Flight Deck Perspectives on the Complexity of Navigating in the Airport Terminal Area

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  - Contributors from USDOT Volpe Center
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  - Many other contributors from the FAA and aviation industry

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Overview

- This talk presents highlights of human factors research on performance-based navigation (PBN) operations from the pilot's perspective.
- Its scope includes airport arrival, departure, and approach routes.
- Agenda
  - Background – Problem description
  - Data – Findings from two studies
  - Concepts – Complexity constructs
  - Application – Transfer to practice

Background

Problem Description

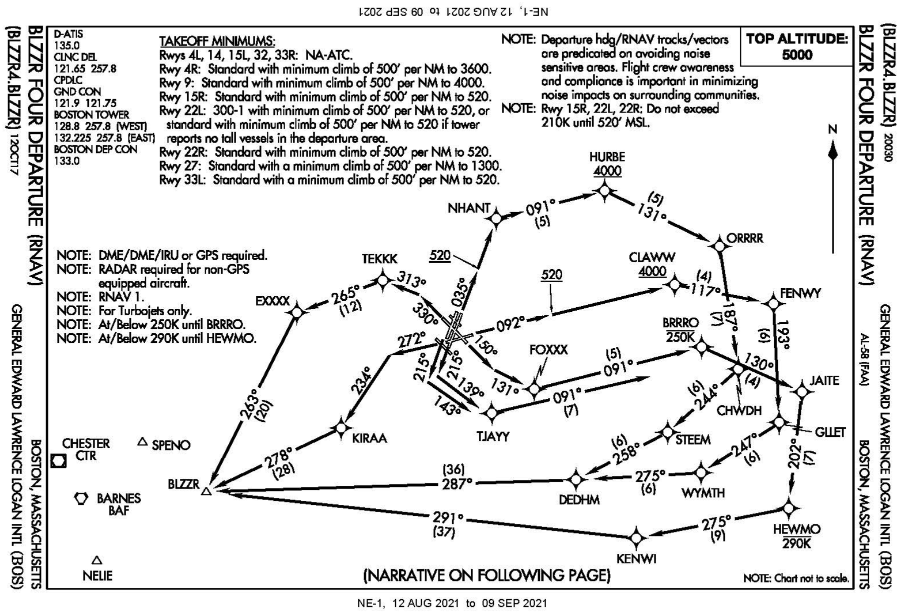
The Big Picture: Goals

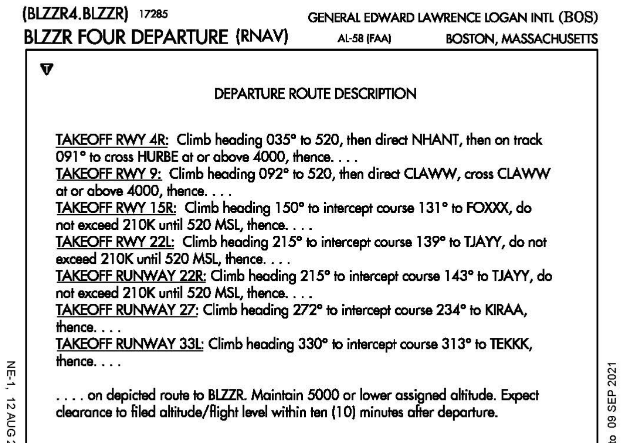
- Give pilots clear instructions for flying arrival, departure, and approach routes
- Clearly convey any restrictions on speed and altitude
- Allow both flexibility and efficiency of operations
- Accommodate as many aircraft types as possible
- Consider human performance, workload, and potential for confusion

http://commons.wikimedia.org/wiki/File:Map-USA-Southwest01.png

Instrument Arrival and Departure Procedures

- Issued as clearances by Air Traffic Control (ATC) for operations under Instrument Flight Rules (IFR)*
- Allow controllers to issue one instruction instead of multiple clearances to get in and out of the airport.
- Charts depict the flight path both graphically and in text.
- The routes are coded into the flight deck navigation database and are typically flown with the flight management system (FMS). They can span many miles.
- The procedures can be modified in real-time. ATC can amend altitudes or speeds as needed.





NE-1, 12 AUG 2021 to 09 SEP 2021

(BLZZR4.BLZZR) 17285
BLZZR FOUR DEPARTURE (RNAV)
GENERAL EDWARD LAWRENCE LOGAN INTL (BOS)
AL-58 (FAA)
BOSTON, MASSACHUSETTS

DEPARTURE ROUTE DESCRIPTION

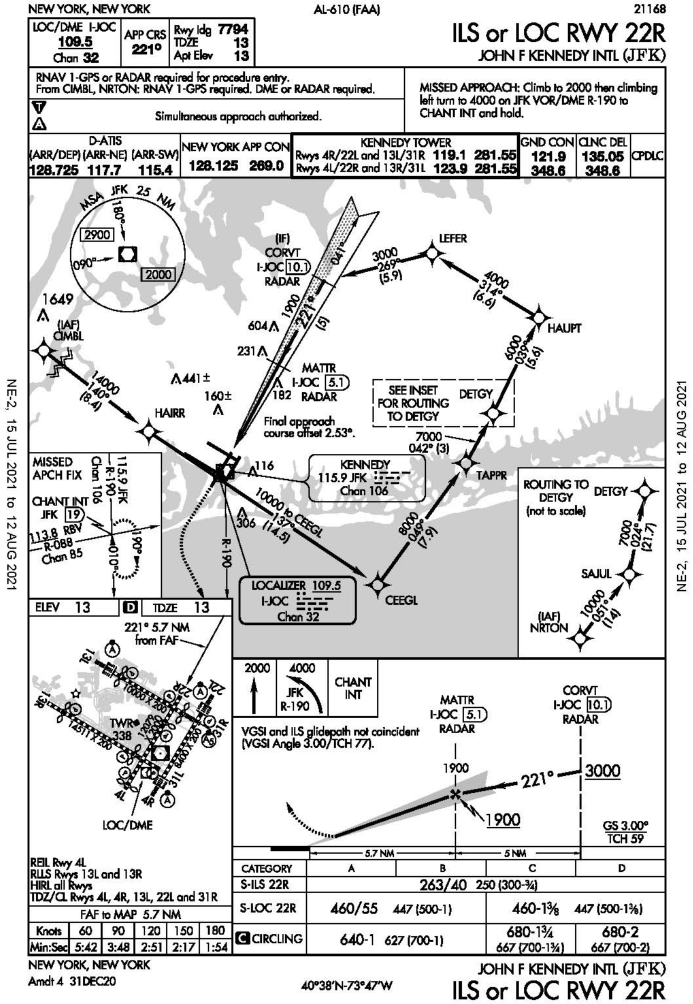
TAKEOFF RWY 4R: Climb heading 035° to 520, then direct NHANT, then on track 091° to cross HURBE at or above 4000, thence. . . .
TAKEOFF RWY 9: Climb heading 092° to 520, then direct CLAWW, cross CLAWW at or above 4000, thence. . . .
TAKEOFF RWY 15R: Climb heading 150° to intercept course 131° to FOXXX, do not exceed 210K until 520 MSL, thence. . . .
TAKEOFF RWY 22L: Climb heading 215° to intercept course 139° to TJAYY, do not exceed 210K until 520 MSL, thence. . . .
TAKEOFF RUNWAY 22R: Climb heading 215° to intercept course 143° to TJAYY, do not exceed 210K until 520 MSL, thence. . . .
TAKEOFF RUNWAY 27: Climb heading 272° to intercept course 234° to KIRAA, thence. . . .
TAKEOFF RUNWAY 33L: Climb heading 330° to intercept course 313° to TEKKK, thence. . . .

. . . . on depicted route to BLZZR. Maintain 5000 or lower assigned altitude. Expect clearance to filed altitude/flight level within ten (10) minutes after departure.

