Integrated Time-Based Management and Performance-Based Navigation Design for Trajectory-Based Operations

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Abstract— The Federal Aviation Administration (FAA) is in the process of developing and deploying a concept called Trajectory-based Operations (TBO), which, among other goals, aims to provide greater predictability and efficiency to flights by increasing the use of Performance-based Navigation (PBN) procedures and Time-based Management (TBM). To fully achieve the benefits from TBO operations, PBN procedure designs and TBM designs must be tightly integrated. To achieve some of the initial TBO objectives that have been identified (i.e., improvements in throughput, predictability, flight efficiency, and flexibility), the research presented here makes the case that PBN and TBM design must be considered together. An integrated design philosophy is needed to ensure: PBN procedures support Air Traffic Control (ATC) in managing trajectories using speed control only; TBM adaptation yields feasible schedules and accurate information for ATC’s management of flights; and predictable paths support pilots’ energy management task throughout the arrival and approach. This paper will outline the case for creating an integrated PBN and TBM design process and associated tools to help ensure TBM and PBN goals can be fully realized. The paper also includes three design examples that demonstrate the need for an integrated design process and supporting design tools.

Keywords - Trajectory Based Operations, Performance Based Navigation, Time Based Management

I. INTRODUCTION

The Federal Aviation Administration (FAA) and other Air Navigation Service Providers (ANSPs) are making strategic investments to transform their operations to better meet the increased demand for Air Traffic Control (ATC) services and to also provide increased efficiencies for users and service providers. One of the major transformations in this domain expected over the next decade, is a shift towards Trajectory Based Operations (TBO) which emphasizes more proactive air traffic management decision making as opposed to relying exclusively on reactive decisions. This is enabled by improved data which is used to generate a strategic plan reflected via a four-dimensional trajectory that serves as a reference for the flight. TBO is a fundamental part of the International Civil Aviation Organization Global Air Traffic Management Operational Concept [1] and consists of several new processes and procedures which will enable ANSPs to safely accommodate increased traffic, while still providing world class safety, efficiency, and the ability to accommodate user preferences. TBO is envisioned to apply to all phases of flight and some surface operations [2] and is dependent on several enabling technologies (ground and flight deck-based capabilities), a new route structure (i.e., Performance Based Navigation [PBN] procedures and routes), and changes to existing policy and procedures key to the transition from distance-based operations to time-based operations [4]. To achieve this, ANSPs have deployed numerous PBN procedures and routes, and some PBN-equipped aircraft operators have already started to realize benefits. However, full utilization of PBN will only be achieved after PBN and ground-based air traffic management decision support tools (DSTs) are fully integrated; achieving this tightly coupled integration is foundational to achieving TBO objectives.

In the United States (US), the FAA is implementing TBO to manage traffic in high-density or high-complexity airspace. Initial TBO implementation initiatives are focused on integrating Time-Based Management (TBM) and PBN; together they define the four-dimensional trajectory (latitude, longitude, altitude, and time) for a given flight. TBM consists of Air Traffic Control (ATC) automation that determines Scheduled Times of Arrival (STAs) (or targeted crossing times) for each flight at designated constraint points (or meter points) in the airspace and ATC managing flights to those STAs using DSTs. Because STAs are defined to result in deconflicted spacing intervals at key points in the airspace, TBM enables ATC to efficiently precondition merging arrival flows. Flight-deck PBN capabilities enable aircraft to fly predictable and repeatable trajectories and aircraft equipped with Required Navigation Performance (RNP) avionics fly PBN procedures with shorter paths to the runway. A key operating assumption of initial TBO is to leave flights on their assigned PBN routes and procedures and manage flight spacing primarily through speed control. Initial TBO also aims to better utilize existing advanced flight-deck capabilities (e.g., Required Time of Arrival functions in the Flight Management System) to manage flights to their STAs.

The current process of integrating PBN procedure design entails an iterative process of performing the PBN airspace design, adapting that design into the TBM systems, refining adaptation and settings, and occasionally performing Human-in-
the-Loop simulations in a laboratory environment to validate the full operational design. Design acceptance is largely based on qualitative assessments by operational and system experts. While this approach has been successfully used, it is time and resource intensive.

This paper presents the motivation for an integrated TBM and PBN design capability. We begin by describing the evolution of arrival time-based metering, procedure development, and their relationship to the overall TBO goals. Next, the interdependency between TBM adaptation design and PBN design is discussed. This is followed by a detailed description of the architecture and functional components of a proposed integrated TBM and PBN design capability. Finally, a set of example applications demonstrate how this capability could support PBN and TBM design activities.

