying aircraft expected crossing time errors for use in sequencing and separation. This convention has the added benefit of providing an intuitive means by which human operators may interpret the relative performance levels of various aircraft operating in the airspace. It also provides guidelines for industry with respect to the design of avionics intended to support trajectory-based operations.

The RTP metric improves upon the TOAC standard described in RTCA DO-236C [8], which prescribes a minimum performance requirement for Total Time Error (TTE) of 10 seconds in descent operations and 30 seconds for cruise operations, with a 95% confidence level. This standard was intended to produce safe operations. Unfortunately, DO-236C created a mixed equipage environment, requiring two fundamentally different forms of air traffic management - one for aircraft that meet the standard and another for those that don’t. Also, the descent environment is very dynamic, with rapidly changing air density, temperature, and winds.

RTP can be applied to indicate any aircraft’s expected TTE. By taking this approach, a mixed equipage problem is avoided and all IFR aircraft can be managed under a single ATM concept. An interval can be assigned between any aircraft pair such that efficiency is optimized while maintaining an acceptable level of safety risk.

The RTP metric has significant advantages over previously documented TOAC standards that fail to control the shape of the underlying error distribution [9]. Flight tests and simulations have demonstrated that proprietary algorithms used by avionics manufacturers to achieve an RTA may result in consistently early or late arrivals, even if performance meets the minimum standard. If multiple manufacturers produce systems that achieve certification through individual system testing, there is a potential for introducing unacceptable collision risk into the system if those aircraft are then combined operationally with other aircraft that display opposite tendencies. In contrast, the RTP metric provides control over the error distribution and accounts for any non-zero average crossing time error.

In both name and function, RTP serves as a complement to existing standards used to describe Required Navigation Performance (RNP), and in the same way RNP communicates navigation performance, RTP is formulated with a variable associated with it. If Y is assigned as a variable to represent this value in an RTP-Y format, the value of Y can be set as:

$$Y = 2*(\mu + \sigma)$$

where μ represents the mean and σ represents the standard deviation of the long-term expected crossing time error distribution of an aircraft.

An advantage of the RTP metric is that it supports scheduling the interval between aircraft according to their quantified error distribution about the STA. As shown in the simulation results below, the current TOAC standard of +/- 30 sec on cruise may require increasing the schedule interval relative to the current distance-based separation standard. On the other hand, scheduling according to the +/- 10 sec TOAC standard for descent may decrease the scheduling interval relative to the current distance-based standard.

Efficiency Metrics

The simulation measured NAS efficiency (e.g., throughput) and individual flight efficiency (e.g., flight time) effects of the MBT environment. See the MBT pOPA [4] for discussion of aircraft flight time.

Airspace Throughput

Increasing airspace throughput allows the NAS to service demand at a higher rate, decreasing delays. We evaluated throughput by examining the number of flights crossing individual arrival fixes within different 15-minute windows throughout the day, and compared descriptive statistics related to the maximum number of flights that could pass through the fix during any 15-minute window. Because the *Baseline* cases in the simulation show what would have occurred in the absence of any controller intervention to maintain separation, the *Baseline* throughput results act as an upper bound on the potential throughput for a fix, and not on the actual achievable capacity.

Results

This section provides the simulation results and analysis comparing the safety, performance, and efficiency across the simulated environments in each condition.

Loss of Separation (LOS) Events

LOS events were calculated separately for each arrival fix; results from the CHPPR fix in Clear Weather are presented here for brevity. Other results can be found in the MBT pOPA [4].

We estimated the likelihood of LOS by computing the percentage of flights in reasonable proximity to each other (i.e., separated by less than 20nm[3]) that crossed the fix within 0, 3.3, 5, and 7.5nm of each other. In addition, because some *MBT* environments used time-based separation, we calculated the proportion of close-proximity flights (those separated by 120 seconds or less at an arrival fix) that crossed the fix within 0, 30, 60, and 90 seconds of each other.

