Time-Based Delivery Accuracy
Requirements for Achieving Performance-Based Navigation Objectives

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What are Trajectory-Based Operations (TBO)?

- Well defined flight paths allow for a time-based schedule to define flight sequence and spacing.
- Time is used at specific merge and crossing points to integrate multiple traffic flows from different airports to define the right flight spacing intervals needed.
- Plans are updated as uncertainties manifest to maintain accuracy.
Problem

What level of delivery precision is necessary to support PBN success at target rates?

If delivery accuracy (relative to a deconflicted schedule) is poor, it is difficult for ATC to allow aircraft to stay on efficient PBN routes.

Key
- PBN: Performance Based Navigation
- ATC: Air Traffic Control
Why Not use HITL or Derive a Direct Result?

Human in the Loop (HITL) Simulation
- Too many variables to explore
- 27,000 input variable combinations

Derive Direct Result
- ATC interventions (and accuracy) with downstream traffic modify conditions for upstream traffic
Simulation Overview

Graph Theoretic

• Entire airspace represented with a graph

• Nodes are waypoints or locations of interest

• Edges define node connections & define probability of use and traversal times

Discrete Event

• Controllers watch nodes

• Events happen when an aircraft reaches a node

• Simulation jumps from event time to event time
Toy Example 1: Perfect Delivery Accuracy
Key
STA  Scheduled Time of Arrival
ETA  Estimated Time of Arrival

STAs are fixed when aircraft cross freeze horizon

scheduled traversal times (ABC1)

$t = 0$

+1 indicates scheduled time includes 1 time unit of delay
STAs are fixed when aircraft cross freeze horizon.

ABC1 and ABC2 advance according to expected ETA.

At t = 0:
- ABC1: Scheduled time (2) + delay (1) = 3
- ABC2: Scheduled time (3) + delay (1) = 4

At t = 3:
- ABC1 at B (2)
- ABC2 at D (3)

Sample ETA/STA timeline for ABC1 and ABC2.
ABC1 advances to merge point
ABC2 does not advance yet because it is on a longer segment

$t = 3$

$t = 5$
ABC2 separated in trail from ABC1 at merge point
ABC1 lands at scheduled time after flying an uninterrupted OPD
t = 7

ABC2 lands at scheduled time after flying an uninterrupted OPD

A   3   B   2
   E   2   F

t = 9

A   3   B   2
C   3   D
   E   2

Toy Example 2: Poor Delivery Accuracy
ABC2 advances but ABC1 is late, so it does not advance.
ABC1 advances, with an updated ETA

red +1 indicates delay extraneous to the schedule
ABC1 advances to merge point behind schedule

ABC1 advances, with an updated ETA

ABC1 advances to merge point behind schedule

ABC2 sequences behind ABC1 by absorbing more delay

ABC1 lands late, but has flown an uninterrupted OPD

orange +1 indicates a tactical delay to maintain spacing

ABC2 sequences behind ABC1 by absorbing more delay. ABC1 lands late, but has flown an uninterrupted OPD.

ABC2 lands late due to required tactical delay. Due to extra delay after TOD ABC2 did not execute the OPD.

Airspace Representation in the Simulation
Directed Weighted Graphs
Graph for Denver International Airport (KDEN)
Simulation Design
Simulation Inputs

- 2 weather conditions (IMC and VMC)
- 2 STAR designs (single & dual STARs)
- 3 runway configurations (one runway, two independent runways, and three independent runways)
- 8 demand values (15 flights per hour per runway up to 50 flights per hour per runway, in 5 flight increments)
- 2 RNP equipage settings (zero and 100 percent equipped)
- 150 delivery error settings (crossing errors at the XMP, CMP, MF, and inside the TRACON)

- 24,000 combinations
- 3 replications each
- 72,000 simulations planned
- 61,600 completed

Key

| IMC | Instrument Meteorological Conditions |
| VMC | Visual Meteorological Conditions |
| STAR | Standard Terminal Arrival |
| RNP | Required Navigation Performance |
| XMP | Extended Meter Point |
| CMP | Coupled Meter Point |
| MF | Meter Fix |
| TRACON | Terminal Radar Approach Control |
STARs, Runway Configurations & Demand

3 Runways  2 Runways  1 Runway

flights per hour
50  100  150

demand / runway
50  40  30  20

number of runways
1  2  3
Delivery Errors

- XMP delivery errors of 0 seconds and 5 minutes
- CMP delivery errors of 0 seconds, 1.5 minutes, and 3 minutes
- MF delivery errors of 0, 15, 30, 50, and 60 seconds
- TRACON delivery errors of 0, 6, 12, 18, and 24 seconds
Tapering Delivery Errors

![Graph showing tapering delivery errors for XMP, CMP, MF, and TRACON](image-url)
Irregular Delivery Errors

![Graph showing delivery errors for XMP, CMP, MF, and TRACON]
Validation
Results
Marginal Main Effects
Fractional Response Regression Model

\[
\ln \left( \frac{\theta(\sigma, X)}{1 - \theta(\sigma, X)} \right) = 0.971 - 0.048\sigma_{XMP} - 0.032\sigma_{CMP} - 0.732\sigma_{MF} - 1.27\sigma_{RWY}
\]

- Left:
  \[ \sigma_{XMP} = \sigma_{CMP} = \sigma_{MF} = \sigma_{RWY} = 0 \]

- Right:
  \[ \sigma_{XMP} = 5 \text{ min}, \sigma_{CMP} = 3 \text{ min}, \sigma_{MF} = 1 \text{ min}, \sigma_{RWY} = 24s \]

- Box plots represent simulation results, points and line from regression model

Effect of Delivery Error on PBN Use

- Increasing error anywhere decreases the probability of flying a fixed path
- Positive interaction terms between delivery error terms mean that the negative effects of increasing error at two MRPs is less than the sum of its parts
Effect of Runway Demand on PBN Use

- Holding all other values at 0, increasing $x_{\text{rwy demand}}$ from 0 to 1 (from 15 to 20 flights/runway/hour) decreases the probability of flying fixed paths by 7.4 percentage points.

- When demand and delivery error both increase, the positive interaction terms partially mitigate the negative effect that each of those changes have.

- Using dual STARs exacerbates the negative effect of increasing runway demand, with $x_{\text{dual STARs}} = 1$, increasing $x_{\text{rwy demand}}$ from 0 to 1 decreases the probability of flying fixed paths by 11.7 percentage points.
Effect of RNP Equipage on PBN Use

- All coefficients for terms involving RNP equipage are positive, so being equipped instead of non-equipped only helps things.

- For example, if all inputs are at their zero-value moving from a non-RNP operation ($x_{is\ RNP}=0$) to a full RNP operation ($x_{is\ RNP}=1$) increases the expected fixed path rate by 8.5 percentage points.

- $x_{is\ RNP}$ was modeled as a categorical indicator variable, so it is not appropriate to use fractional values to estimate mixed equipage effects.
Effect of Dual STARs on PBN Use

- Dual STARs help in some contexts (e.g., low errors, modest demand)
- In higher demand operations they decrease the fixed path rate
Summary & Next Steps

PBN Utilization is Harder When:

- Arrival demand increases
- Delivery error at meter points increases
- No RNPs exist (vs. with RNPs and full RNP equipage/authorization)
- Dual STARs are mixed with high demand and/or poor delivery accuracy

More Research Needed To:

- Assess mixed RNP equipage
- Investigate the impact of internal departure release time errors
- Validate results against more realistic extended metering designs
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