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

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What is the Definition of Trajectory-Based Operations (TBO)?

...an ATM method for strategically planning, managing, and optimizing flights throughout the operation by using time-based management, information exchange between air and ground systems, and the aircraft’s ability to fly precise paths in time and space.

Source:
https://my.faa.gov/org/staffoffices/ang/reports_plans.html
What is Initial TBO (iTBO)?

- iTBO reflects new technology and new process
  - **Technology**: Integrated Use of new and existing capabilities and procedures to achieve TBO objectives
    - Time-based Management (TBM)
    - Performance-based Navigation (PBN)
  - **Process**: Integrated Approach to implementation
    - Integrated TBM and PBN design (focus of this presentation)
    - Incremental implementation to provide a reasonable operational evolution

- iTBO scope focuses on delivery of capabilities for next 5 years
What is Time-Based Management?

- Time-Based Management involves the use of the Time-Based Flow Management (TBFM) system to determine a sequence and schedule of aircraft at Meter Reference Points (MRPs) in the airspace.
- Scheduled Times of Arrival (STAs) at MRPs are deconflicted to assist controllers in merging flows.
- Air Traffic Controllers will manage flights to their STAs to merge flows and deliver acceptable flow rates to downstream controllers operating in capacity-constrained airspace.
- TBM is a fundamental change from ATC managing flights using distance (Miles in Trail) to managing flights using time.
What is the role of PBN in TBM?

- The PBN National Airspace System (NAS) Navigation (NAV) Strategy describes the FAA’s vision for PBN.
- The use of TBM in mixed-equipage environments is a key strategy to maximize PBN usage.
- TBM and PBN integration is especially important when aiming to maximize arrival throughput and PBN usage at busy airports.
Integrated TBM and PBN Design Research Capability
MITRE has been conducting research to analyze and integrate TBM and PBN design.

Integrated design involves understanding relationships between:
- Route design and throughput
- PBN procedure design and TBFM predictability
- PBN procedure design and delayability
- Delivery accuracy, delayability, and route conformance
Motivation for the Research

- There is currently no integrated capability available for relating and evaluating PBN procedure and airspace elements with Time Based Management systems (i.e., TBFM System)
- Integrated PBN and Arrival Management operational design requires data-driven analysis to inform decision making
Overview of Prototype Functions & Components

Existing Procedure Design and Analysis Platform

User Selects and Visualizes Adaptation Data

New Features

Adaptation Files

Parsers

Data Model

User Builds and Schedules a Scenario

Scenario

Route Analysis

Scheduler

Analysis

User Alters Adaptation and Reanalyses a Scenario

Scheduler

Analysis

Visualization & Modification

Modeling, Simulation & Reporting

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Integrated TBM and PBN Design Analyses

Three analyses illustrating integrated design:

1. Approach Procedure Design for Mixed-Equipage Environments
2. TBFM Design for Dual RNAV STAR Procedures
3. TBFM Estimated Time of Arrival (ETA) Variability in En Route
Design Analysis 1: Designing Instrument Approach Procedures Compatible with TBM
Approach Procedure Design Problem

Problem Description:
- RNP-equipped aircraft may fly a shorter path to the runway than non-RNP aircraft
- Mixed-equipage environment requires TBM to support scheduling and merging
- Need to understand the relationship between approach geometries, RNP equipage, and runway throughput

Non-RNP IAP assumption: all aircraft on the Non-RNP IAP fly the same defined path (with variability in turns due to aircraft performance)

No guidelines currently exist on the design of RNP and Non-RNP IAPs to support TBM objectives
- HITL activities have revealed this design challenge when trying to develop procedures for a study
- Without clear guidelines, the design process becomes iterative, which is expensive and inefficient
All Aircraft on Downwind Approaches

- Examine relationship between IAP design, RNP equipage rate, and throughput for downwind approaches only

**Diagram: All Aircraft on Downwind Approaches**

- Smaller flight time differences between approach paths prevent sequence swaps between TMP B and TMP A.
- Larger flight time differences between approach paths allow sequence swaps between TMP B and TMP A.
Scheduling Example

**Scheduler logic:**
- Start with aircraft as close as possible at TMP A (sep std + buffer)
- If there’s a conflict at TMP B, adjust STA at B and update STA at A → this is where a loss in potential throughput happens
- If spacing at A is insufficient, move aircraft back in sequence at B and update STA at A → this is where a loss in potential throughput happens