*Instrument flight rules (IFR). Rules and regulations established by the Federal Aviation Administration to govern flight under conditions in which flight by outside visual reference is not safe. IFR flight depends upon flying by reference to instruments in the flight deck, and navigation is accomplished by reference to electronic signals. [FAA Instrument Flying Handbook, FAA-H-8083-15B, 2012]

Instrument Approach Procedures

- Arrivals join runway approaches for landing, sometimes directly and sometimes through ATC vectors.
- Approach flight paths avoid terrain, obstacles, restricted areas, etc.
- ATC cannot amend an instrument approach path. It must be flown as published.
- There are many types of instrument approaches. The flight paths can rely upon different types of navigation and have different levels of lateral and vertical precision.



Viewpoints on the Design of Airport Terminal Arrival, Departure, and Approach Flight Paths

- Design of the flight path
  - Content and instructions
  - “Instrument flight procedure” (IFP)
- Cartographic design / chart depictions
  - Communicating the content
- Interrelated with operations, avionics, aircraft performance, pilot training

ATC

http://en.wikipedia.org/wiki/Switchboard_operator

Airplane

Pilot

Designer

Operator

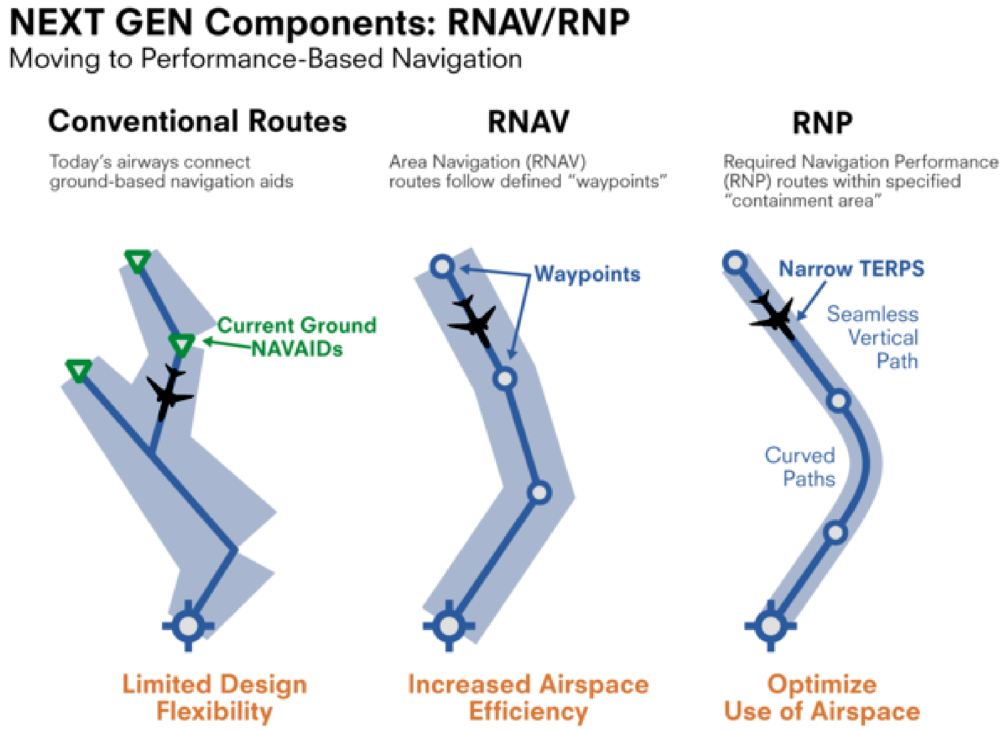
Chart

Regulator

Human Factors?

The PBN Instrument Flight Procedure (IFP) Design Toolbox

PBN = Area Navigation (RNAV) + Required Navigation Performance (RNP)

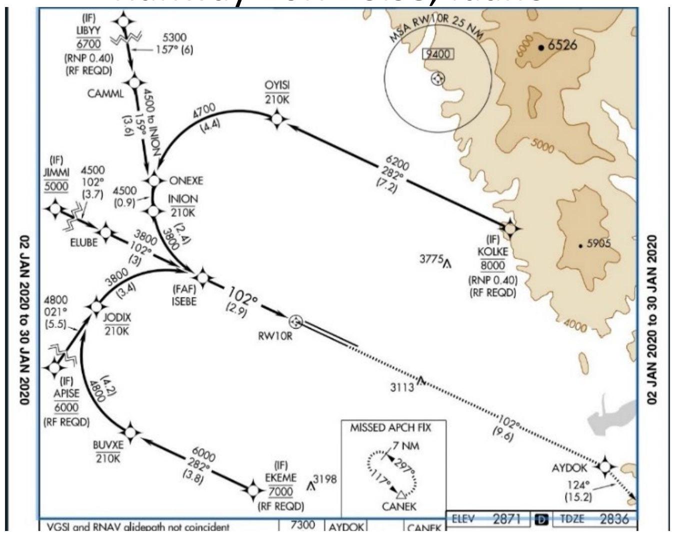


Source: Federal Aviation Administration

More About PBN

- PBN is a key component of the FAA's NextGen system
  - Improves safety and efficiency of flight paths
  - Used for airport terminal IFPs (i.e., departures, arrivals, and approaches)
- PBN introduces **challenges** for pilot performance such as
  - More precise routes and constraints
  - New types of terminal IFPs
  - More branches on IFPs
  - More waypoints/segments
  - More notes and information to process
- These challenges can result in
  - More reliance on automated systems
  - More complicated decisions about whether to accept (or reject) a PBN IFP clearance
  - Difficulties during operational deployment of new PBN IFPs

RNAV (RNP) Approach to Runway 10R Boise, Idaho



Nonstandard chart layouts

Data

Findings from Two Studies

Highlighted Studies

1. **Can pilots use charts effectively?**
   - Part-task experiment to examine response time and accuracy of finding specific data on charts.
2. **In addition to charts, what factors influence whether an arrival, departure, or approach is flown correctly?**
   - Structured interviews with line pilots and observation of crew briefings to understand how they interpret and fly arrival, departure, and approach procedures.

Overview of Visual Complexity Study*

- Can charts be simplified by separating route branches onto different pages?
  - Hypothesis: It is faster to find information from modified charts that show fewer branches of the flight path.
- Compared time and accuracy of finding answers to specific questions from current and modified charts
  - 47 professional pilots
  - High-fidelity modified departure and approach charts made by two different producers (FAA and Jeppesen)
  - Showed chart images on a computer monitor, one at a time
  - Recorded answers and response times

Example Questions

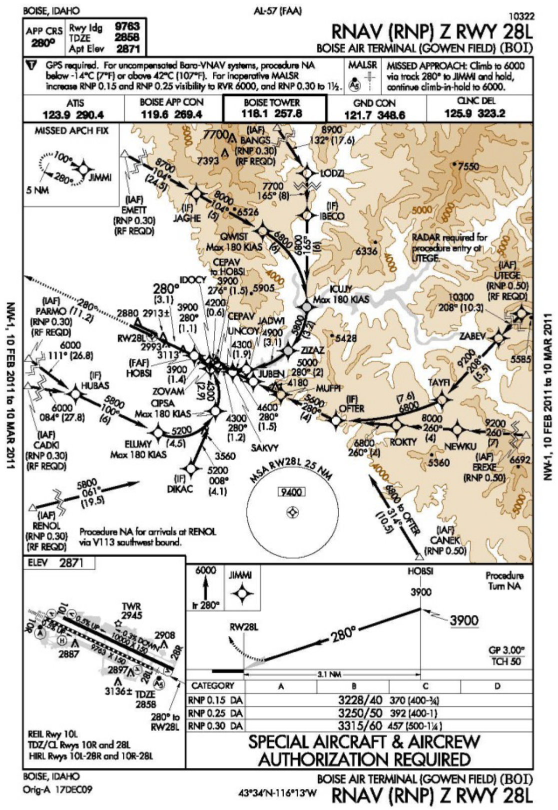
- You are cleared to the DeKalb-Peachtree Airport (PDK) for RNAV (RNP) Z RWY 20L via BUNNI. *What is the missed approach fix?*
- You are cleared to depart from the Los Angeles International (LAX) via HOLTZ NINE departure via RWY 24R. *What is the distance from FABRA to ENNEY?*