II. RESEARCH BACKGROUND

TBM requires ground-based planning tools that assist the controller in managing aircraft to their STAs, ensuring the safe and efficient flow of inbound traffic into an airspace and airport. TBM tools depend on a complex set of static and dynamic site-specific parameters and logic (e.g., general airspace, routing, runways, and scheduling constraints) that can adapt the arrival management tool for use at an ATC facility with unique operational needs and constraints. The airspace design and associated procedures (i.e., PBN-enabled Standard Terminal Arrival [STAR] and Instrument Approach Procedures [IAPs]) used by the TBM tools play a key role in their effectiveness and must be appropriately adapted.

This section provides an overview of the current and near-term TBM DSTs along with processes for adapting the tools and for creating the arrival and approach procedures.

A. Time Based Management (TBM)

Time-based scheduling of arrival flows is not a new concept in air traffic management. In the US, the original concept of metering goes back to at least the mid-1970’s with the development of the En Route Metering (ERM) program. The ERM program (1970’s-80’s) was based on a simple concept of proactively spacing flights in en route airspace based on projected demand to avoid excessive holding and vectoring near the destination airport. The second-generation metering tool was an evolution of the ERM system into the first national metering program called Arrival Sequencing Program (ASP) (1980’s-90s), which introduced low-fidelity aircraft trajectory prediction calculations as part of the scheduling.

The current generation Time-Based Flow Management (TBFM) system comprises the key scheduling and schedule-management functions. TBFM is based on the Traffic Management Advisor (TMA) [6] system, largely developed by the National Aeronautics and Space Administration (NASA).

TMA was a component of the Center–Terminal Radar Approach Control (TRACON) Automation System, a suite of air traffic management tools developed at NASA Ames Research Center [6]. The system was adopted by the FAA and was first deployed in the early 2000s. Since that time, the TMA system continued to expand and evolve. In 2003, the Adjacent Center Metering capability was developed, which allowed multiple en-route systems to provide input to TMA, effectively removing center boundaries for traffic management purposes. In 2006, the En-route departure capability (EDC) was added, extending the metering concept to managing departures. By August 2007, TMA was deployed at all Air Route Traffic Control Centers (ARTCCs) in the US. TMA evolved into what is now called TBFA, which included a complete re-architecture and modernization of the technology.

In addition to the current generation TBFM technologies, there are plans to implement the Terminal Sequencing and Spacing (TSAS) capability, also based on NASA research [15]. TSAS enhances TBFM to apply time-based metering operations in the terminal environment with the objective of reducing tactical decision-making related to aircraft sequencing and spacing and to enable mixed equipage use of curved-path PBN procedures (i.e., procedures including Radius-to-Fix [RF] legs) and more traditional PBN and Area Navigation (RNAN) procedures (i.e., procedures that only contain Track-to-Fix [TF] legs). TSAS achieves these objectives by displaying information that assists terminal controllers in meeting STAs at Terminal Meter Points (TMPs).

As indicated in Figure 1, with each evolution, starting from the original ERM/ASP metering to current generation TMA/TBFM and moving towards planned next generation technologies [11], there is a shift to more precise trajectory prediction and scheduling methodologies to achieve operational objectives. This increased precision relies on increasing congruence between the arrival management system adaptation and published procedure conformance.

Although this paper focuses on US TBM systems (i.e., TBFM) and their evolution under the FAA’s Next Generation Air Transportation System program, prevalent use of arrival management technologies also exists in Europe and there is emerging use in Asia. Unlike in the US, Europe has a variety of arrival management systems available with different levels of functionality [16]. Some arrival management DSTs currently in operation, such as the “Means to Aid Expedition and Sequencing of Traffic with Research of Optimization” (MAESTRO) [7], and the “Computer Oriented Metering, Planning and Advisory System” (COMPAS) [8], have a similar foundation and origin as the TMA/TBFM. Given that they are undergoing a similar evolution as TBFM under the broad European Single European Sky Air Traffic Management Research (SESAR) [3] program, it is expected that many of the concepts and the design philosophy presented here could be translated to those systems as well.
B. TBM and PBN Interdependency

TBM and PBN designs used together increase predictability of the arrival and approach operation. Furthermore, TBM is designed to improve airport efficiency through sequencing and scheduling functions and supporting ATC’s management of flights to their schedules, and PBN is designed to improve aircraft efficiency. Ideally, these objectives can be achieved simultaneously, but in some circumstances, individual TBM and PBN designs may work against each other. It is hypothesized that a holistic, integrated design is required to accomplish both objectives.

As depicted in Figure 2, TBM enables PBN procedure conformance by allocating schedule delay such that aircraft may stay on their assigned procedures using speed changes alone. PBN supports TBM usage by providing more predictable paths from which predicted flight times and TBM sequences and schedules are determined.

![Figure 2. PBN & TBM Interdependency](image)

C. Integrated TBM and PBN Design

To achieve the integrated design objective presented in Section II.B, an Integrated Design Capability software system is proposed to support TBM and PBN development and implementation activities for the FAA. A previous analysis showed current processes and tools are not enough to support integrated TBM and PBN design [12]. Additionally, the concept of integrating TBM and PBN design elements is emerging; therefore, a new system is envisioned to support evolving needs and applications.