The total number of LOS events across each fix was compared between cases. Figure 3 shows the distribution of separation distances for flights crossing the CHPPR fix in each environment in the Clear Weather condition. The *Baseline*, *Baseline with Metering*, and *MBT* environments are shown in red and the *MBT RTP-25*, *-15*, and *-10* environments are shown in blue.

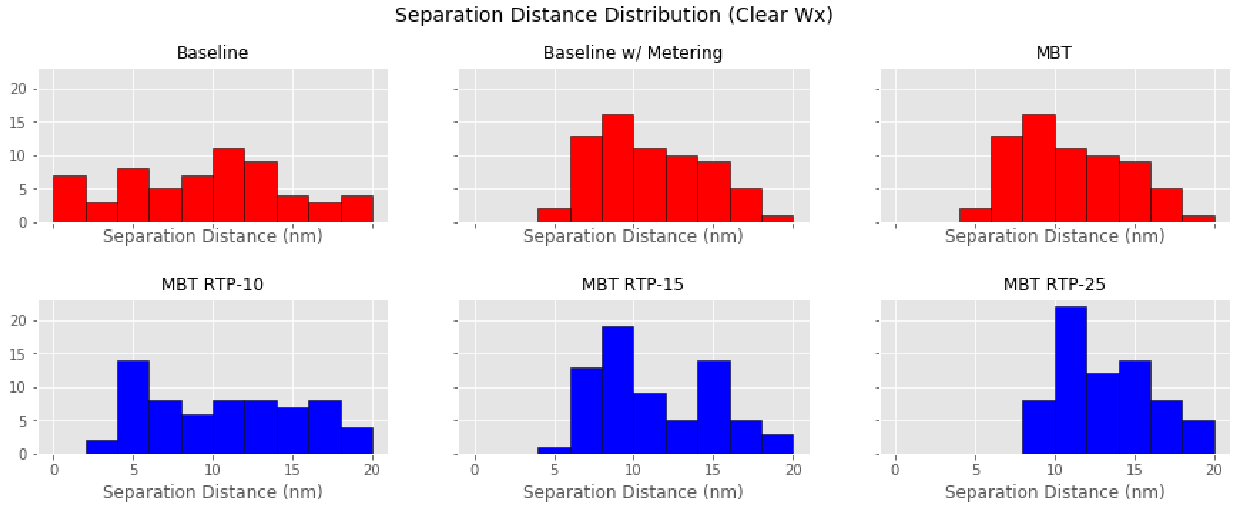

Figure 3. CHPPR Arrival Fix Separation Distances, Clear Weather Condition

As noted above, the *Baseline* environment did not involve controller intervention or arrival metering to create and/or maintain separation. Thus, the distribution of separation distance in the Baseline environment represents the "natural" demand, and shows that several flights would have crossed with less than 7.5 nm of separation without controller intervention to create spacing. The reduction of flights crossing so close to one another in the *Baseline with Metering* and *MBT* environments reflects the utility of scheduling (time-based metering) in supporting controllers in maintaining spacing.

The *MBT RTP-10*, *-15*, and *-25* environments are shown in blue because they should be interpreted differently from the other environments. Scheduling at the arrival fix was based on a time-based separation

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[3] It was assumed that flights that crossed the fix with more than 20 nm separation reflected a low-demand situation that would not require significant controller action to maintain separation.

standard in these environments and not a distance-based standard. That is, the performance capability associated with RTP-10 aircraft allowed scheduling aircraft using a time interval that corresponded to less than 5 nm separation distance but an acceptable collision risk probability.

Table 1 provides the cumulative percentage of LOS events in the Clear Weather condition. Similar to the figures above, in the *Baseline*, *Baseline with Metering*, and *MBT* environments a distance-based separation standard was assumed. The data reflect a significant reduction in the number of LOS events in the *Baseline with Metering* and *MBT* environments relative to the *Baseline* environment. However, the number of LOS events is equivalent in the *MBT* and *Baseline with Metering* environments. This result was expected, since the scheduling approach was the same for the two environments; the key difference was the trajectory information available during metering operations, which affected trajectory predictability.