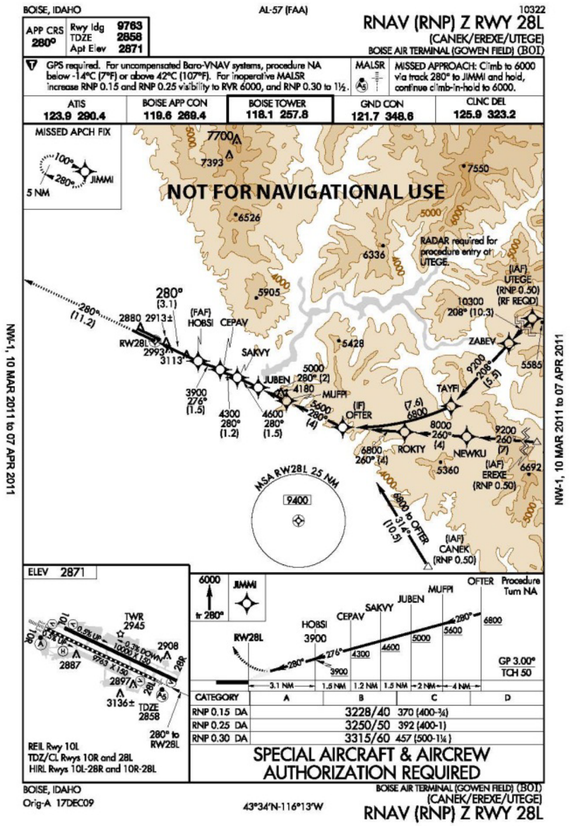
*Part of A. Butchibabu's SM thesis 2012 (MIT)

Sample Chart Modification

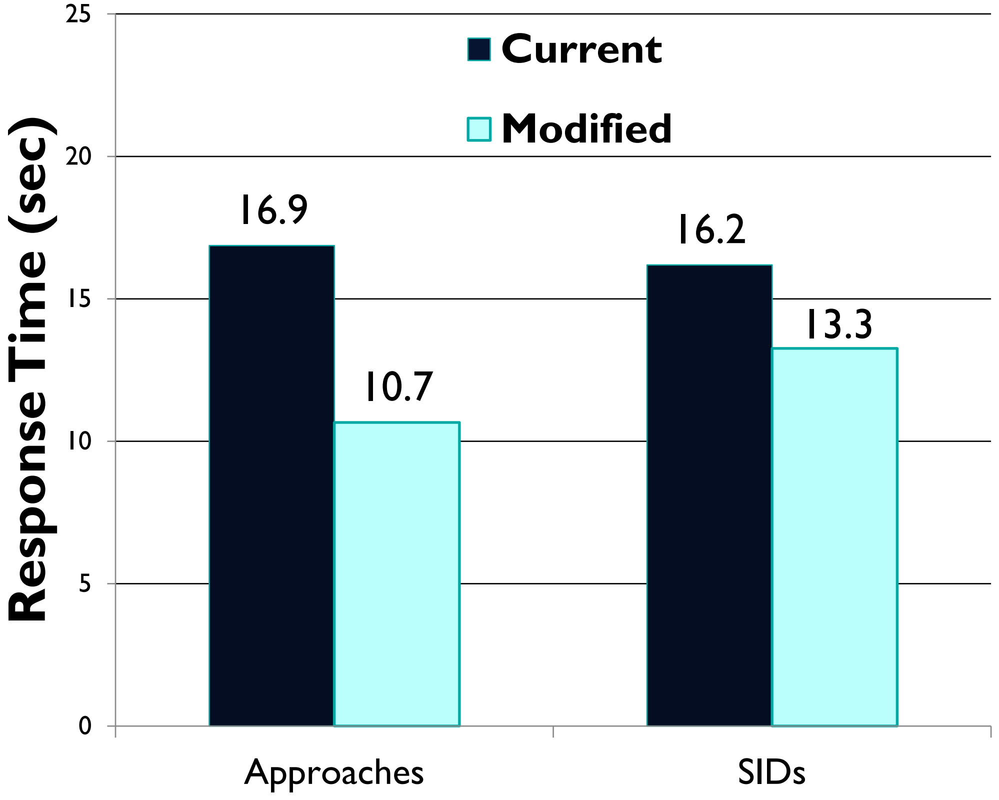
- High fidelity chart images
- Erased path(s), but did not zoom or re-center the chart
- Added line to chart title and updated vertical profile view

➢ The modifications result in multiple chart images from one original chart





Key Results



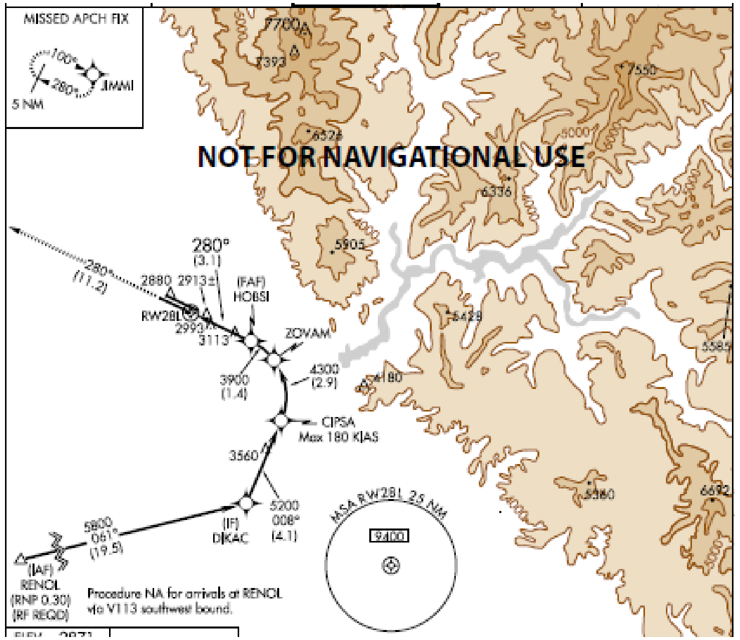
SID = Standard Instrument Departure procedure

*Data includes all trials.

- Pilots **find data significantly faster** from modified charts
- All charts showed benefits of modification
- Some charts benefited more than others
- Benefits also varied by charting convention (Jeppesen or FAA)
- Good response accuracy (>90%) for most questions, but some questions had more errors than others, especially related to altitude constraints

Response Time by Element Count: Method

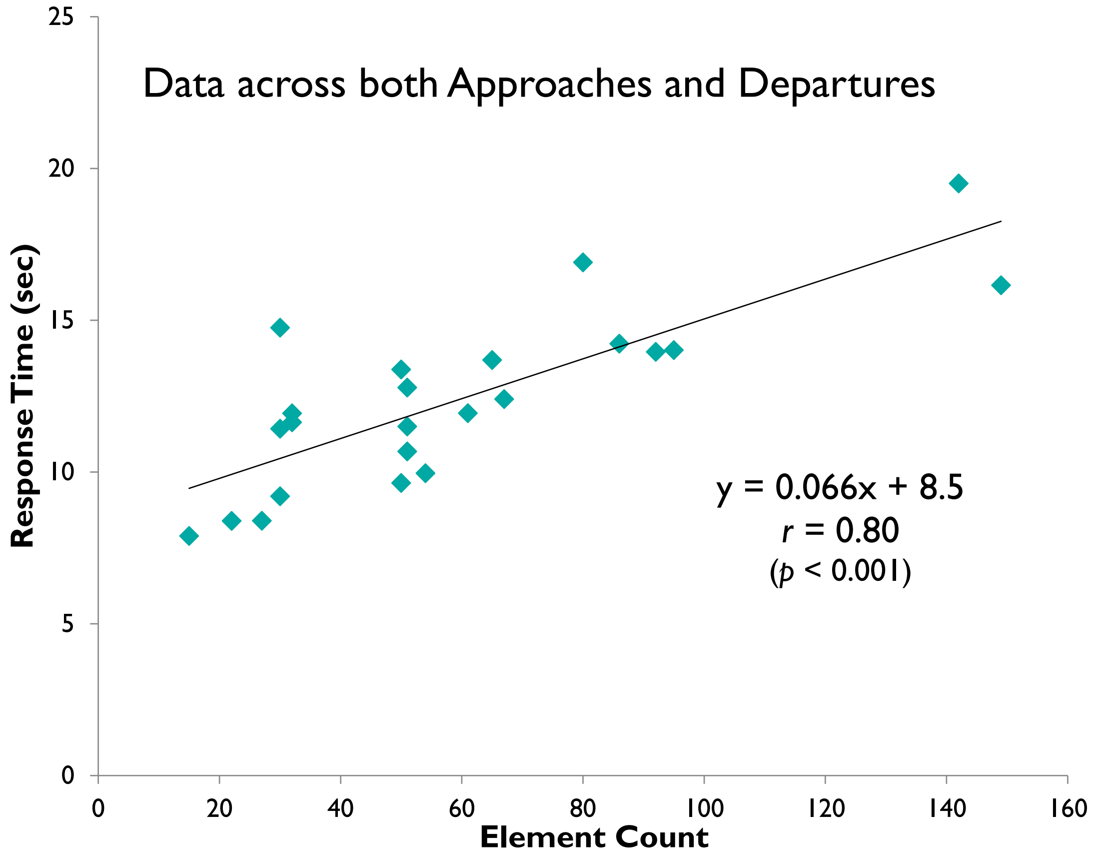
- Counted elements on the graphical view
  - Different element count for each modified chart image
- Correlated number of elements with average response time for that image