The envisioned system will be capable of ingesting TBM adaptation data, depicting geo-referenced adaptation elements and the underlying data parameters to the user. The system will also support the input and visualization of navigation procedures throughout the NAS. The combination of the TBM adaptation parameters and PBN navigation procedures within a single system will provide key aeronautical information needed to enable integrated design applications.

III. INTEGRATED TBM AND PBN DESIGN CAPABILITY

Optimization of aircraft arrival schedules has been the subject of numerous studies [5] [6] [13]; however, no comprehensive analysis tools, accounting for both the design of the airspace procedures and TBM adaptation design, currently exist. To address this need, The MITRE Corporation’s Center for Advanced Aviation System Development (CAASD) has conducted research and developed a prototype capability to provide a means for performing integrated PBN and TBM design as part of an integrated design environment. Design requirements are meant to address shortfalls identified in the previous research [12] and to address the envisioned need described in Section II. The requirements are organized into the areas below and have informed the software design to date.

- Adaptation Visualization & Modification
  The adaptation visualization and modification requirements focus on the depiction of TBM adaptation elements and the underlying TBM configuration parameters.

- Modeling & Simulation
  The modeling and simulation requirements focus on the evaluation of candidate operational scenarios to gain insight into the operational performance and sensitivity of design changes.

- Analysis & Reporting
  The analysis and reporting requirements focus on the evaluation of modeled TBM traffic scenarios. Additionally, reporting requirements are included for supporting the TBM adaptation modifications.

A modular software architecture organizes the capability’s functionality into reusable components with clear responsibilities. This modular approach enables future research to use some or all of the components, as needed, as well as facilitating subsequent replacement or independent improvement of the individual capabilities. Figure 3 provides a high-level overview of the information flow through the proposed integrated design capability and the components that support the primary functions.

![Figure 3. Overview of Prototype Functions & Components](image)
IV. DESIGNING INSTRUMENT APPROACH PROCEDURES COMPATIBLE WITH TBM

In the future, TBM is expected to be used in the terminal environment to manage flights all the way down to the runway [10]. Additionally, PBN procedures will be developed (where appropriate) to enable aircraft equipped with RNP avionics to fly consistent and defined paths to the runway along RNP RF IAPs. Those aircraft not equipped with RNP avionics will be cleared for non-RNP IAPs, which typically have longer final approach join points from the downwind leg. The non-RNP IAPs may be defined all the way to the runway with waypoints that define where aircraft should turn from the downwind leg to the base leg and then to join the final approach. Alternatively, some arrival procedures may end on the downwind leg and ATC will notify aircraft when to turn to join the IAP on the final approach course. This application and associated analysis are described in more detail in reference [13].

Figure 4 illustrates notional RNP RF and non-RNP IAPs to parallel runways. The assumed flight paths along the non-RNP IAPs are shown by dashed lines to represent a notional path aircraft will fly, whereas aircraft strictly adhere to the defined RF turn on the RNP RF IAP. The red points in the figure denote TMPs, where STAs would be calculated to deconflict arrival times at merge points, helping ATC manage flights that later merge with other arrival flows.

![Figure 4. Notional IAPs going to parallel runways.](image)

Currently, there is limited guidance for designing the RNP RF and non-RNP IAPs to support TBO objectives. The lack of guidelines leads to an inefficient trial-and-error design process. In the past, this trial-and-error design process has been done in a real-time laboratory environment, as referenced in Section I, which is costly and inefficient.

A. Problem and Approach

Given the metering design (i.e., the TMP placement) shown in Figure 4, the relative path length between the RNP RF and the non-RNP IAPs affects the potential runway throughput.

Figure 5 shows simplified versions of Figure 4 where only downwind approaches to single runways are shown. In each illustration, TMP B is the upstream point where the RNP RF and non-RNP IAPs diverge, and TMP A is the point on the final approach where the two approaches join again. It is assumed aircraft #1 (AC1) is RNP-equipped and has been cleared to fly the shorter RNP RF IAP; AC2 is not RNP-equipped and is cleared to the non-RNP IAP. In Figure 6 (a), AC1 precedes AC2 at TMP B. Because the relative distance between the approach procedures is too small to allow an aircraft sequence swap between TMP B and TMP A, the sequence is maintained at TMP A. In contrast, Figure 6 (b) shows a larger relative distance between the two approach procedures, which allows the sequence to swap between TMP B and TMP A. Therefore, AC2 precedes AC1 at the upstream point and trails AC1 at the downstream point.

In either case, the impact of IAP design on runway throughput is not immediately clear. An analysis of the downwind approaches only, described in Reference [13], suggests that the flight times along the RNP RF and non-RNP IAPs should be matched to maximize throughput. As the non-RNP flight time increases relative to the flight time along the RNP RF IAP, a large change in throughput happens as the flight time difference allows a swap in the sequence between TMPs B and A, as illustrated in Figure 5 (b). In cases when the flight times along the IAPs are different, the RNP equipage rate can also have a significant impact on potential throughput, with the lowest throughput occurring between 40-60% RNP equipage.