**Scheduler Example**

<table>
<thead>
<tr>
<th>Initial Schedule at A</th>
<th>Initial Schedule at B</th>
<th>Deconflicted Schedule at B</th>
<th>Updated Schedule at A</th>
</tr>
</thead>
<tbody>
<tr>
<td>RNP STA1 = 2:20</td>
<td>RNP STA1 = 0:50</td>
<td>RNP STA1 = 0:50</td>
<td>RNP STA1 = 2:20</td>
</tr>
<tr>
<td>Non-RNP STA2 = 3:20</td>
<td>Non-RNP STA2 = 0:00</td>
<td>Non-RNP STA2 = 0:00</td>
<td>Non-RNP STA2 = 3:20</td>
</tr>
<tr>
<td>RNP STA3 = 4:20</td>
<td>RNP STA3 = 2:50</td>
<td>RNP STA3 = 2:50</td>
<td>RNP STA3 = 4:20</td>
</tr>
<tr>
<td>Non-RNP STA4 = 5:20</td>
<td>Non-RNP STA4 = 2:00</td>
<td>Non-RNP STA4 = 2:00</td>
<td>Non-RNP STA4 = 5:20</td>
</tr>
<tr>
<td>Non-RNP STA5 = 6:20</td>
<td>Non-RNP STA5 = 3:00</td>
<td>Non-RNP STA5 = 3:40</td>
<td>Non-RNP STA5 = 7:00</td>
</tr>
</tbody>
</table>

RNP Flight Time = 90 sec; Non-RNP Flight Time = 200 sec
Min Spacing at A = 60 sec; Min Spacing at B = 50 sec
Scheduling Timelines

Red lines = losses in the scheduled runway throughput relative to maximum throughput

Blue lines = non-RNP flights

Green lines = RNP flights

50% RNP Equipage
Scheduled Runway Throughput

- Theoretical runway throughput as a function of Non-RNP IAP flight time and RNP equipage

- Flight Time along Non-RNP IAP becomes large enough to allow a sequence swap

- Throughput changes of 2-3 ac/hr possible based on RNP Equipage alone

- Target design region here

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Use Integrated TBM and PBN Design Tool and Incorporate Straight-in Approaches

- Evaluate theoretical runway throughput for:
  - 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%
    - Different percentages of aircraft on the downwind approaches (between 0% and 100%) versus the straight-in approach

### Flight-time Along Non-RNP IAP

<table>
<thead>
<tr>
<th>Original Geometry</th>
<th>Middle Geometry</th>
<th>Matched Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>280.7 seconds (+187%)</td>
<td>188.8 seconds (+93%)</td>
<td>97.8 seconds</td>
</tr>
</tbody>
</table>
Use Integrated TBM and PBN Design Tool and Incorporate Straight-in Approaches

IAP design used in NASA and MITRE Terminal Metering studies

Different lines are % of Flights to Downwind Approaches

RNP-equipped and non-RNP flights have the same flight time along downwind approaches
Design Analysis 2: Use of Dual STARS with TBM
Evaluate use of Dual STARs with TBFM

- **Problem Description:** current TBFM delivery accuracy performance may result in ties at the meter fix when aircraft are on Dual STARs
  - Some TBFM workarounds have been proposed and implemented
- **Objective:** determine best practices for integrating TBFM and Dual RNAV STARs
- **Approach:**
  - Given current procedure design, determine how TBFM could be adapted to enable TBM operations given:
    - Procedure geometry (distance from Meter Fix to terminal merge point)
    - Stream-class scheduling design and MF Miles-in-Trail spacing
    - Use of Terminal Metering for terminal merge deconfliction vs. no Terminal Metering
  - Determine TBFM design impact on:
    - Throughput
    - Need to vector in the terminal to ensure separation at the merge point
Modeling Approach: Scheduling Parameters

- Scheduling Parameters available to manage Dual STARs:
  - Separate super-streams (STARs sequenced separately)
  - Combine super-streams (STARs sequenced together)
  - Deconflict at merge point in terminal (Terminal Metering-only feature)
  - Super-stream Miles-in-Trail (MIT) value
Modeling Approach: Procedure Geometries

- The approach evaluated the impact of the distance between the Meter Fix and the terminal merge point
  - Two different designs: 10 NM and 20 NM

10 NM from Meter Fix to Terminal Merge

20 NM from Meter Fix to Terminal Merge
How Does the Use of Terminal Metering Affect Scheduling and Vectoring Results?

Without TSAS, the only STAs are at the runway or FAF and the Meter Fix.