Elements Counted for Both Approaches and Departures	Boise Approach Renol Image Example Count
Minimum En route Altitudes	4
Headings	3
Distances	5
Waypoints	5
Altitude Restrictions	0
Speed Restrictions	1
Notes	1
Additional Elements Counted for Approaches	
Radius-to-Fix Legs	2
Holding Patterns	1
Additional Element Counted for Departures	
Minimum Obstruction Clearance Altitudes (MOCAs)	

Response Time by Element Count

- Removed outliers (response times > 60 sec)
  - 1.8% of approach trials
  - 1.8% of departure trials
  - One bad departure question (1.6%)
- Linear relationship between count of elements and response time
  - Approaches $r = 0.86$, $r^2 = 0.76$
  - Departures $r = 0.88$, $r^2 = 0.78$
- No correlation with questions from outside the plan view on approaches
- Implication
  - Serial (random) search across the graphical elements
  - Classic visual search



Overview of Line Pilot Perspectives Study

- Participants, Procedure, and Task
  - 3 hours of observation and discussion with groups of 2-3 line pilots from the same operator
  - Office setting
  - Brief and discuss 2 Departures, 2 Arrivals, and 2 Approaches
  - Informed consent & modest payment ($200)
- Equipment
  - Static chart images, current for each session
  - Jeppesen paper (or electronic) charts*
- Data
  - Two researchers took notes, real-time transcripts
  - Summarized all sessions into a common format
  - Look for patterns in the responses

* Used the "old" Jeppesen format (2014-15).

Participants

- 45 US pilots across 19 sessions
  - From three major airlines, one regional airline, one air taxi, three corporate operators
  - 23 qualified for RNP “Authorization Required” (AR) procedures, 22 not qualified
  - High comfort levels with FMS, RNAV, RNAV (RNP) AR
  - All used Jeppesen charts
- Broad range of aircraft types
  - All equipped with FMS
  - Advisory VNAV or Coupled VNAV
  - Some with autothrottle, some without

Photo by Divya Chandra

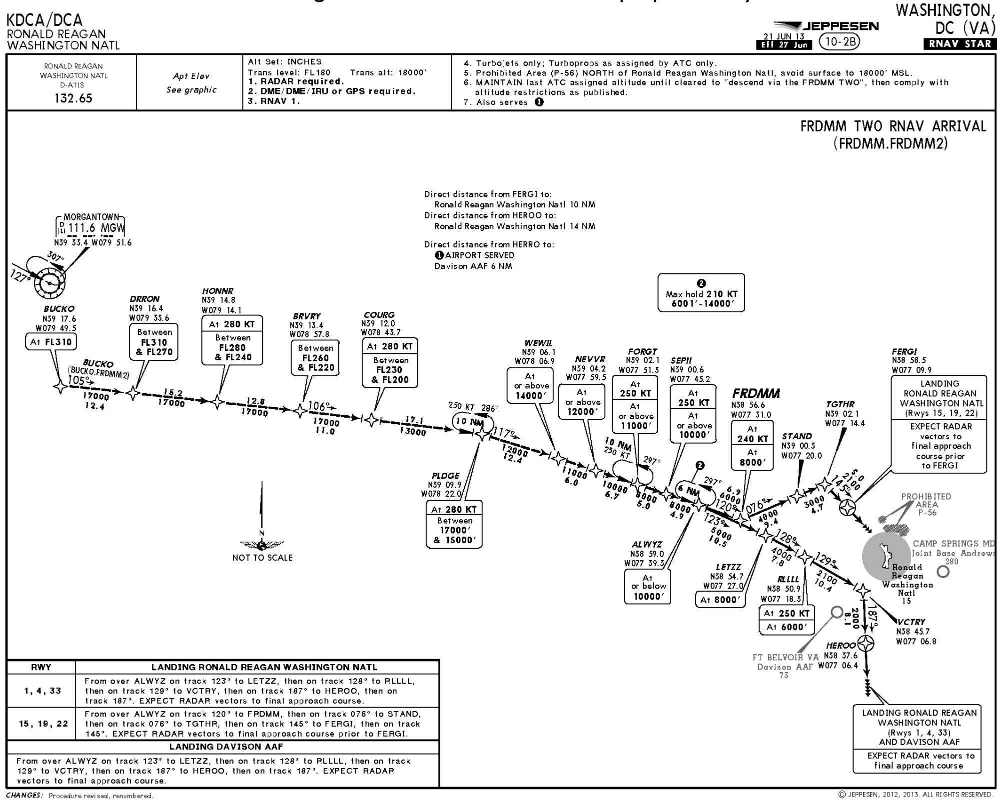
US = United States
RNP = Required navigation performance
FMS = Flight Management System
VNAV = Vertical Navigation

Task Fidelity

- No simulator
  - Participants had to explain what they would look at and why
- No assigned clearance or weather scenario
  - Picked their own, or discuss different situations
- Alternated “pilot flying” and “pilot monitoring” roles
- Talked through anything they would do before doing “the” briefing (for context)
- Balance between formality and informality
  - Good to have at least two pilots in the room

Example: KDCA FRDMM TWO

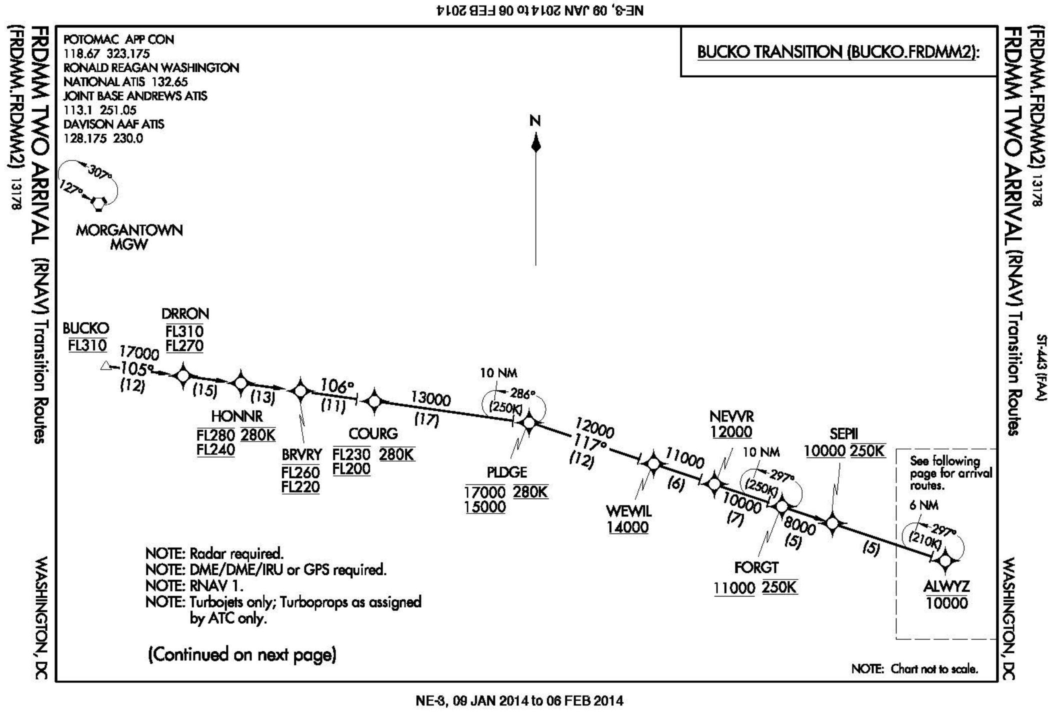
- Join the RNAV Arrival at BUCKO at FL310. Fly eastbound while descending and meeting several altitude and mandatory speed constraints.
- Then fly either the north or south transition to the correct bottom altitude. Vectors to the approach.
- Primary landing airport is Washington National (KDCA). Prohibited areas nearby.
- Key characteristics
  - Optimized profile descent (to conserve fuel and reduce noise profile)
  - Many waypoints (11 on common route, 3 on one transition, 4 on the other)
  - Many different types of altitude constraints including at, at or above, at or below, windows, and co-located altitude and speed constraints
  - Jeppesen chart is one full size page*

