# Operational Complexity in Performance-Based Navigation (PBN) Arrival and Approach Instrument Flight Procedures (IFPs)

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U.S. Department of Transportation

**Final Report – February 2020**

DOT-VNTSC-FAA-20-02

Prepared for:

**U.S. Department of Transportation Federal Aviation Administration (FAA)**
**NextGen Human Factors Division (ANG-C1)**
**Washington, DC**



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# Notice

# REPORT DOCUMENTATION PAGE

*Form Approved*
*OMB No. 0704-0188*



| 1. AGENCY USE ONLY (Leave blank) | 2. REPORT DATE<br>14 February 2020 | 3. REPORT TYPE AND DATES COVERED<br>Final Report |
|---|---|---|

| | |
|---|---|
| 4. TITLE AND SUBTITLE<br>Operational Complexity in Performance-Based Navigation (PBN) Arrival and Approach Instrument Flight Procedures (IFPs) | 5. FUNDING NUMBERS<br>FA6YCE TF347, FA6YCE SF437<br>FA6YCE RF437, FA6YCE TH965<br>FA6YCE TG657, FA6YCE TH964 |
| 6. AUTHOR(S)<br>Divya C. Chandra, Andrea Sparko, Andrew Kendra, and Janeen Kochan | |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>U.S. Department of Transportation<br>John A. Volpe National Transportation Systems Center<br>Office of the Assistant Secretary for Research and Technology<br>Cambridge, MA 02142-1093 | 8. PERFORMING ORGANIZATION REPORT NUMBER<br>DOT-VNTSC-FAA-20-02 |
| 9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>U.S. Department of Transportation Federal Aviation Administration<br>NextGen Human Factors Division (ANG-C1)<br>Washington, D.C. 20591<br>Program Manager: Sabreena Azam | 10. SPONSORING/MONITORING AGENCY REPORT NUMBER |
| 11. SUPPLEMENTARY NOTES | |
| 12a. DISTRIBUTION/AVAILABILITY STATEMENT<br>This document is available to the public through the National Technical Information Service, Springfield, VA 22161. | 12b. DISTRIBUTION CODE |

13. ABSTRACT (Maximum 200 words)

We studied how pilots handle operational variations during arrival and approach instrument flight procedures (IFPs), focusing on factors that may be related to Performance-Based Navigation (PBN). PBN is a key enabler of the Next Generation Air Transportation System (NextGen). We developed a factor rubric based on an iterative review of events in the Aviation Safety Reporting System (ASRS) public database and prior research. We coded 164 ASRS reports selected for relevance to PBN. We identified where each event occurred relative to the route of flight, tallied the coded factors and event outcomes, and gathered data on crew actions that indicated resilience to operational variations such as unexpected behavior of aircraft automated systems. We conclude that PBN appears to magnify the effects of operational complexity for these events. Pilots would benefit from training that provides opportunities to experiment with new situations they could encounter in PBN scenarios, to develop adaptive expertise and resilience. This report includes the full results, rubric, and sample reviews.

| | |
|---|---|
| 14. SUBJECT TERM<br>PBN, RNAV, RNP, STAR, OPD, ASRS, NextGen, resilience, training | 15. NUMBER OF PAGES<br>61 |
| | 16. PRICE CODE |

| 17. SECURITY CLASSIFICATION OF REPORT | 18. SECURITY CLASSIFICATION OF THIS PAGE | 19. SECURITY CLASSIFICATION OF ABSTRACT | 20. LIMITATION OF ABSTRACT |
|---|---|---|---|
| Unclassified | Unclassified | Unclassified | Unlimited |