Table 1. Cumulative Percentage of LOS Events in Clear Weather, CHPPR Arrival fix

	Baseline	**Baseline with Metering**	**MBT**	***MBT RTP-10***	***MBT RTP-15***	***MBT RTP-25***
0 nm	0.0%	0.0%	0.0%	*0.0%*	*0.0%*	*0.0%*
3.3 nm	14.0%	0.0%	0.0%	*12.9%*	*0.0%*	*0.0%*
5 nm	16.1%	15.3%	15.3%	*15.2%*	*0.0%*	*0.0%*
7.5 nm	19.2%	18.9%	18.9%	*18.5%*	*18.1%*	*0.0%*

Estimated Time of Arrival (ETA) Predictability

ETA predictability analyses used predictions made within the freeze horizon 250nm from the arrival metering fix. Linear mixed models were constructed to estimate the prediction error as a function of a flight’s distance from the arrival fix, the environment, and the interaction between distance and environment.

The box plots in Figure 4 show the prediction error for each environment in each of the three conditions. Overall, errors tended to be because the predicted ETA was earlier than the ATA, as indicated by the majority of all boxplots lying below the horizontal dotted line representing 0 error. From the spread of the boxplots, we can see that the errors tended to be larger for the *Baseline with Metering* environment than the other environments, and that this was particularly pronounced in the Disruptive Weather condition.