Without TSAS, there are no tools to help ATC deconflict aircraft at merge points.

Meter Fix STAs may be adjusted if required delay to TMP is too large.

STAs and TSAS tools will help ATC deconflict aircraft at the merge point.
## Evaluation Scenarios

<table>
<thead>
<tr>
<th>Scenario</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>10 NM</td>
</tr>
<tr>
<td>4</td>
<td>20 NM</td>
<td>No</td>
<td>Separate</td>
<td>10 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>

- Generated scenarios for the dual STARs over one corner-post at PHX
- Used MITRE’s TBFM scheduler emulation to generate STAs at the MF
  - Aircraft were randomly assigned to each STAR
  - 500 aircraft over a six-hour period to generate statistical results
- If Terminal Metering was assumed (Scenarios 7 and 8), the scheduler also determined STAs at the terminal merge point
Results: Throughput

- The MF throughput for each scheduling strategy and geometry is compared against a theoretical MF throughput.
- The geometry of the terminal merge does not significantly impact the throughput results.
**Results: Probability of Vectoring**

- The probability of vectoring in the terminal area is compared for each scheduling strategy and geometry.
Results: Summary

- A combined super-stream scheduling configuration allows for larger MF delivery errors. However, this design reduces MF throughput.
- Using separate super-stream scheduling with Terminal Metering provides a good balance between required delivery accuracy and throughput. However, the delivery accuracy required is still higher than what the combined super-stream scheduling configuration allows.
- The delivery accuracy requirements are alleviated by increasing the distance between the MF and the terminal merge point.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Terminal Merge Distance</th>
<th>Terminal Deconfliction</th>
<th>Super-Stream Sched</th>
<th>Super Stream MIT</th>
<th>MF Throughput (ac/hr)</th>
<th>Prob of Vectoring 40 s</th>
<th>Prob of Vectoring 60 s</th>
<th>Prob of Vectoring 90 s</th>
<th>Variance 40 s</th>
<th>Variance 60 s</th>
<th>Variance 90 s</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 NM</td>
<td>No</td>
<td>Combined</td>
<td>7 NM</td>
<td>43.22</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>20 NM</td>
<td>No</td>
<td>Combined</td>
<td>7 NM</td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>10 NM</td>
<td>No</td>
<td>Separate</td>
<td>10 NM</td>
<td>60.56</td>
<td>2.1%</td>
<td>3.4%</td>
<td>5.8%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>20 NM</td>
<td>No</td>
<td>Separate</td>
<td>10 NM</td>
<td>60.59</td>
<td>0.5%</td>
<td>1.5%</td>
<td>3.6%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>10 NM</td>
<td>No</td>
<td>Separate</td>
<td>5 NM</td>
<td>73.56</td>
<td>15.3%</td>
<td>17.4%</td>
<td>17.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>20 NM</td>
<td>No</td>
<td>Separate</td>
<td>5 NM</td>
<td>72.11</td>
<td>4.5%</td>
<td>4.2%</td>
<td>4.7%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>10 NM</td>
<td>Yes</td>
<td>Separate</td>
<td>5 NM</td>
<td>73.56</td>
<td>4.5%</td>
<td>7.3%</td>
<td>8.4%</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>20 NM</td>
<td>Yes</td>
<td>Separate</td>
<td>5 NM</td>
<td>72.11</td>
<td>0%</td>
<td>0%</td>
<td>1.0%</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Design Analysis 3: 

**USE OF ALTITUDE AND SPEED CONSTRAINTS IN PBN TO SUPPORT TBM**
TBFM ETA Variability in En Route

Altitude and Speed Constraints on PBN Procedures

Increased TBFM Predictability (Improved STAs, DCTs, and GIM-S Speed Advisories)

Improved Delivery Accuracy at the Meter Fix

Decreased Flexibility To Optimize Flight Path for an Individual Aircraft*

Reduced Vectoring in Terminal Airspace

*With poor delivery accuracy at the Meter Fix, aircraft are more likely to be vectored in the terminal. This is the tradeoff in PBN procedure design.
TBTFM ETA Variability in En Route