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102

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| **fl oz** | fluid ounces | 29.57 | milliliters | mL |
| **gal** | gallons | 3.785 | liters | L |
| **$ft^3$** | cubic feet | 0.028 | cubic meters | $m^3$ |
| **$yd^3$** | cubic yards | 0.765 | cubic meters | $m^3$ |
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| | | **MASS** | | |
| **oz** | ounces | 28.35 | grams | g |
| **lb** | pounds | 0.454 | kilograms | kg |
| **T** | short tons (2000 lb) | 0.907 | megagrams (or "metric ton") | Mg (or "t") |
| **oz** | ounces | 28.35 | grams | g |
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| **°F** | Fahrenheit | 5 (F-32)/9 or (F-32)/1.8 | Celsius | °C |
| | | **ILLUMINATION** | | |
| **fc** | foot-candles | 10.76 | lux | lx |
| **fl** | foot-Lamberts | 3.426 | candela/$m^2$ | cd/$m^2$ |
| | | **FORCE and PRESSURE or STRESS** | | |
| **lbf** | poundforce | 4.45 | newtons | N |
| **lbf/$in^2$** | poundforce per square inch | 6.89 | kilopascals | kPa |
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| | | **LENGTH** | | |
| **mm** | millimeters | 0.039 | inches | in |
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| **$mm^2$** | square millimeters | 0.0016 | square inches | $in^2$ |
| **$m^2$** | square meters | 10.764 | square feet | $ft^2$ |
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| **ha** | hectares | 2.47 | acres | ac |
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| | | **VOLUME** | | |
| **mL** | milliliters | 0.034 | fluid ounces | fl oz |
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| **g** | grams | 0.035 | ounces | oz |
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| **°C** | Celsius | 1.8C+32 | Fahrenheit | °F |
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| **lx** | lux | 0.0929 | foot-candles | fc |
| **cd/$m^2$** | candela/$m^2$ | 0.2919 | foot-Lamberts | fl |

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# List of Abbreviations

| Abbreviation | Term |
|---|---|
| AC | Advisory Circular |
| ARTCC | Air Route Traffic Control Center |
| ASRS | Aviation Safety Reporting System |
| ATC | Air Traffic Control |
| ATL | Atlanta |
| AVS | Office of Aviation Safety |
| BOI | Boise Airport |
| CAST | Commercial Aviation Safety Team |
| CDA | Continuous Descent Approach |
| CFR | Code of Federal Regulations |
| CLT | Charlotte Airport |
| CRM | Crew Resource Management |
| DEN | Denver International Airport |
| DFW | Dallas-Fort Worth Airport |
| EFB | Electronic Flight Bag |
| FAA | Federal Aviation Administration |
| FMS | Flight Management System |
| GPS | Global Positioning System |
| HOU | Houston (Hobby Airport) |
| IAH | Houston (Bush Intercontinental Airport) |
| IAP | Instrument Approach Procedure |
| IFP | Instrument Flight Procedure |
| ILS | Instrument Landing System |
| IMC | Instrument Meteorological Conditions |
| LAS | Las Vegas International Airport |
| LNAV | Lateral Navigation |
| LOSA | Line operations safety audit |
| MCP | Mode Control Panel |
| MSA | Minimum Safe Altitude |
| NAS | National Airspace System |

| Abbreviation | Term |
|---|---|
| NASA | National Aeronautics and Space Administration |
| NOTAM | Notice to Airmen |
| OAPM | Optimization of Airspace Procedures |
| OPD | Optimized Profile Descent |
| PARC | Performance-based Operations Aviation Rulemaking Committee |
| PBN | Performance Based Navigation |
| PF | Pilot flying |
| PM | Pilot monitoring |
| RA | Resolution Advisory |
| RNAV | Area Navigation |
| RNP | Required Navigation Performance |
| SA | Situation Awareness |
| SID | Standard Instrument Departure |
| SOP | Standard Operating Procedure |
| STAR | Standard Terminal Arrival Route |
| TCAS | Traffic Alert and Collision Avoidance System |
| TRACON | Terminal Radar Approach Control |
| VFR | Visual Flight Rules |
| VNAV | Vertical Navigation |

# Preface

This document was prepared for the FAA NextGen Human Factors Division (ANG-C1), the Office of Aviation Safety (AVS), and the Flight Technologies and Procedures Division (Flight Operations Group, AFS-410 Section B) under the FA6YCE Interagency Agreement (Human Factors of Flight Operations and Technologies) with funding via the Fiscal Year 2017 RE&D System Development – NextGen Air/Ground Integration Project Level Agreement, Task 12. This document was completed as part of the Terminal Instrument Procedures project under the FA6YCE Interagency Agreement (IAA) tasks TF347, SF437, and RF437, TH965, TG657, and TH964.

The Volpe Center thanks the FAA technical sponsors, Dr. Kathy Abbott and Jeff Kerr, and the program manager, Sabreena Azam. We thank the NASA Aviation Safety Reporting System (Director, Dr. Becky Hooey) for selecting the reports analyzed in the study. We also thank Dr. Mark Shelhamer of the Volpe Center for his insights and feedback on this work.