![Figure 5. Illustration of impact of IAP geometries on the sequence between TMP B and TMP A.](image)

The integrated TBM and PBN design capability was used to evaluate the impact of the relative runway geometries on throughput given a realistic traffic scenario including aircraft on the downwind approaches and on straight-in approaches, as shown in Figure 4.

B. Experiment Design

Using the integrated TBM and PBN design capability, a fast-time study was designed to evaluate the impact of IAP geometries on theoretical runway throughput. The following parameters were studied:

- Three IAP designs with different relative distances and flight times between the RNP RF IAP and the non-RNP IAP.
- Different RNP equipage rates between 0% and 100% in increments of 10%.
- Different percentages of aircraft (regardless of equipage) on the downwind approaches versus the straight-in approach, where the percentage of aircraft to the downwind approaches ranged from 0% to 100% in increments of 10%.
In all cases, the traffic scenarios were designed to provide the maximum theoretical throughput at the runway. A single aircraft type was assumed with a constant separation distance and buffer size at the runway, which related to a minimum (time-based) spacing of 91.8 seconds between aircraft. Therefore, the maximum runway throughput was 39.2 aircraft/hour.

The scenarios were designed assuming 120 aircraft arriving to the terminal airspace over two hours. This arrival rate exceeds the maximum runway throughput stated previously but ensures enough flow to the runway from which the throughput for a given set of parameters can be measured. Each combination of parameters was simulated 100 times to determine the average throughput given random sequences of aircraft on the downwind and straight-in approaches and random sequences of RNP-equipped and non-RNP-equipped aircraft.

The three IAP designs studied were implemented at Phoenix Sky Harbor International Airport (KPHX) and are referred to as: the Original, Middle, and Matched Geometries. The Original Geometry design was used for several studies at MITRE and the FAA [10]. In the Matched Geometry, the non-RNP procedure was designed to provide the same flight time as the RNP RF IAP, and the Middle Geometry places the non-RNP IAP where the flight time is halfway between flight times along the RNP RF IAP and the non-RNP IAP in the original geometry.

Figure 6 shows a top-down view of the Original Geometry, as displayed in the integrated TBM and PBN design capability. Aircraft flying the downwind approaches crossed the metering fix (MF) HOMRR which is a waypoint on the procedure from the northeast. Additionally, aircraft flying the straight-in approach crossed the meter fix GEELA from the southwest. Waypoints BONOZ and WAZUP are TMPs, where schedule times were deconflicted.

C. Experiment Results

Results of the experiment are shown in Figures 7, 8, and 9 for the Original, Middle, and Matched Geometries, respectively. The average runway throughput is shown as a function of RNP equipage with the percentage of aircraft on the downwind approaches given by the different lines. In the Original and Middle Geometry cases, Figures 7 and 8, respectively, straight lines are shown for 0, 10, 20, and 30% of aircraft on the downwind approaches. This result shows a reduction in throughput sensitivity to RNP equipage when most aircraft are on the straight-in approaches. However, as the percentage of aircraft on the downwind approaches increases, the average throughput becomes a function of RNP equipage. As indicated in Figures 7, 8, and 9, the maximum throughput is achieved for 0% or 100% RNP equipage with the worst throughput between 40 and 60% RNP equipage. For the case when all aircraft are on the straight-in approaches, throughput at MF GEELA becomes more constraining than the throughput at the runway, limiting throughput to about 37 aircraft/hour. This throughput constraint is eased as some flights arrive via the downwind approaches.

In all three cases, the nominal flight time along the RNP RF IAP (between BONOZ and WAZUP) was 97.8 seconds. Table I shows nominal flight times along the non-RNP IAP (also between BONOZ and WAZUP) for the three designs. The values in parentheses are flight time increases relative to flight times along the RNP RF IAP. As indicated and previously described, in the Matched Geometry, both the RNP RF and non-RNP IAPs had the same nominal flight times.

### Table I. Nominal Flight Times along the Non-RNP IAP

<table>
<thead>
<tr>
<th>Geomety</th>
<th>Non-RNP Flight Time (seconds)</th>
<th>RNP RF Flight Time (seconds)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original Geometry</td>
<td>280.7 (187%)</td>
<td>97.8</td>
</tr>
<tr>
<td>Middle Geometry</td>
<td>188.8 (93%)</td>
<td>97.8</td>
</tr>
<tr>
<td>Matched Geometry</td>
<td>97.8</td>
<td>97.8</td>
</tr>
</tbody>
</table>

Figure 7. Average throughput as a function of RNP equipage and percent of aircraft on the downwind approaches for the Original Geometry design.