- **Background:**
  - TBTFM can be adapted to use procedural altitude and speed constraints when modeling the trajectory to the meter fix
  - If there are no speed constraints on the en route portion of the STAR, TBTFM will assume a descent speed for the aircraft

- **Problem:** errors in the assumed descent speed lead to significant ETA errors, impacting schedule feasibility and leading to errors in DST information

- **Objective:** evaluate the sensitivity of TBTFM ETA variability to different parameters, such as descent speed, aircraft mass, winds
En-Route Arrival: Conventional (Unconstrained) STAR

Unconstrained

Restrictions

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>Lower Altitude (feet)</th>
<th>Upper Altitude (feet)</th>
<th>Indicated Airspeed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOMSN</td>
<td>21000</td>
<td>21000</td>
<td>250</td>
</tr>
</tbody>
</table>
En-Route Arrival: Constrained RNAV STAR

Constrained

Restrictions

<table>
<thead>
<tr>
<th>Waypoint</th>
<th>Lower Altitude (feet)</th>
<th>Upper Altitude (feet)</th>
<th>Indicated Airspeed (knots)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DAIRL</td>
<td>27000</td>
<td>none</td>
<td>none</td>
</tr>
<tr>
<td>FRNCH</td>
<td>23000</td>
<td>27000</td>
<td>270</td>
</tr>
<tr>
<td>SKARF</td>
<td>24000</td>
<td>28000</td>
<td>260</td>
</tr>
<tr>
<td>TOMSN</td>
<td>21000</td>
<td>21000</td>
<td>250</td>
</tr>
</tbody>
</table>
Approach: Sensitivity Variables

**Approach:** Compare TBFM prediction variability between a conventional and constrained RNAV STAR under different factors affecting TBFM Trajectory Model Predictive Accuracy

1. **AC Type**
   - 4 characters, such as B74N, B738, CL60 etc.

2. **Procedure**
   - F for FRENCH3
   - mF for modified FRENCH3

3. **Cruise Altitude**
   - 2 digits, i.e. FL380 = 38, FL400 = 40, etc.

4. **Wind**
   - Nominal = WN
   - +15 knots = W15
   - -15 knots = W_15

5. **Distance**
   - 3 digits, i.e. 235 NM = 235, etc.

6. **Mass**
   - Nominal = MN
   - +10% = M10
   - -10% = M_10

7. **Cruise Mach**
   - 0.78 = Mach78 nominal
   - + 17 / 22 / 38 kts (tracker error)

8. **Descent CAS**
   - 280 = CAS280, etc.
## Descent Speed Variability Results

<table>
<thead>
<tr>
<th>Large Jet</th>
<th>Time Range</th>
<th>Delta Time between Min. and Max. (sec)</th>
<th>Median Time (sec)</th>
<th>Delta Time from Median (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FL280</td>
<td>1761 - 1773</td>
<td>12</td>
<td>1765</td>
<td>2</td>
</tr>
<tr>
<td>FL290</td>
<td>1765 - 1780</td>
<td>15</td>
<td>1768</td>
<td>3</td>
</tr>
<tr>
<td>FL300</td>
<td>1768 - 1787</td>
<td>19</td>
<td>1771</td>
<td>3</td>
</tr>
<tr>
<td>FL310</td>
<td>1771 - 1793</td>
<td>22</td>
<td>1775</td>
<td>4</td>
</tr>
<tr>
<td>FL320</td>
<td>1774 - 1799</td>
<td>25</td>
<td>1779</td>
<td>5</td>
</tr>
<tr>
<td>FL330</td>
<td>1777 - 1804</td>
<td>27</td>
<td>1782</td>
<td>5</td>
</tr>
<tr>
<td>FL340</td>
<td>1781 - 1809</td>
<td>28</td>
<td>1785</td>
<td>4</td>
</tr>
<tr>
<td>FL350</td>
<td>1784 - 1813</td>
<td>29</td>
<td>1788</td>
<td>4</td>
</tr>
<tr>
<td>FL360</td>
<td>1790 - 1820</td>
<td>30</td>
<td>1794</td>
<td>4</td>
</tr>
<tr>
<td>FL370</td>
<td>1797 - 1818</td>
<td>31</td>
<td>1792</td>
<td>5</td>
</tr>
<tr>
<td>FL380</td>
<td>1798 - 1818</td>
<td>30</td>
<td>1792</td>
<td>4</td>
</tr>
<tr>
<td>FL390</td>
<td>1805 - 1816</td>
<td>31</td>
<td>1790</td>
<td>5</td>
</tr>
<tr>
<td>FL400</td>
<td>1786 - 1817</td>
<td>31</td>
<td>1790</td>
<td>4</td>
</tr>
<tr>
<td>Largest Variation within one FL</td>
<td>31</td>
<td>5</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>All FLs together</td>
<td>1761 - 1809</td>
<td>59</td>
<td>1786</td>
<td>25</td>
</tr>
</tbody>
</table>