The views expressed herein are those of the authors and do not necessarily reflect the views of the Volpe National Transportation Systems Center or the United States Department of Transportation.

# Executive Summary

The Volpe Center has been leading a multi-year research program to provide the Federal Aviation Administration (FAA) with data and analyses to understand and address the complexities of flight deck operations associated with Next Generation Air Transportation System (NextGen) terminal Instrument Flight Procedures (IFPs). This study is a follow-on effort to prior research on the different types of complexities associated with Performance-Based Navigation (PBN) operations. PBN is an important component of NextGen.

In this study, we focus on *operational* complexity, which is associated with real-time variations in aviation operations (e.g., Air Traffic clearances and flightcrew factors such as crew resource management, CRM). We analyzed 164 safety reports filed with the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS) to address four goals:

1) Develop and test a method to differentiate between operational-complexity factors that exist independently of PBN from operational-complexity factors that are related to PBN.
2) Refine the list of operational-complexity factors, starting from the high-level list discussed in a previous study on line pilot perspectives of IFP and chart complexity (Chandra and Markunas, 2017).
3) Explore how operational-complexity factors interact with each other.
4) Address gaps in the Chandra and Markunas (2017) study by analyzing real events from the public ASRS database and by reviewing reports filed by controllers to gain insights into the Air Traffic perspective on PBN operational complexity.

The ASRS events were selected by NASA in coordination with the FAA. They were selected for relevance to PBN operations specifically on arrivals and approaches. Although there are many limitations of ASRS data, there are insights to be gained. More highly documented events would still be difficult to analyze and may be inconclusive or incomplete as well.

We developed a set of tools for the analysis, including (a) a comprehensive list of operational-complexity factors with examples, (b) a review template, and (c) a database. These tools may be useful for future analyses of ASRS reports related to PBN.

We analyzed four aspects of the data. First, we examined where the event occurred relative to the phase of flight and geographical location. Although most events were either on an arrival or on an approach, several of the events happened during transitions from arrival to an approach. Second, we looked at the event outcomes. Altitude deviations were the most common adverse outcomes for this dataset, confirming results of prior studies of ASRS events for PBN arrivals and approaches. However, now we also noted several events where pilots *prevented* deviations. Third, we tallied the different factors in the events. The most common factors in the data we analyzed were related to PBN. We also found that operational complexity was highly varied in these events. Finally, we extracted some examples of resilient crew behaviors that that were effective in mitigating negative outcomes.

We provide some training recommendations for flight deck operations that could be helpful in improving how pilots manage operational complexity in real-time. In particular, we recommend that pilots be trained in a manner that allows them to develop *adaptive expertise.* Pilot training should also reinforce basic skills and knowledge related to flying with automated systems, area navigation, and required navigation performance, the building blocks of PBN. Finally, operators should provide opportunities to reinforce, strengthen, and practice CRM in scenarios with PBN operations.

# 1 Introduction and Background

Since 2008, Volpe Center has been leading a research program that provides the Federal Aviation Administration (FAA) with data and analysis to understand and address the complexities of flight deck operations for Next Generation Air Transportation System (NextGen) terminal Instrument Flight Procedures (IFPs). Terminal IFPs include Standard Terminal Arrival Routes (STARs), Standard Instrument Departures (SIDs), and Instrument Approach Procedures (IAPs). Performance-Based Navigation (PBN), a component of NextGen, enables pilots to fly precise lateral and vertical terminal IFP routes through the use of area navigation (RNAV) and Required Navigation Performance (RNP).

PBN IFPs have the potential to increase the safety, predictability, and efficiency of the National Airspace System (NAS) when flown as the designers intended. However, many factors can increase the complexity of terminal IFPs for flightcrews and the added complexity can affect the crew's ability to fly the route as intended. So, it is important to understand the complexity associated with flying PBN IFPs and to develop recommendations for handling this complexity.

Overall, the effect of complexity in the context of PBN is to increase the number of tasks that pilots must manage and prioritize. The extra pilot tasks could be either cognitive or physical (Chandra and Markunas, 2017). Extra cognitive tasks could require additional memory or attention resources. Extra physical tasks could be, for example, more button pushes. Extra tasks require pilots to update and manage their "task agenda" effectively. Funk (1991) defines a task agenda as "a hierarchy of tasks to be completed during a mission" where "each task is defined to achieve a specific goal." In effect, more complexity produces more tasks for the pilot, and more decisions.