Figure 8. Average throughput as a function of RNP equipage and percent of aircraft on the downwind approaches for the Middle Geometry design.
Figure 9 shows the average throughput for the Matched Geometry design. As expected, the similar flight times eliminates the impact of RNP equipage, and the maximum theoretical throughput is achieved as the percentage of flights on the downwind approaches increases.

Results from this analysis demonstrated key relationships between PBN IAP designs and potential throughput given by a TBM scheduler. For aircraft going to downwind approaches, differences in flight times along non-RNP and RNP RF IAPs impact achievable scheduling throughput. Designing the non-RNP IAP and the associated TBM adaptation to enable RNP-equipped and non-RNP-equipped aircraft to swap sequence during the approach can lead to a local maximum in theoretical throughput; however, small changes in flight time along the non-RNP IAP, eliminating the opportunity to swap RNP-equipped and non-RNP-equipped aircraft, can lead to a local minimum and large changes in potential throughput. To avoid this undesirable design region and to maximize potential throughput, it is recommended flight times along the non-RNP IAP and the RNP RF IAP be as close as possible. Additionally, incorporation of straight-in approaches shows how sensitivity to RNP equipage can be reduced with well-balanced utilization of the different approaches.

V. USE OF DUAL STARS WITH TBM

A dual STAR design provides two arrival feeds from en route airspace to terminal airspace and is becoming increasingly common for managing arrival traffic in large terminal airspace. A more traditional corner-post design provides a single arrival feed for each TRACON arrival corner post, whereas a dual STAR design provides two separate routes to each corner post that later merge in terminal airspace. This analysis used dual STARS in the context of TBM and explored different strategies for configuring the TBM design to support dual STAR operations.

A. Problem and Approach

Dual STARS provide more efficient routing in addition to other benefits. For example, terminal airspace requires 3 nautical mile (NM) separation versus the 5 NM separation required in en route, and aircraft are merged at reduced speeds, so the merge is more precise with increased throughput due to reduced separation. Design teams identified the need for successful TBM operational integration to realize the full benefits from airspace and procedure designs being developed. Several sites have attempted, with various degrees of success, to manage traffic on dual STARS using TBM to assist in merging. Figure 10 provides an example of such an implementation for a new set of dual STARS in Denver, Colorado that are currently being considered for implementation.

With the advent of TBM operations, researchers have encountered challenges when trying to utilize dual STAR procedures in a TBM environment. There are no clear guidelines for designing PBN procedures or for adapting TBM to use a dual STAR design. In this section, different TBM design strategies for dual STAR procedures are explored with the goal of informing future design activities. The analysis leveraged the integrated TBM and PBN design capability described in Section III, which provides a software emulation of TBM systems including the scheduling algorithm, to evaluate different strategies for managing dual STARS.

B. Experiment Design

Using the Integrated TBM and PBN design capability, a fast-time study was designed to evaluate the impact of dual STAR designs on theoretical throughput. First, several parameters were selected for evaluation.

The merge distance between the meter fix and the merge point inside the TRACON, as illustrated in Figure 11, was one parameter.

Another parameter was the presence of deconfliction at the terminal merge point. This parameter was added because the current TBFM capabilities do not provide deconflicted schedule times at the terminal merge point (schedules are only
deconflicted at the MF). TSAS will deconflict schedule times at TMPs, which could be placed at terminal merge points.

Next, we looked at the airspace design. As shown in Figure 12, TBFM provides two different super-stream class configurations that can be adapted to support dual STAR operations. The combined super-stream design (on the left) shows a single MF arc used to meter both STARs as a single stream, whereas the separate super-stream design (on the right) consists of two independent MFs and separate streams associated with each STAR. In the separate super-stream design, flows are treated independently; therefore, STAs at each meter fix are independent and will not account for the later merge in the terminal.

![Combined Super Stream Design](image1)

![Separate Super Stream Design](image2)

Figure 12 Notional Dual STAR Design – Scheduling Method

Finally, different super-stream class separation settings in the TBFM adaptation were considered. The settings represent the separation constraint that TBFM will enforce when determining the schedule for each super-stream class.

The resulting experiment matrix which utilizes all the parameters that were summarized in this section is shown in Table II. As indicated, eight individual scenarios were evaluated.

<table>
<thead>
<tr>
<th>No.</th>
<th>Terminal Merge</th>
<th>Terminal Deconfliction</th>
<th>Super Stream</th>
<th>Super Stream MIT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 NM</td>
<td>No</td>
<td>Combined</td>
<td>7 NM</td>
</tr>
<tr>
<td>2</td>
<td>20 NM</td>
<td>No</td>
<td>Combined</td>
<td>7 NM</td>
</tr>
<tr>
<td>3</td>
<td>10 NM</td>
<td>No</td>
<td>Separate</td>
<td>10NM</td>
</tr>
<tr>
<td>4</td>
<td>20 NM</td>
<td>No</td>
<td>Separate</td>
<td>5 NM</td>
</tr>
<tr>
<td>5</td>
<td>10 NM</td>
<td>No</td>
<td>Separate</td>
<td>5 NM</td>
</tr>
<tr>
<td>6</td>
<td>20 NM</td>
<td>No</td>
<td>Separate</td>
<td>5 NM</td>
</tr>
<tr>
<td>7</td>
<td>10 NM</td>
<td>Yes</td>
<td>Separate</td>
<td>5 NM</td>
</tr>
<tr>
<td>8</td>
<td>20 NM</td>
<td>Yes</td>
<td>Separate</td>
<td>5 NM</td>
</tr>
</tbody>
</table>