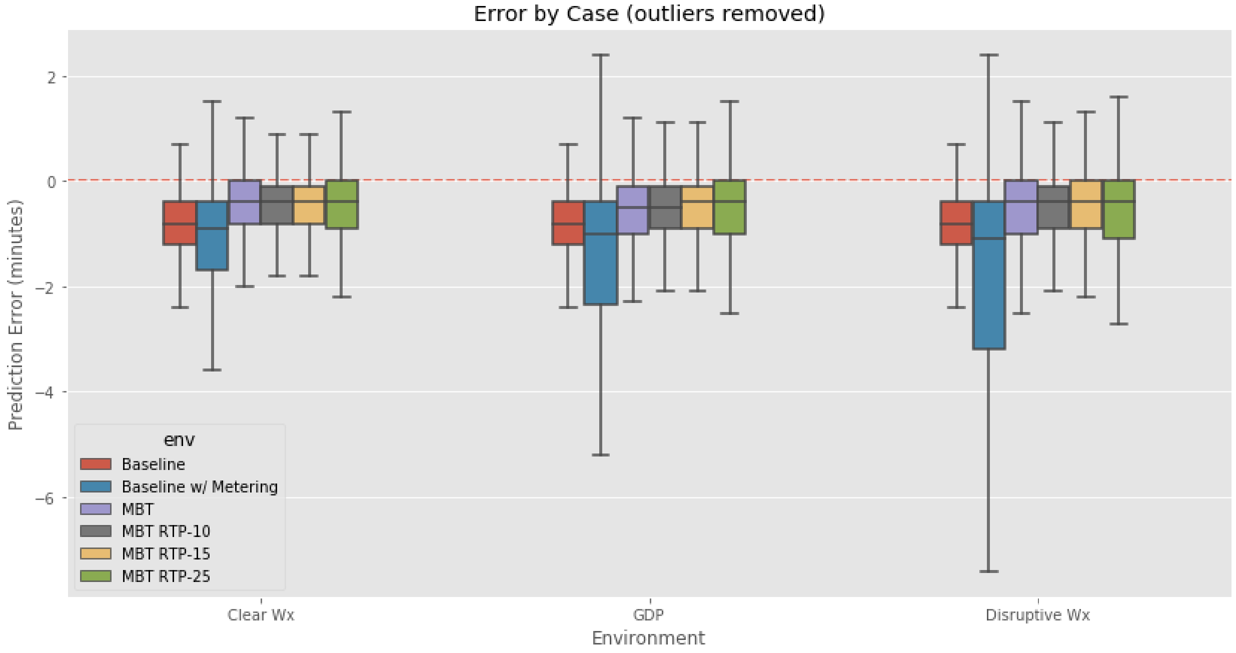

Figure 4. Prediction Error across all Predictions Made for all Simulated Flights

The scatterplot in Figure 5 shows the prediction error for the *Baseline with Metering* (red dots) and *MBT* (blue dots) environments in the Clear Weather condition. It is evident that the magnitude of ETA prediction error was much larger in the *Baseline with Metering* environment than in *MBT*. Flights in the *MBT* environment had consistently low error from the freeze horizon to the arrival fix, with only slightly greater prediction errors at the freeze horizon than close to the arrival fix. The number of large errors was much smaller than in the *Baseline with Metering* environment; the vast majority of ETA predictions in *MBT* were off by a couple of minutes at most. Thus, it appears that *MBT* yielded greater prediction accuracy at greater distances than *Baseline with Metering*,. This result held across the simulation cases [4].

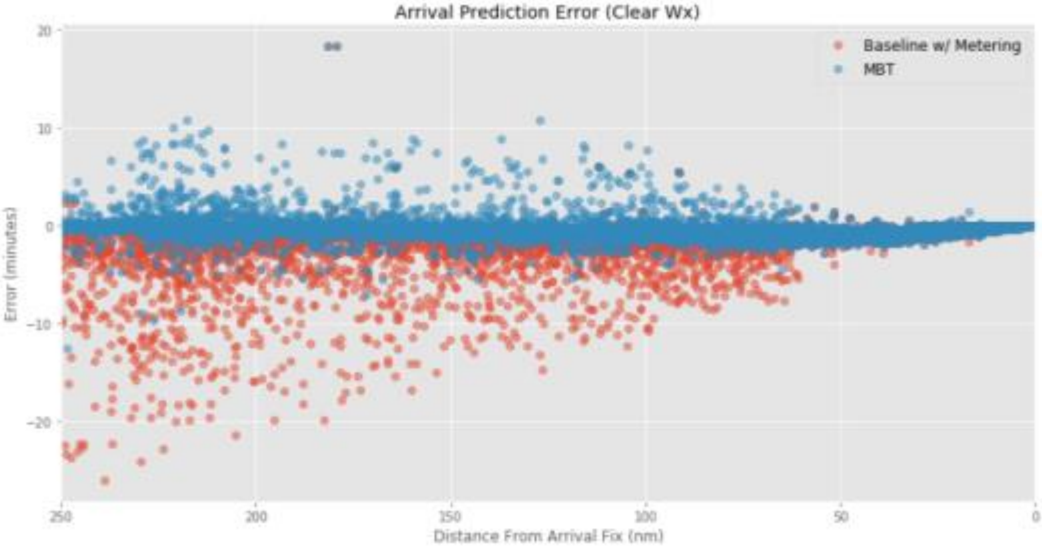

Figure 5. Arrival Prediction Error vs. Distance from Fix for Baseline with Metering and MBT Environments, Clear Weather

Linear Mixed Regression Models

To verify whether the effects of MBT on trajectory predictability hold when controlling for differences between flights, and to investigate the effects of the other environments on prediction accuracy, absolute ETA predictability was estimated using linear mixed regression models that estimated the absolute prediction error for a given ETA prediction as a function of a flight's distance from the arrival fix at the time the prediction was made, the environment in which the flight was operating, and the interaction between these two variables.

A mixed modelling, or hierarchical, approach was used in which predictions were nested within flight simulations to control for the correlation between predictions made for the same simulated flight at different time points. This is similar to a standard linear regression model, except that there is flexibility for data points to be non-independent or hierarchically-structured. Since we can accommodate all predictions for each flight in a single regression model, we are not restricted to comparing predictions made at similar distances from the fix. This is particularly useful because both the number of ETA predictions and the distance at which they were made (relative to the arrival fix) varied between flights.

One regression model was constructed for each of the three conditions (Clear Weather, GDP, and Disruptive Weather). The *Baseline* environment was used as the reference class in all three models. For brevity, the reader is referred to the MBT pOPA [4] for results from the GDP condition.