*Operational complexity* is a term we use to describe the day-to-day variations that pilots handle during normal flight operations (e.g., weather, air traffic, aircraft equipment). Rarely does a flight operation run exactly as planned. Operational complexity is not new in aviation, but it has not been studied formally in this context. Operational complexity has been studied in manufacturing, where it is associated with uncertainty, variety, and unpredictability in the degree of connectivity and interaction among system elements (Sivadasan, Efstathiou, Frizelle, Shirazi, and Calinescu, 2002; Wu, Frizelle, Efstathiou, 2007). The same characteristics apply to operational complexity in flight operations.

Although operational complexity can arise in common situations and events, even normal variations can be difficult for flightcrews to manage. PBN operations are relatively new, and their use has expanded greatly over the past few decades since approaches using the Global Positioning System (GPS) were first implemented. We are interested in understanding the relationship between PBN and operational complexity.

Previous research has hinted at possible connections between PBN and the complexity of pilot tasks, so we use that as a starting point. For example, earlier research explored the objectively measurable complexity of PBN IFPs (Chandra, Grayhem, and Butchibabu, 2012) and the visual complexity of aeronautical charts for PBN IFPs (Chandra and Grayhem, 2013). Chandra and Markunas (2017) interviewed line pilots to learn about their perspectives on the subjective complexity of IFPs and the charts that depict IFPs. While they successfully developed a comprehensive list of sources of subjective complexity, Chandra and Markunas (2017) point out that even good IFP designs and good charts cannot eliminate operational complexity. Pilots have to manage operational complexity in real-time, as the need arises.

The current research aims to gain a deeper understanding of flight deck operational complexity in order to make recommendations to the FAA for flightcrew PBN operations. Although PBN can also affect Air Traffic Control (ATC) tasks (e.g., aircraft sequencing and internal coordination), those implications are outside the scope of this project. This work addresses only ATC actions that have an effect on pilot tasks. The data analyzed for this study are safety reports filed with the National Aeronautics and Space Administration (NASA) Aviation Safety Reporting System (ASRS).

In the next section, we consider what features of PBN are different from conventional navigation, and therefore could affect operational complexity (Section 1.1). In Section 1.2, we review related studies and concepts. Section 1.3 discusses goals and limitations of this study.

## 1.1 <u>Operational Complexity and PBN</u>

One goal for this study is to try to distinguish, if possible, between operational complexity that exists independently of PBN from operational complexity that is related to PBN. In order to make progress on this goal, we first had to identify aspects of PBN that might be associated with additional tasks for pilots. Pilots are trained, of course, for different aspects of PBN operations, such as RNAV and RNP (see FAA Advisory Circular (AC) 90-100A, 2007; AC 90-101A, 2011; and AC 90-105A, 2016). This training is assumed as baseline knowledge.

Chandra, Grayhem, and Butchibabu (2012) identified some measurable differences between PBN and conventional IFPs. For SIDs and IAPs, they found that PBN IFPs have more lateral route branches (i.e., flight paths). For STARs, they found that PBN IFPs had more flight path segments (i.e., more waypoints) and more altitude constraints. Finally, for IAPs that use RNP, the paths had more curved (radius-to-fix) segments than conventional IAPs. We also know that PBN operations can involve precise lateral navigation (e.g., closer to restricted areas or terrain, especially with RNP), more notes (and more complicated notes), as well as more reliance by flightcrews on autoflight systems for navigation and meeting constraints (Performance-based Operations Aviation Rulemaking Committee (PARC)/Commercial Aviation Safety Team (CAST), 2013; Chandra and Markunas, 2017).

In addition, Chandra and Grayhem (2013) explain that:

> Because RNAV and RNAV (RNP) allow more path design flexibility, there is inevitably more variation in how the route looks as well. Procedures that show multiple paths can be visually complex, which may increase the time pilots need to scan the chart image for necessary information. Therefore, one consequence of the flexibility offered by RNP is that it may take more time and effort to read and review those charts to fully understand the procedure.