To evaluate the different scenarios identified in Table II, a simulation was conducted first by constructing a scenario with aircraft on the two arrivals. The scenario consisted of approximately 500 aircraft over a six-hour period with each flight arriving on one of the dual STARs in a random order. Dual STAR flight plan data along with initial aircraft start times were simulated first by calculating Estimated Times of Arrival (ETAs) and then producing STAs using the integrated TBM and PBN design capability. The resulting STAs represent the baseline schedule.

In the actual operational environment, aircraft will not perfectly meet their STAs at the MF. The accuracy with which ATC can manage flights to their STAs is referred to as “delivery accuracy.” To evaluate the different scenarios defined in Table II, a Monte-Carlo simulation modeled different levels of STA delivery accuracy. The error in meeting the STA was varied by randomly sampling from a normal probability distribution with zero mean and different levels of variance (e.g., 20, 40, 60, and 90 seconds).

C. Experiment Results

The first scenario used a combined super-stream configuration where both MFs used in this example (SQUEZ and BRDEY) are deconflicted together using a 7 NM super-stream class separation. Resulting separations at the terminal merge point for each delivery accuracy variance are shown in Figure 13. These findings indicate that if this design is used, resulting separation at the merge point is predicted to violate the minimum 3 NM required separation if the MF delivery accuracy exceeds a 20 second standard deviation MF delivery error.

![Combined SQUEZ – BRDEY Separation](image3)

Figure 13. Combined 7 NM Super Stream Design

Similar results from the Monte-Carlo simulation were also derived for Scenarios 2 through 8. The results for each design strategy were compared using throughput at the terminal merge point and the probability of vectoring that might be required once an aircraft enters the terminal airspace. The probability of vectoring was derived based on checking that the required separation at the terminal merge point is at least 3 NM. If separation was found to be less than 3 NM, a time-based separation adjustment value was calculated such that the minimum 3 NM separation is achieved at the terminal merge point considering any delay the aircraft can take with a speed-only change. If the required delay exceeds what can be absorbed using speed changes only, that flight is counted as vectored.

Table III provides a summary of analysis scenarios described in Table II, associated results for throughput, and probability of vectoring based on different levels of delivery accuracy to the TRACON boundary.

<table>
<thead>
<tr>
<th>#</th>
<th>Term Merge</th>
<th>TD</th>
<th>Super Stream</th>
<th>SS MIT</th>
<th>TMP Throughput ac/hr</th>
<th>Prob. Vectoring – Var 40 Sec</th>
<th>Prob. Vectoring – Var 60 Sec</th>
<th>Prob. Vectoring – Var 90 Sec</th>
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<td>1</td>
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<td>0%</td>
<td>0%</td>
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<tr>
<td>2</td>
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<td>No</td>
<td>Combined</td>
<td>7 NM</td>
<td>43.20</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
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<tr>
<td>3</td>
<td>10 NM</td>
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<td>Separate</td>
<td>10 NM</td>
<td>60.56</td>
<td>2.1%</td>
<td>3.4%</td>
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<tr>
<td>4</td>
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<td>No</td>
<td>Separate</td>
<td>10 NM</td>
<td>60.59</td>
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<td>1.3%</td>
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<tr>
<td>5</td>
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<td>Separate</td>
<td>5 NM</td>
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<td>15.3%</td>
<td>17.4%</td>
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<td>Separate</td>
<td>5 NM</td>
<td>72.11</td>
<td>0%</td>
<td>0%</td>
<td>1%</td>
</tr>
</tbody>
</table>

As shown in Table III, results indicate utilizing a combined super-stream scheduling configuration with a 7 NM MIT separation allows for more MF delivery variability. However,
this design choice can affect throughput resulting in approximately a 40% reduction when compared to using a separate 5 NM MIT super-stream scheduling configuration. This also resulted in the highest possible throughput but also resulted in approximately 18% of flights requiring vectoring.

Additionally, using separate super-stream scheduling along with terminal MF deconfliction (as provided by TSAS) provides a good balance between required delivery accuracy and throughput. However, the delivery accuracy required is still higher than what a combined super-stream scheduling configuration allows. Finally, the required delivery accuracy can, in part, be lowered by increasing the distance between the MF and the terminal merge point to allow for more time/distance for ATC to apply speed control to correct flight crossing time variances.