The models were specified as follows, where y_{ij} equals the absolute prediction error for ETA prediction i for simulated flight j (a flight within a specific environment):

$$\begin{aligned} y_{ij} = \beta_0 + \beta_1 * distance_{ij} + \beta_2 \\ * baseline\ with\ metering + \beta_3 \\ * MBT + \beta_4 * MBT\ RTP10 + \beta_5 \\ * MBT\ RTP15 + \beta_6 * MBT\ RTP25 \\ + \beta_7 * distance_{ij} \\ * baseline\ with\ metering + \beta_8 \\ * distance_{ij} * MBT + \cdots + \beta_{11} \\ * distance_{ij} * MBT\ RTP25 + u_j \\ + \varepsilon_{ij} \end{aligned}$$

In the model, u_j represents a random intercept for simulated flight j. The coefficient on the distance from arrival fix at which the ETA prediction was made (β_1) indicates the increase in ETA prediction error due to a 1nm increase in distance from the arrival fix in the *Baseline* environment. The coefficients of the environment variables ($\beta_2, \ldots, \beta_6$) represent the typical difference in ETA prediction error across all predictions for flights in one environment (e.g., *MBT*) compared to the *Baseline* environment. The coefficients on the interaction terms ($\beta_7, \ldots, \beta_{11}$) represent the difference in ETA prediction error associated with a 1nm increase in distance in the non-*Baseline* environments. These coefficients, known as fixed effects, were estimated across all ETA predictions in all flights used in each model. In addition, a random intercept was calculated for each simulated flight (which controls for a linear difference in the errors across ETA predictions for an individual flight). We report the model results and results of paired comparisons between the fixed effects of operationally relevant pairs of environments. This tells us the average difference in prediction error between environments and whether there was a statistically significant difference in prediction error in the different environments.

Linear regression results and paired comparisons for the Clear Weather condition are presented in Table 2 and Table 3. Only operationally relevant pairs are included in Table 3. In Table 3, statistically significant results at the mean distance from the arrival fix across all predictions are in *italicized* text and highlighted in gray. From the tables, we can see that in Clear Weather, *MBT* had lower prediction errors than the *Baseline*, *Baseline with Metering*, and *MBT RTP-25* environments, and slightly greater errors than *MBT RTP-10* and *MBT RTP-15*.

The reader is referred to the MBT pOPA [4] for results in the GDP and Disruptive Weather conditions.

Table 2. Clear Weather Absolute ETA Prediction Error Linear Mixed Effects Model Results

Fixed Effects	Estimate (SE)	T-statistic
Intercept	0.56 (0.03)	16.02

Environment: Baseline w/ Metering	-0.42 (0.05)	-8.96
Environment: MBT	-0.05 (0.05)	-1.05
Environment: MBT RTP-10	-0.01 (0.05)	-0.28
Environment: MBT RTP-15	-0.01 (0.05)	-0.30
Environment: MBT RTP-25	-0.06 (0.05)	-1.32
Distance from Arrival Fix	0.00 (0.00)	14.29
Distance * Environment: Baseline w/ Metering	0.01 (0.00)	36.26
Distance * Environment: MBT	0.00 (0.00)	-2.45
Distance * Environment: MBT RTP-10	0.00 (0.00)	-5.43
Distance * Environment: MBT RTP-15	0.00 (0.00)	-5.97
Distance * Environment: MBT RTP-25	0.00 (0.00)	2.58
Variance of Random Effects	Variance (SD)	
Simulation ID	0.65 (0.81)	
Residual	1.13 (1.06)	
Number of Observations	42,127	
Number of Simulation ID Groups	8,071	

Table 3. Clear Weather ETA Prediction Error Case Comparisons at 110.74nm from Arrival Fix

Comparison	**Estimate (SE)**	**Z-ratio**	**P-value**
Baseline - Baseline w/ Metering	*-0.66 (0.04)*	*-17.76*	*<.0001*
Baseline - MBT	*0.12 (0.04)*	*3.28*	*0.013*
Baseline w/ Metering - MBT	*0.78 (0.04)*	*21.79*	*<.0001*
MBT - MBT RTP-10	0.05 (0.04)	1.48	0.677
MBT - MBT RTP-15	0.07 (0.04)	1.95	0.370
MBT - MBT RTP-25	*-0.14 (0.04)*	*-3.80*	*0.002*
MBT RTP-10 - MBT RTP-15	0.02 (0.04)	0.47	0.997
MBT RTP-10 - MBT RTP-25	*-0.19 (0.04)*	*-5.27*	*<.0001*
MBT RTP-15 - MBT RTP-25	*-0.21 (0.04)*	*-5.75*	*<.0001*