The variation in PBN IFP designs has also resulted in a need for nonstandard chart layouts, which can vary in terms of number of pages, size of page, and position of data within the chart. Chart formats also vary by manufacturer. While the *content* of a chart (e.g., the IFP design) is standardized, there are only general conventions on how these data are presented.

Another new aspect of PBN operations that may affect the complexity of flight deck operations indirectly is that, in many cases, new *sets* of PBN IFPs are developed as part of a major redesign of the airspace. So, while the pilot may only be aware of the one IFP he/she is flying, in fact, that IFP is integrated with other arrival, departure, and approach routes, sometimes covering major and satellite airports. After an airspace redesign, there may be many more terminal IFPs to choose from (as happened at Denver in the 2012 redesign), and the new IFPs have different (unfamiliar) names. For pilots, this means they must relearn the airspace, either through direct flight experience or by reviewing operator information bulletins. Even so, pilots may have only partial knowledge of how the airspace is designed to work overall; for example, they may not know where arrivals and departures cross, but they may be aware of parallel arrival routes through flight experience.

## 1.2 Related Studies

Here we describe analyses and concepts related to the study. First, we look at previous analyses of RNAV and RNP flight operations based on ASRS events. Next, we consider the subjective complexity framework developed by Chandra and Markunas (2017). Then we look at the connection between subjective complexity and pilot tasks, which is *agenda management*. Then, we look at the *Safety II* concept, which is part of the system resilience framework. Finally, we consider research on acute stress for flightcrews in challenging situations, which they could encounter in PBN operations.

### 1.2.1 Past Analyses of ASRS Events Related to RNAV/RNP

Barhydt and Adams (2006) was the first study to analyze ASRS events related to RNAV and RNP. They found that flightcrew issues could be traced back to Air Traffic procedures, airline operations, aircraft systems, instrument procedure design, or some combination of these factors. Butchibabu, Midkiff, Kendra, Hansman, and Chandra (2010) did an updated review, with similar conclusions, that operational issues arise from a combination of factors related to Air Traffic, aircraft equipment, and instrument procedure design.

NASA also reviews ASRS reports internally and issues newsletters with findings from their analyses. The program has issued newsletters on RNAV/RNP issues. The first one was issued in June 2013 (Callback Issue 401). It covered problems flying Optimized Profile Descents (OPDs) at Washington Dulles airport (GIBBZ), Phoenix (GEELA), and Washington National airport (TRUPS). In 2017, there was a separate NASA ASRS Alert Bulletin (issued only internally to the FAA) about the Atlanta OPDs. An issue from February 2017 (No. 445) explored the question of whether PBN operations are creating more operational complexity. This analysis indicated that many PBN issues are not new; they have roots in the basic knowledge and fundamentals of instrument flight and use of automated systems.

### 1.2.2 Pilot Perspectives on Subjective Complexity

We use the work of Chandra and Markunas (2017) as a foundation. Their study identified "subjective" complexity factors related to terminal IFP design and charting through pilot interviews. Figure 1 shows a framework that Chandra and Markunas (2017) developed for subjective complexity, which they define in terms of extra mental or physical steps for the flightcrew. These factors are a source of difficulty for pilots both when flying or reviewing IFPs because they create additional tasks to manage and prioritize. In Figure 1, each group of subjective complexity factors is shown as a gear to demonstrate how they drive each other.

Operational-complexity factors are listed separately in the cloud in Figure 1 because they exist independently of IFPs and charts. Chandra and Markunas (2017) identified five general categories of operational complexity: ATC actions, aircraft factors, flightcrew factors, operator factors, and environment factors. A second goal for this study is to refine these broad categories of operational complexity.