The results from this analysis indicate that TBFM can be effectively used with dual STARS and to support that, dual STARS should be used in TBFM using separate super-stream scheduling along with terminal deconfliction provided by TSAS, and the distance between the MF and the terminal merge point should be sufficiently long such that expected variations in the delivery accuracy to the MF can be accommodated using speed control alone.

VI. USE OF ALTITUDE AND SPEED CONSTRAINTS IN PBN TO SUPPORT TBM

In operational TBM systems, trajectory prediction is a key function, generating nominal trajectories that are the basis for undelayed ETAs, which are inputs to the scheduling function. Additionally, in terminal airspace, slow and fast profiles are also computed to determine the amount of delay aircraft can be allocated when deconflicting STAs at TMPs as part of the scheduling process for TSAS. Finally, another slow and fast profile, based on different assumptions, is computed to determine the speed envelope meet-time advisory functions can use for speed advisory generation. The meet-time advisory function in TBM is used to generate a trajectory solution which meets the TBM-generated schedule and forms the basis for computing speed advisories which can be used by controllers as aids to conduct metering operations.

The creation of each profile relies on altitude and speed constraints, which may or may not be a part of a navigation procedure for which a trajectory is predicted. Figure 14 provides a depiction of the different profiles used in a TBM system for the generation of a trajectory prediction segment.

Using these definitions, an analysis was performed to quantify the impact of altitude and speed constraints on TBFM ETA variability for arrival procedures. While increased use of altitude and speed constraints may limit the amount of error that may be corrected using speed alone, the constraints serve to improve TBFM system trajectory modeling predictability.

A. Problem and Approach

In TBM, the nominal profile is used for predicting the undelayed flight’s trajectory and provides the basis for all TBFM sequencing and scheduling. In the absence of published altitude and speed constraints on a PBN procedure, different assumptions are used to generate a predicted trajectory, which can lead to variability in the accuracy of the prediction.

B. Experiment Design

This section provides the results of a sensitivity analysis that compares ETA prediction variability given unconstrained (i.e., only one altitude and speed constraint at the MF) and constrained (i.e., interim altitude and speed constraints between top of descent and the MF) procedures with respect to slight perturbations in five trajectory modeling input variables: descent speed, cruise speed, aircraft mass, wind, and descent path angle. One variable was tested at a time for a range of cruise altitudes between flight level (FL) 280 to FL400. For cruise speed and wind perturbations, two cases were examined: one with a longer cruise phase and total flight length of 235 NM and one with a shorter cruise phase and total flight length of 155 NM. Obtaining data for five variables and two path distances, yielded a set of seven experiments. ETA variability was evaluated for both an unconstrained and a constrained procedure. Figure 15 (top left) shows the vertical profile for the unconstrained procedure, and in the top right, the constrained vertical profile with associated restrictions is shown.

C. Experiment Results

The resulting vertical profiles for the unconstrained arrival (left) and the constrained arrival (right) across all test cases are depicted in Figure 16. As expected, the constrained procedure results in less variability in the vertical profile.
Additionally, the resulting speed profiles for the unconstrained arrival (left) and the constrained arrival (right) across all test cases are depicted in Figure 17. As expected, the constrained procedure also results in less variability in the speed profile.

![Resulting Speed Profiles](image)

Figure 17 Resulting Speed – Unconstrained (left) – Constrained (right)

As previously indicated, one of the most significant error sources that can introduce variability in TBFM ETA calculations consists of the uncertainty in aircraft descent Calibrated Airspeed (CAS) used by TBFM. Without knowing the actual descent CAS to be used by the aircraft, TBFM must assume a value. The ETA error resulting can be significant depending on the difference between the actual descent CAS and the assumed descent CAS used by the aircraft and can range between 250 and 320 knots [14].

A subset of detailed results obtained for large jets is shown in Table IV. The table shows the minimum and maximum time at each flight level for the flight to reach the meter fix, given that the CAS on descent was varied from 250 to 320 knots. The delta between the minimum (min) and maximum (max) times is listed in the fourth column, with the largest variation within one flight level and the largest variation combining all flight levels shown in the second-to-last and last rows, respectively. The min and max values for each data set or flight level correspond to the values listed in the table. The last three columns of the table are also significant because they show the effect of varying descent speed with respect to the median descent speed. As the variations were designed to go to either side of a nominal, expected value, it is of interest to see how the time of arrival at the meter fix was affected as compared to the median of the data set.