Estimated Time of Arrival (ETA) Stability

Figure 6 shows the distribution of average absolute ETA prediction differences for all flights in a condition-environment combination. The black dotted vertical lines show the average value across all flights in each case. These results show that although there were slightly larger tails on the distributions in the *MBT* and *MBT RTP* environment, on average, predictions did not jump by significantly larger amounts than in the *Baseline* condition. While this does not indicate the overall magnitude of change in predictions, it does indicate relative stability from one prediction to the next, with predicted arrival times changing by an average of less than 2 minutes even in the least stable case (*MBT RTP-25* with Disruptive Weather).

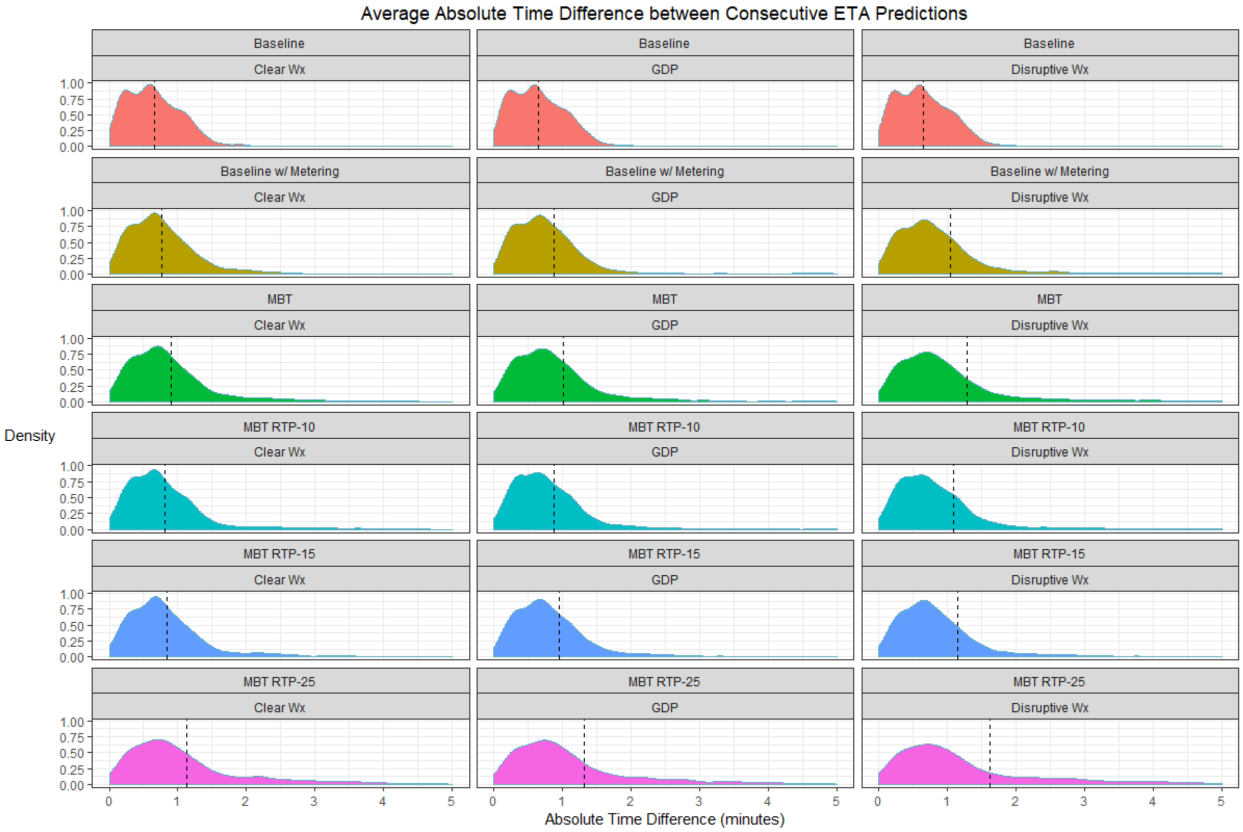

Figure 6. Distribution of Average Absolute Time Differences between Consecutive ETA Predictions