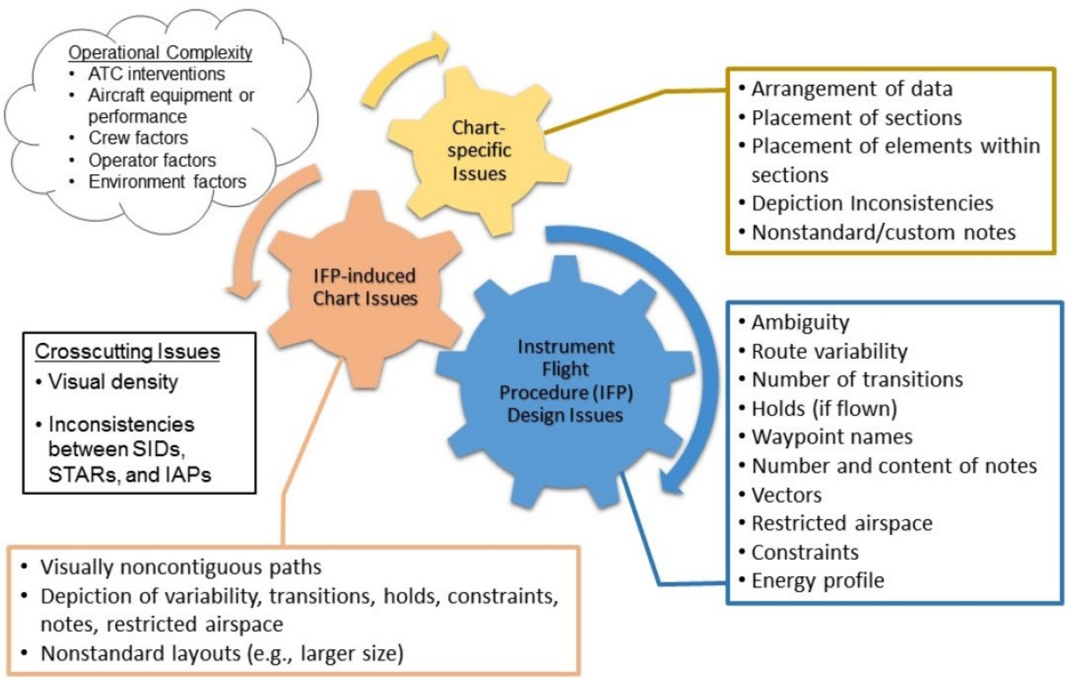


**Figure 1. Framework for IFP and chart complexity from Chandra and Markunas (2017).**

Our third goal for this study is to understand how interactions between operational-complexity factors affect flightcrew compliance with terminal IFPs, particularly in the context of PBN IFP operations. Flightcrew compliance with the IFP may be affected particularly when multiple factors occur in combination during a flight operation. This is the concept of "emergent" safety outcomes described in Hollnagel, Wears, and Braithwaite (2015). The idea of interaction among operational-complexity factors is also mentioned by Wu, Frizelle, and Efstathiou (2007).

Our final goal for this study is to address gaps in the Chandra and Markunas (2017) study, at least in part. The 2017 study collected data from pilot interviews, not from observations of pilot behavior. In addition, it did not gather information on ATC perspectives. ASRS reports describe actual events. And, while most ASRS reports are filed by pilots, some are filed by controllers, giving us insights into their perspectives (e.g., their rationale for issuing revised clearance).

### 1.2.3 Flight Deck Agenda Management

The concept of subjective complexity is closely related to flight deck task management, but it is not about task switching or multi-tasking. Instead, subjective complexity has to do with setting and managing the agenda of tasks (Funk, 1991), which is defined as follows (p. 275):

> 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 and McCoy (1996) expand upon the concept of agenda management. *Agenda management* consists of managing not only tasks, but also goals, functions, actor assignments, and resource allocations. For example, a pilot whose goal is to fly a particular IFP may need to initiate a task to monitor whether the aircraft will meet an altitude crossing restriction. This task may have subtasks, such as ensuring the constraint is correctly programmed into the Flight Management System (FMS), monitoring altitude as the aircraft nears the constraint, or monitoring the Vertical Navigation (VNAV) system. Depending on how the flight is progressing, the pilot might have to initiate other tasks, such as asking ATC for relief from the altitude constraint, or deploying speed brakes to slow the aircraft down while descending. The pilot has to make a judgment call at many points to determine what tasks are necessary, how they will be ordered, and who (or what) will do them (the pilot, a crew member, or an automated system). Some pilots make conscious decisions about when to monitor more carefully, a sort of meta-monitoring task.

In other words, more subjective complexity results in more pilot tasks. Pilots have to determine resources and priority for every task. The pilot has to decide when to initiate the task, who or what should do it, etc.