Each data set comes from one FL.
Speed and Altitude Profile Variability

- Comparing variability in unconstrained arrival (left) and constrained arrival (right) profiles across all test cases
# Summary of Sensitivity Study Results

## Unconstrained ETA Variability Results

<table>
<thead>
<tr>
<th>Constraint Descent</th>
<th>Descent Speed</th>
<th>Cruise Speed</th>
<th>Cruise Speed (short flight)</th>
<th>Wind</th>
<th>Wind (short flight)</th>
<th>Weight</th>
<th>Flight Path Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large Jets</td>
<td>58</td>
<td>42</td>
<td>58</td>
<td>42</td>
<td>58</td>
<td>42</td>
<td>58</td>
</tr>
<tr>
<td>Medium Jets</td>
<td>107</td>
<td>70</td>
<td>107</td>
<td>70</td>
<td>107</td>
<td>70</td>
<td>107</td>
</tr>
<tr>
<td>Regional Jets</td>
<td>134</td>
<td>85</td>
<td>134</td>
<td>85</td>
<td>134</td>
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<td>134</td>
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<tr>
<td>All Aircraft</td>
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<td>115</td>
<td>175</td>
<td>115</td>
<td>175</td>
<td>115</td>
<td>175</td>
</tr>
</tbody>
</table>

## Constrained ETA Variability Results

<table>
<thead>
<tr>
<th>Constraint Descent</th>
<th>Descent Speed</th>
<th>Cruise Speed</th>
<th>Cruise Speed (short flight)</th>
<th>Wind</th>
<th>Wind (short flight)</th>
<th>Weight</th>
<th>Flight Path Angle</th>
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<tbody>
<tr>
<td>Large Jets</td>
<td>31</td>
<td>24</td>
<td>31</td>
<td>24</td>
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<td>Medium Jets</td>
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<td>All Aircraft</td>
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<td>179</td>
<td>120</td>
<td>179</td>
<td>120</td>
<td>179</td>
</tr>
</tbody>
</table>
Reduction in ETA Variability at MF with Speed-Constrained Arrival

**Summary**

- Constraining the arrival procedure reduces the TBFM ETA variability at MF for all the sensitivity variables.
- TBFM ETA Variability was most improved when using a speed-constrained procedure in lieu of the descent speed assumptions in TBFM.
- Using a constrained procedure can thus lead to improved prediction accuracy but has to be balanced by leaving the ability to “delay” a flight on that procedure.

### Constrained vs Unconstrained ETA Variability Reduction

<table>
<thead>
<tr>
<th>Improvement with Constraint</th>
<th>Large Jets</th>
<th>Medium Jets</th>
<th>Regional Jets</th>
<th>All Aircraft</th>
</tr>
</thead>
<tbody>
<tr>
<td>Descent Speed</td>
<td>25</td>
<td>13</td>
<td>13</td>
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<tr>
<td>Cruise Speed (short flight)</td>
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<tr>
<td>Wind</td>
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Summary

- Integrated design and analysis informs TBO benefits trade-offs when designing TBFM adaptation and PBN procedures at specific sites
- Three applications were presented to demonstrate how the proposed prototype could be used for integrated PBN and TBM design and analysis
  - Effective TBM Design
  - Use of Dual STARs with TBM
  - Use of Altitude and Speed Constraints in PBN to Support TBM
- 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 integrated PBN and TBM design and development of best practices to assist the aviation community in transitioning to TBO
- Ongoing discussions with FAA stakeholders on standardizing integrated design practices
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