Paired comparisons between operationally relevant pairs of environments within the Clear Weather condition are reported in Table 4. Pairs with a statistically significant difference in average absolute ETA prediction changes are shown in *italic text* and highlighted in gray. The *Baseline* and *Baseline with Metering* environments showed greater stability than the *MBT* environment, as did *RTP-10*. Note that a key feature of the *MBT* environments was that the trajectory predictions were informed of the flight's STA when it was assigned; thus, a jump in the flight's ETA was expected at the time that the flight crossed the freeze horizon. According to our stability metric, this is an indicator of decreased stability relative to the *Baseline* and *Baseline with Metering* environments, in which the trajectory predictions were not informed of the STA and gradually drifted toward the STA as the aircraft modified its speed to meet the STA. However, as shown above, the MBT environments showed increased ETA predictability as soon as the flight crossed the freeze horizon.

Results for the GDP and Disruptive Weather conditions were similar [4].

Table 4. Clear Weather Stability Comparisons

Comparison	**Estimate (SE)**	**df**	**T-statistic**	**P-value**
Baseline - Baseline w/ Metering	*-0.11 (0.03)*	*8070*	*-4.56*	*0.0001*
Baseline - MBT	*-0.25 (0.03)*	*8070*	*-9.96*	*<.0001*
Baseline w/ Metering - MBT	*-0.14 (0.03)*	*8070*	*-5.40*	*<.0001*
MBT - MBT RTP-10	*0.09 (0.03)*	*8070*	*3.41*	*0.009*
MBT - MBT RTP-15	0.07 (0.03)	8070	2.66	0.084
MBT - MBT RTP-25	*-0.22 (0.03)*	*8070*	*-8.84*	*<.0001*
MBT RTP-10 - MBT RTP-15	-0.02 (0.03)	8070	-0.75	0.976
MBT RTP-10 - MBT RTP-25	*-0.31 (0.03)*	*8070*	*-12.24*	*<.0001*

MBT RTP-15 - MBT RTP-25	*-0.29 (0.03)*	*8070*	*-11.49*	*<.0001*

Airspace Throughput

For brevity, only results for CHPPR in the Disruptive Weather condition are shown here; the remaining results can be found in the MBT pOPA [4]. Figure 7 shows the cumulative number of flights crossing CHPPR in the Disruptive Weather condition. The spike in throughput in the *Baseline* environment (red line) at 13:45 shows the increase in demand after the weather cleared. This illustrates how the other environments metered demand to reduce the number of LOS events as discussed above.

The *MBT* environment (periwinkle line) showed similar throughput to *Baseline with Metering*, indicating that MBT did not increase throughput. Most notably, however, throughput was lower in the *MBT RTP-25* environment. This is important because RTP-25 represents a small improvement in aircraft TOAC performance over the current standard, indicating that using current TOAC capabilities would require a decrease in throughput to maintain a consistent target level of safety.