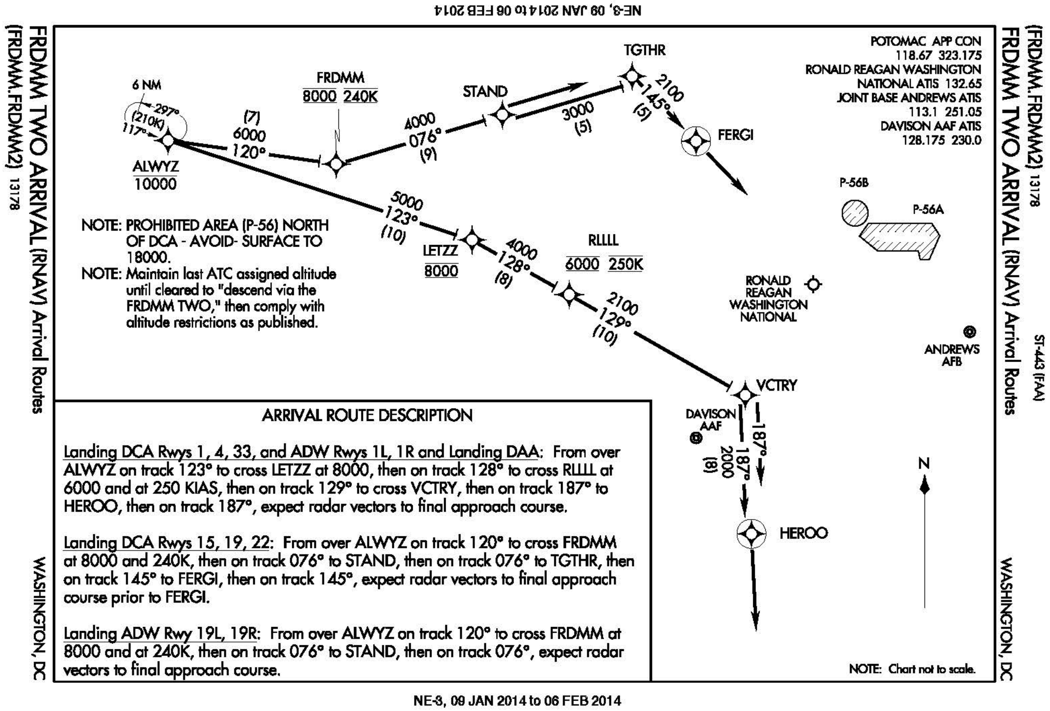


RNAV Optimized Profile Descent (OPD) arrival
Multiple window altitude constraints

*Used the "old" Jeppesen format. Current FRDMM FIVE is drawn largely to scale.

FAA Depiction for KDCA FRDMM TWO

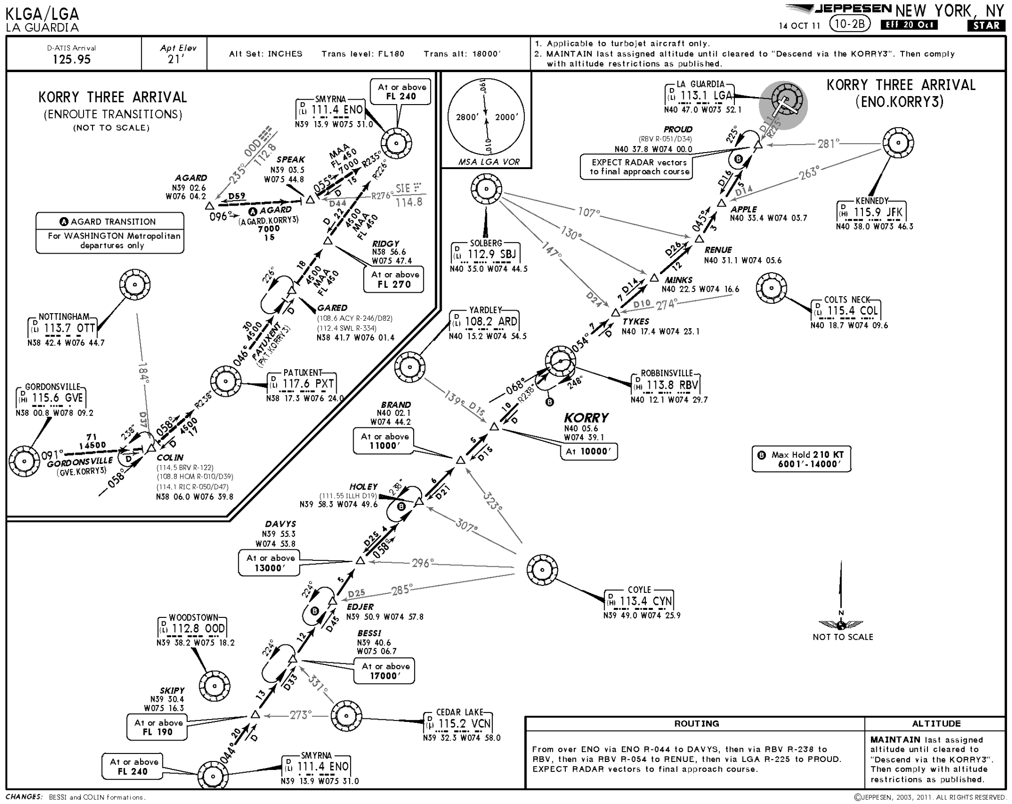




FAA draws the IFP across two pages.

Example: KLGA KORRY THREE

- Join the arrival to LaGuardia (KLGA) from either Agard or Gordonsville enroute transition. Both meet at Smyrna.
- Continue descending to 10000 ft (and 250 knots) at KORRY, meeting “at or above” altitude constraints along the route.
- Vectors to the approach.
- Key characteristics
  - Conventional arrival that uses ground-based navigation aids, not PBN
  - Many waypoints (14 on common route, five on one transition, four on the other)
  - Seven “at or above” altitude constraints and one mandatory altitude with an implied speed constraint at KORRY
  - Jeppesen version of chart shows enroute transitions in “inset” box*
  - ATC often dictates speeds in actual operations