TABLE IV. LARGE JETS RESULTS FOR ANALYSIS OF SENSITIVITY OF TIME AT METER FIX (MF) DUE TO VARIATIONS OF DESCENT SPEED IMPROVEMENT OF VARIABILITY OF PREDICTION TIME

<table>
<thead>
<tr>
<th>Large Jet</th>
<th>Time Range</th>
<th>Delta Time between Min. and Max.</th>
<th>Median Time</th>
<th>Delta Time from Median</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL2800</td>
<td>FL2900</td>
<td>FL3000</td>
<td>FL3500</td>
<td>FL3600</td>
</tr>
<tr>
<td>FL2800</td>
<td>1720 - 1740</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL2900</td>
<td>1733 - 1753</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3000</td>
<td>1736 - 1756</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3500</td>
<td>1740 - 1760</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3600</td>
<td>1743 - 1763</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3700</td>
<td>1747 - 1767</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3800</td>
<td>1750 - 1770</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL3900</td>
<td>1753 - 1773</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL4000</td>
<td>1756 - 1776</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL4200</td>
<td>1760 - 1780</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL4400</td>
<td>1763 - 1783</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
<tr>
<td>FL4600</td>
<td>1766 - 1786</td>
<td>270 - 275</td>
<td>1750</td>
<td>1750</td>
</tr>
</tbody>
</table>

As indicated in Table IV, when using an unconstrained trajectory, the variability introduced by the uncertainty in the descent CAS used by TBFM, can be as big as 1 minute (min), independent of other error sources such as wind forecast which can have a cumulative effect. Figure 18 shows a graphical representation of the data with all times between the max and min values indicated by circular markers.

![Graphical representation of the data in Table IV](image)

Figure 18 Graphical representation of the data in Table IV

Finally, Table V shows the experiment results for all five trajectory modeling input variables studied along with the associated differences between the arrival time variability for flights with unconstrained descent as compared to the same flights with constrained descent. The results represent the prediction variability in time at the meter fix in seconds. The variability is caused by variations in the input variables listed in the first column.

TABLE V. IMPROVEMENT OF VARIABILITY OF PREDICTION TIME

<table>
<thead>
<tr>
<th>Improvement with Constraint</th>
<th>All Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arrival Time Spread (sec)</td>
<td>Med. To Min. Time (sec)</td>
</tr>
<tr>
<td>Descent Speed</td>
<td>27</td>
</tr>
<tr>
<td>Cruise Speed</td>
<td>9</td>
</tr>
<tr>
<td>Cruise Speed (short flight)</td>
<td>9</td>
</tr>
<tr>
<td>Wind</td>
<td>7</td>
</tr>
<tr>
<td>Wind (short flight)</td>
<td>7</td>
</tr>
<tr>
<td>Weight</td>
<td>4</td>
</tr>
</tbody>
</table>

The values in Table V represent the worst case of all the cruise flight levels tested. The Arrival Time Spread in seconds (sec) is the difference between the earliest to latest arrival time at the MF. Therefore, the 27 sec value in the descent speed row represents a 27 sec reduction in arrival time spread when the constrained arrival procedure was assumed. The Med. To Min. Time (sec) is the difference between the median and minimum arrival time at the MF, and the Med. To Max. Time (sec) is the difference between the median and the maximum arrival time at the MF.

As the results in Table V show, most of reduction in variability is achieved when the descent speed is constrained, which provides the trajectory prediction function with improved information about the descent speed of the aircraft. The error due to descent CAS variation can be significant depending on the difference between the assumed descent CAS used in the trajectory prediction function and the aircraft’s actual descent CAS. The analysis described in this section showed how one of the biggest sources of variability in nominal ETA prediction can be reduced by using a constrained procedure; however, additional research is needed to understand the effects of this constraint from the perspective of its impact on other profiles such as the scheduling and meet-time advisory profiles.
VII. CONCLUSIONS

The need for integrated TBM and PBN design and analysis to achieve TBO objectives and benefits was presented. A description of the design, development, and application of a tool being developed by MITRE CAASD to support integrated TBM and PBN design was also presented. Prototype capabilities were described, and three applications were presented to demonstrate how the proposed prototype could be used for integrated PBN and TBM design and analysis.

The first application investigated the design of IAPs and impact on throughput in a TBM environment with mixed aircraft equipage. Results from this analysis indicate to maximize potential throughput, it is recommended flight times along the non-RNP IAP and the RNP RF IAP be as close as possible.

The second application investigated TBM design to support use of dual STAR procedures. Results indicated improved throughput is maintained when using separate super-stream scheduling along with terminal deconfliction. Additionally, the distance between the MF and terminal merge point should be sufficiently long such that expected variations in delivery accuracy to the MF can be accommodated using speed control alone.

The third application investigated use of altitude and speed constraints on PBN procedures to improve trajectory predictability in TBM automation. The research found the biggest source of variability in nominal ETA prediction (assumption in descents speeds) can be reduced by using a constrained procedure; however, additional research is needed to understand the effects of this constraint from the perspective of its impact on other trajectory profiles such as those used for schedule delayability and meet-time advisory generation.

The example applications explored in this paper represent only a subset of the type of research questions that must be investigated in the integrated TBM and PBN design space. It is envisioned this research and resulting capability presented here will provide the basis for continued research into combined PBN and TBM design and development of best practices to assist the aviation community in transitioning to TBO.

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REFERENCES