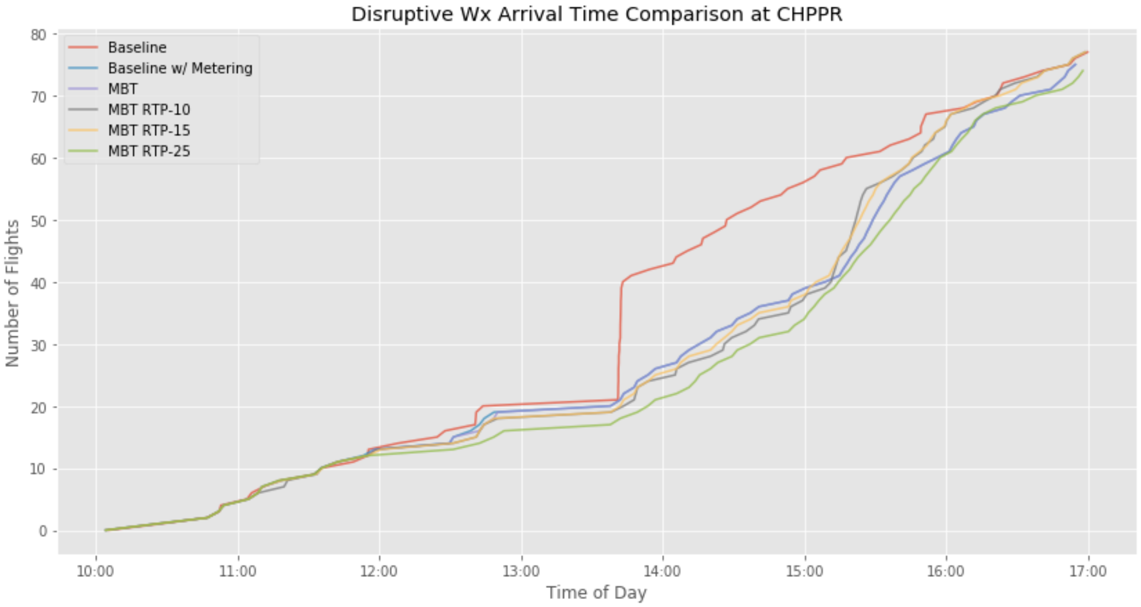

Figure 7. Cumulative Number of Flights Crossing CHPPR in Disruptive Weather Condition

Conclusion

MBT did not increase safety risk. The safety metrics – LOS events and inter-arrival times – did not change with the *MBT* environment. The *MBT RTP-25* environment reduced separation losses and increased inter-arrival times, reducing the safety risk. However, this came at the cost of reduced efficiency. On the other hand, the *MBT RTP-10* environment reduced inter-arrival times without increasing collision risk probability, increasing airspace efficiency.

MBT also showed a significant effect on the performance metrics – trajectory prediction accuracy and stability and time spent on a closed trajectory. In all conditions, MBT had lower prediction errors than the *Baseline with Metering* environment, indicating that the increased trajectory information associated with MBT supported more accurate trajectory predictions. These more accurate trajectory predictions came without decreasing the stability of the predictions relative to the Baseline environment.

MBT did not show a significant effect on throughput. The *RTP-25* environment, however, significantly reduced throughput, indicating that applying the current aircraft performance standard for RTA that requires aircraft to arrive within +/- 30 sec may reduce efficiency relative to the current (*Baseline*) environment.

Whereas MBT did not significantly affect throughput, an open question is whether it improves the ability for the ATM system to respond more effectively when new capacity becomes available.

Collision Risk versus Separation Distance

In the *MBT RTP-10, -15,* and *-25* environments, aircraft certified to operate at RTP-10, 15, and 25, respectively, were sequenced by time using a TOAC function. In each of these cases, the simulation design consisted of a sample in which all aircraft operated at the same RTP level, and based on collision risk modeling, the aircraft were assigned crossing times that satisfied a minimum time-based interval necessary to achieve the desired level of safety risk. This method of managing aircraft leads to operations in which all aircraft are assigned crossing times that satisfy a minimum interval based on their performance. Further, these crossing times are independent of both environmental conditions and any published restrictions such as crossing speed or altitude.

The simulation results show that because RTP-10 aircraft were scheduled to cross the arrival fixes with significantly lower time intervals than RTP-15 aircraft, and dramatically less than RTP-25, their actual crossing times led to reduced separation distance. However, the results also show that *none of the MBT operations resulted in adverse safety events*, and based on the inter-arrival times at all fixes and for all aircraft, collision risk was relatively constant regardless of the separation distance. The results also indicated the MBT concept meets or exceeds the target level of safety established by FAA policy for both general and commercial aviation operations.

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