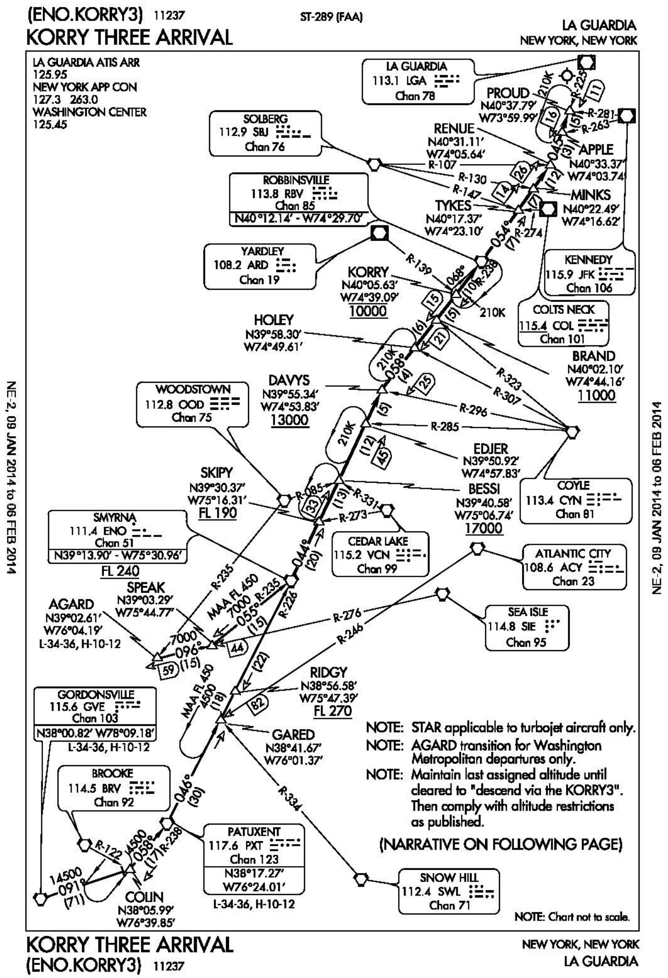


Conventional arrival with VOR radials

*Used the “old” Jeppesen format. Current KORRY FOUR is drawn largely to scale.

FAA Depiction of KLGA KORRY THREE

- Conventional arrival includes data for ground-based navigation aids
- Only one hard altitude constraint
- One-page FAA graphic with text narrative on separate page



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FRDMM vs. KORRY Data

- 2 groups thought FRDMM was easier to fly than KORRY
  - Felt it was easier to have altitude or speed constraints at each point than to NOT have altitude and speed directives
  - Newer, high-end aircraft avionics

- 11 groups thought KORRY was easier to fly than FRDMM
  - FRDMM has many different types of altitude constraints
  - FRDMM has more hard altitude constraints than KORRY
  - FRDMM has speed restrictions, KORRY does not
  - KORRY has no window altitude constraints (which are harder than At or Above)

FRDMM is "designed for aircraft that have vertical navigation (VNAV)."
~from a pilot who flew it with and without VNAV

KORRY vs. FRDMM Pros and Cons

- 2 groups thought workload was equal for FRDMM and KORRY
  - FRDMM has more restrictions, but altitudes load in the FMS
  - Vectors at the end of both

- 3 had mixed opinions. Either the pilots disagreed, or the groups found pros and cons for each.

	KORRY	FRDMM
Pros	Fewer restrictions, less rigid path	Less complicated chart. Only one path and no inset on Jeppesen chart.
Cons	Inset on the Jeppesen chart* (“busy to the eyes”)	Split path for north/south landing transitions Looks more cluttered because of speed restrictions “Excessive number” of altitude constraints

*On the “old” Jeppesen format.

Cleaning up the Raw Data

- Participants didn’t always clearly distinguish between IFP and chart complexity. Had to clear up the overlap.

- A lot of the IFP complexity factors participants mentioned are not under the control of IFP designers. Participants were actually describing “operational” complexity.

- We had to define “subjective complexity” more formally and separate it from “operational complexity.”

Across all studies, we learned…

- Visually complex (“busy”) charts are harder to search
- Instrument flight procedure (IFP) design affects chart visual complexity
- IFP complexity is hard to measure and quantify objectively
- IFPs versus charts
  - Charts depict the IFP
  - Should consider both the IFP and chart to understand complexity fully
- “Operational complexity” has to be handled in real-time
- PBN magnifies the impacts of “operational complexity”

Concepts

Complexity Constructs

IFP Designer's Perspective on Complexity

- IFP designers may not be pilots. They develop flight paths using software tools.
- They break down the flight path analytically.
  - Lateral path
  - Vertical path
  - Speed profile
  - Other
    - Visual depiction
    - "Flyability"
    - Clarity
    - FMS navigation database coding

But how does the (line) pilot see IFP complexity?

IFP = Instrument Flight Procedure (flight path)

Line Pilot Perspective: The Complexity Space

- Subjective complexity is when a task requires extra mental or physical steps by the pilot; this is related to agenda management
- Flight path
  - Lateral complexity (related to turns) is handled well by the FMS.
  - Vertical complexity covers both vertical path and speed issues. These are wrapped up in constraints from the pilots' point of view.
- Chart depiction
  - Visual complexity (affects visual search)
- Operations
  - Operational complexity is the big bucket of complexity that cannot be controlled through IFP or chart design.
- Airspace
  - Airspace complexity for pilots consists of factors that are external to the pilot and operator. It is a mix of operational complexity factors and IFP/airspace design factors. It is related to airspace complexity for ATC.

Defining Subjective Complexity

- **Subjective complexity** is present when a task requires *extra* mental or physical steps by the pilot.
  - Examples
    - Increased memory/awareness/attention
    - More button pushes than necessary
  - Phrases such as “be careful when” or “pay attention to” or “don’t forget to” or “better ask” or “it only works when” indicate subjective complexity.

Subjective Complexity and Agenda Management

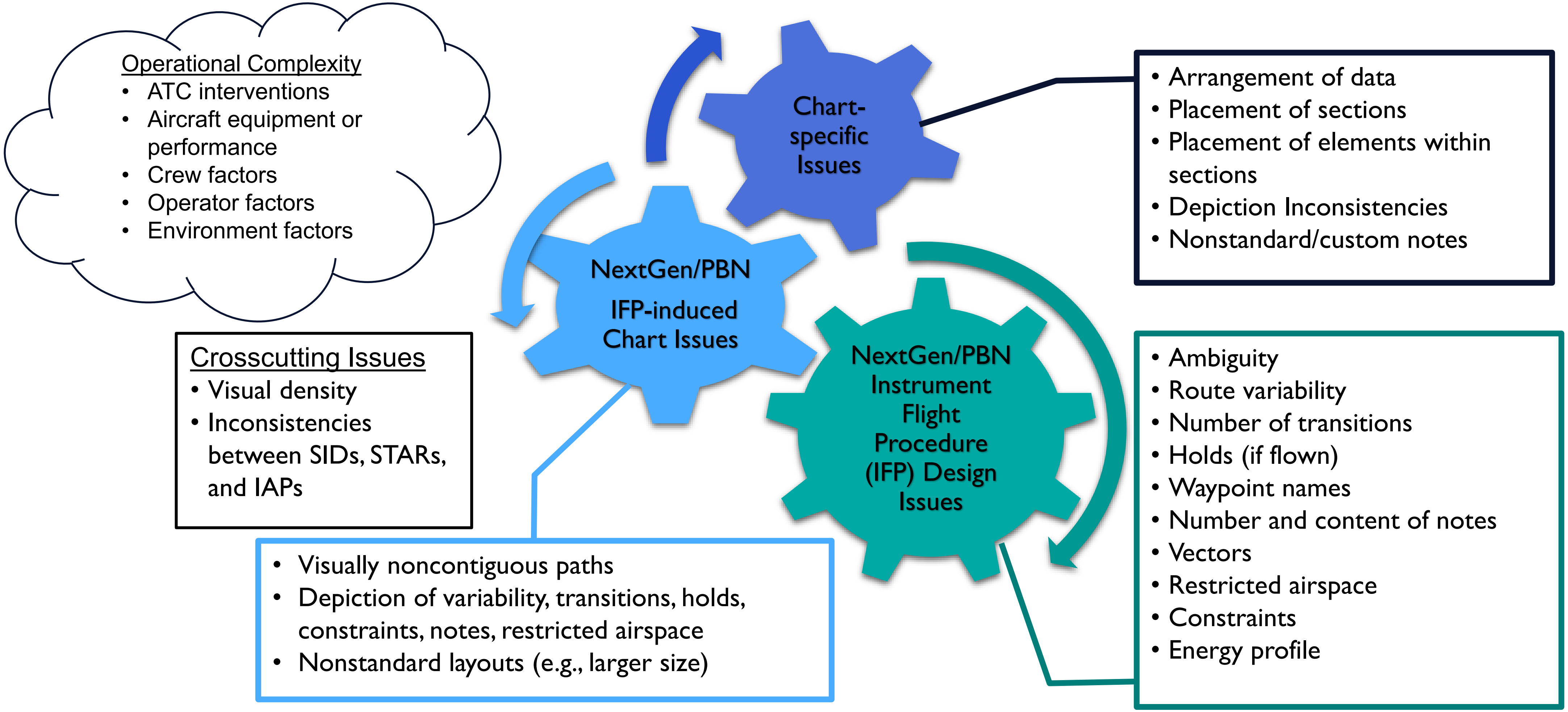
An ***agenda*** is a hierarchy of tasks to be completed during a mission. Each task is defined to achieve a specific goal and should become active when the goal's initial event occurs. (Funk, 1991)

- In other words, more subjective (and operational) complexity means more pilot tasks, and pilots have to determine resources and priority for every task.
- Pilots have to decide when to initiate the task, who or what should do it, etc.

More complexity → more tasks → more decisions

Funk, K. (1991). Cockpit task management: Preliminary definitions, normative theory, error taxonomy, and design recommendations. *International Journal of Aviation Psychology 1(4)*, pp. 271-285.

Subjective Complexity Framework



Chandra, D.C., & Markunas, R. (2017). "Line Pilot Perspectives on Complexity of Terminal Instrument Flight Procedures," DOT-VNTSC-FAA-17-06. U.S. DOT Volpe National Transportation Systems Center. https://rosap.ntl.bts.gov/view/dot/12502

Why is the framework important?

- Because it helps to identify the origin of the problem. Once you know where the complexity is coming from, you have a better chance of fixing it.
- It also identifies interactions between the chart and the IFP design, so that different groups can work together to resolve issues.
- And it identifies areas of complexity that won't be solved by chart manufacturers and IFP designers.

What is operational complexity?

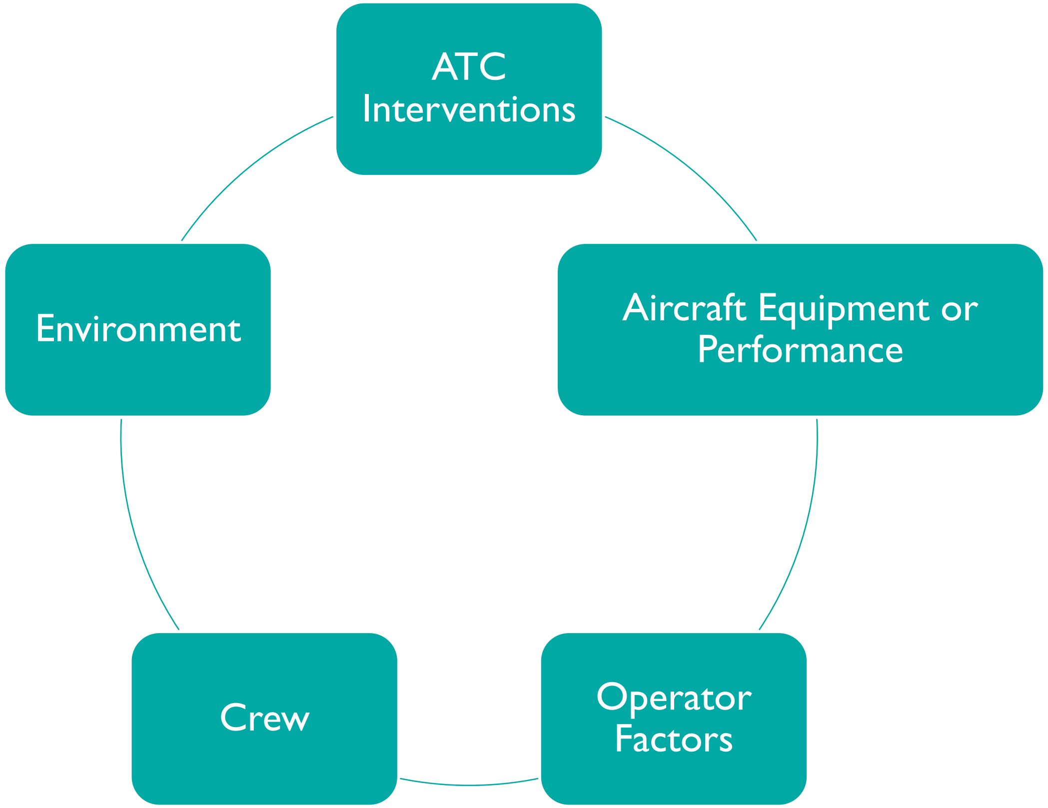
- Intuitively?
  - “The best laid plans of mice and men often go awry.”
  - Google Scholar result

    “In manufacturing and supply chain management, complexity implies *number of elements or subsystems, degree of connectivity and interaction among the elements, unpredictability, uncertainty, and variety* in products and in system states.”*
- In aviation?
  - Day-to-day variation…weather, traffic, equipment problems…
- On the flight deck?
  - Stuff happens and the pilot has to deal with it
- Operational complexity is not new.

*Wu, Frizelle, and Efstathiou (2007). A study on the cost of operational complexity in customer-supplier systems. Int. J. Production Economics 106 217-229.

Operational Complexity and PBN

- Operational complexity factors can increase pilot tasks
- Cannot be planned for in advance through IFP design
- These factors and situations occur in normal operations, day-to-day variability.
- The pilot and ATC have to resolve operational complexity issues together in real-time.
- PBN can complicate the situation, but operational complexity exists even without PBN.



Chandra, D.C., Sparko, A., Kendra, A., & Kochan, J. (2020). "Operational Complexity in Performance-Based Navigation (PBN) Arrival and Approach Instrument Flight Procedures (IFPs)," DOT-VNTSC-FAA-20-02. U.S. DOT Volpe National Transportation Systems Center. https://rosap.ntl.bts.gov/view/dot/43835

Chandra, D.C., & Markunas, R. (2017). "Line Pilot Perspectives on Complexity of Terminal Instrument Flight Procedures," DOT-VNTSC-FAA-17-06. U.S. DOT Volpe National Transportation Systems Center. https://rosap.ntl.bts.gov/view/dot/12502

Application

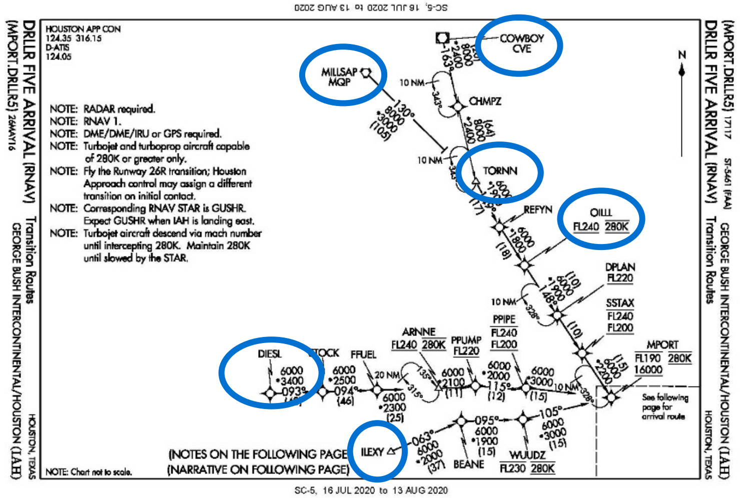
Transfer to Practice

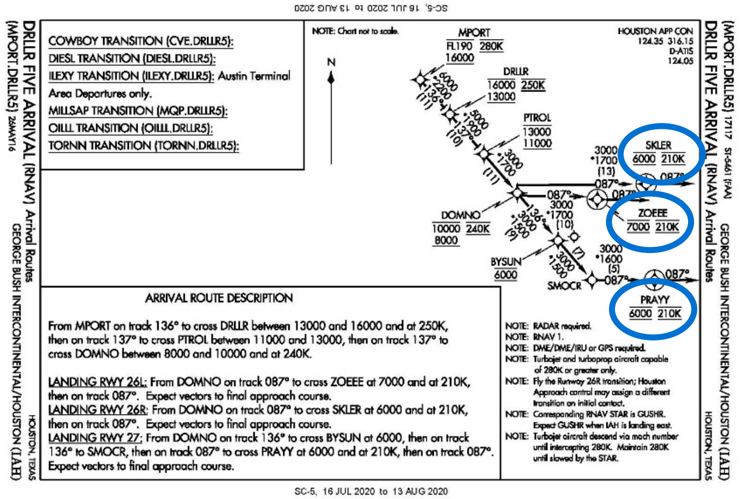
Review

- Project began by studying approaches, arrivals, and departures and the demands of PBN on flightcrews
  - Design of aeronautical charts and their impact on the usability of PBN IFPs
  - Partitioned the complexity space
  - Studied impacts of real-world operational environment on execution of these routes

- At each stage, we also developed recommendations for government and industry to help anticipate and reduce issues with flying PBN IFPs.

- And we coordinated research plans with, and communicated results to, government-industry working groups continuously so that our work could be considered in their discussions and recommendations.





Houston (IAH) DRLLR5 RNAV arrival route
- 6 arrival enroute transitions
- Common route from MPORT to DOMNO
- 3 arrival runway transitions

Example: Assessment of Chart Modification Technique

- Benefits

  The technique could help simplify IFPs with multiple route branches, especially when depicted on electronic (real-time data-driven) displays (rather than static PDF depictions).

  - The branches could be turned on and off in real-time through software logic or user customization.
  - Related enhancements should also be evaluated, such as zooming and re-centering of the modified chart images.

But…

- Practical considerations may outweigh the benefits of this technique.
  - It does not address other types of complexities (e.g., multiple constraints along an arrival).
  - The number of chart images would increase.
    - More difficult search/access for pilots.
    - Pilots may be less aware of alternative routes or may have difficulty switching charts if their clearance is amended.
    - Higher maintenance costs for chart manufacturers.
  - Criteria need to be developed for consistent and predictable use of the technique.

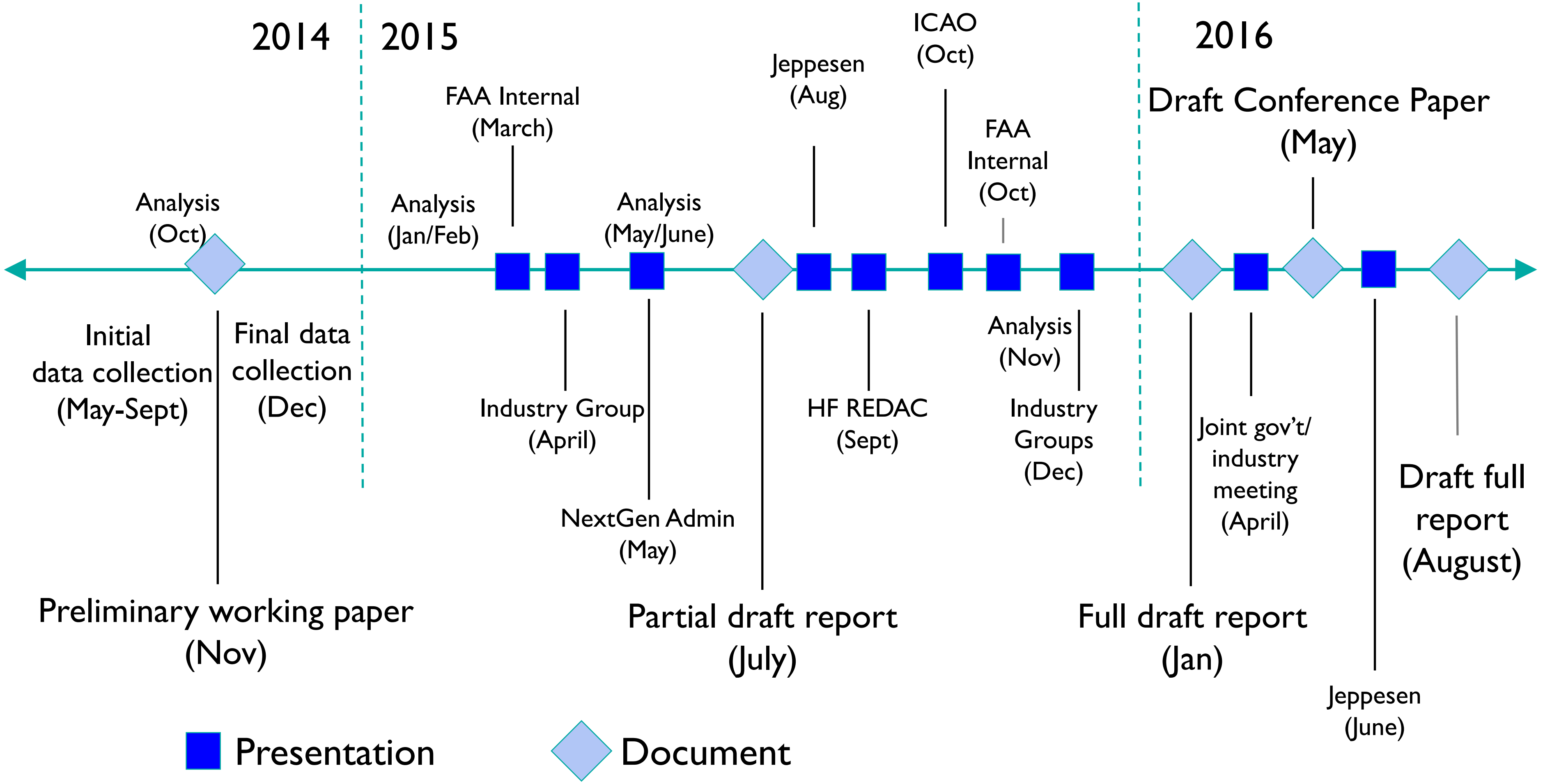
Lessons for Human Factors Researchers

- What researchers need
  - Positive and regular engagement and dialogue with stakeholders
  - Broad understanding of context, technology, application, and “literature”/technical documents (beyond the “human factors”)
- What researchers should do
  - Define a problem statement and select a method to address the research need
    - Generate and “test drive” multiple options before selecting the approach
  - Consider different levels of fidelity (for equipment, task, and participants) and different types of data to collect
    - Face validity is important for transfer to practice, but it can complicate the data collection. Find a balance.
- What output researchers should generate
  - Make recommendations for industry and government stakeholders, not just for other researchers
  - Communicate results often and to a variety of audiences.
    - Update analyses based on their questions and feedback
    - Shorter documents and briefings that are publicly available are more likely to reach a broad audience

Recommendations for Recommendations

- Readable (language and construction), actionable, understandable (make sense, tell a believable story), trustable (face validity)…
- Recommendations should be traceable to their impact on pilot tasks.
- It helps to highlight recommendations by separating them from other text.
- Let others (not researchers) determine who implements the solution and how.

Example: Communicating Results Early and Often



HF REDAC = Human Factors Research, Engineering, and Development Advisory Committee
ICAO = International Civil Aviation Organization

⚠ Constant Cultivation Required

- People turn over; need to continuously educate new stakeholders about past work
  - "Lessons learned" are not easy to access or recall
- Draw connections between past work and new questions
  - Can previous results be generalized?
  - Can the past studies make predictions for new situations?
  - Why or why not?

Concluding Thoughts

Summary

- We have a better understanding now of why it is so difficult to implement PBN instrument flight procedures (IFPs) in real operations. There are many sources of complexity.
- Resolving issues requires coordination between many stakeholders.
- Our research has impacted dialog in the broader stakeholder community about how to anticipate and mitigate complexities in practice.

Rowing-Wallpaper-For-Desktop.jpg (2600×1734) (yesofcorsa.com)

Project Publications

Research Plan

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Publications available at www.volpe.dot.gov

Questions?

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