### 1.2.4 Safety II Concept

Our approach is based on the concept of *resilience*, which is an expression of how people and organizations cope with everyday situations by adjusting their performance to the conditions. Hollnagel, (2009) discusses four resilient behaviors: learning, responding, monitoring, and anticipating. Holbrook, et al. (2019) explored these behaviors in the aviation context. They explored methods for identifying when humans demonstrated behaviors that prevented adverse outcomes in everyday situations. Pruchniki, Key, and Rao (2019) provide a comprehensive overview of the resilience literature as applied to unexpected events, for which there may not be established flightcrew procedures or guidance. They explain different resilient behaviors in this context and discuss the concept of adaptive crew responses. However, they point out that there is no established way to measure resilience at this time.

We consider the concept of *Safety II* in addition to resilient behaviors. Safety II focuses on understanding how things go right, particularly in systems that are highly complex and unpredictable. This is in contrast to the more traditional view of safety, known as *Safety I*, in which prevention of deviations and adverse outcomes is the goal. While valuable, Safety I only focuses on a subset of operations. Safety II takes a broader approach. Safety II is based on the premise that there is normal variability in daily operations and that performance adjustments are needed for the system to function. Because of this variability, safety outcomes cannot always be described based on cause and effect; often, outcomes are “emergent rather than resultant” (Hollnagel, Wears, and Braithwaite, 2015). To understand the emergent properties that lead to safety outcomes in terminal IFP operations, this research will attempt to gain a deeper understanding of complexity factors, and, if possible, synthesize that information to identify properties that emerge from the interactions of those factors.

### 1.2.5 Acute Stress in Flight Deck Operations

The *cognitive appraisal* model of stress (Lazarus and Folkman, 1984), shows that individuals encountering a challenging situation develop both cognitive and physiological effects. The increased operational complexity associated with PBN can include a situational response in the following manner. A pilot will focus attention on the situation, and if the appraisal is such that the pilot is uncertain or unable to deal with the event (e.g., ATC instructions to change a published arrival speed or altitude) then anxiety arises. This resulting stress response can degrade human performance in many ways with disruption to specific cognitive structures and processes. During challenging situations, pilots may be cognitively overloaded so that they are less able to seek out information, process, and assess it. They are also less able manage concurrent tasks, recall facts from memory, and communicate and coordinate with other crewmembers (Dismukes, Kochan, and Goldsmith, 2018).

The types and frequency of errors made most often by flightcrews in stressful situations found in the Dismukes et al. (2018) study involved inadequate comprehension, interpretation and/or assessment of situations. From a training perspective, the authors suggest more emphasis on tools to help crews recognize, interpret, assess, and comprehend the full implications of a challenging situation and how to establish a high-level (meta-cognitive) mental model to guide action in light of the effects of stress. Although situation awareness, workload management, communication, and decision-making are often discussed in Crew Resource Management (CRM) training (see FAA AC 120-51e, 2004), it is important to go into much more depth to help pilots understand the cognitive factors that make them vulnerable to common forms of error, especially under stress, and to identify specific techniques to reduce vulnerability to error.

## 1.3 Goals and Limitations

In summary, there are four goals for this study. We will analyze ASRS event narratives to:

1) Develop and test a method to differentiate between operational-complexity factors that exist independently of PBN from operational-complexity factors that are related to PBN.
2) Refine the list of operational-complexity factors, starting from the high-level list in Chandra and Markunas (2017).
3) Explore how operational-complexity factors interact with each other.
4) Address gaps in the Chandra and Markunas (2017) study by analyzing real events from the public ASRS database and by reviewing reports filed by controllers to gain insights into the ATC perspective on PBN operational complexity.

We acknowledge that the number of reports we have to analyze is not large, that ASRS reports come with their own set of limitations, and the analysis is difficult because it requires trained reviewers making consistent judgments.

Limitations of ASRS data are well known (e.g., PARC/CAST, 2013 Section 3.9.2 and Finding 23). To summarize these points:

- ASRS events are self-reported, subjective, and written from memory.[1]
- The reporters are not trained observers. The reports can be biased because of difficulty in observing one's own behavior.
- The frequency of events in the database cannot be assumed to represent the frequency of occurrence in actual operations.
- There is no standard for level of detail or type of information to include.

There are additional specific limitations related to our analysis, described below:

- The events often refer to IFPs and charts that are no longer current and are not archived, so we cannot see what the pilot saw at the time of the event.
- The narratives are usually from a single-reporter perspective (either pilot or controller), and the reporters themselves make inferences about the other's perspective. (For example, pilots make inferences about what controllers were thinking and vice versa.)
- The narratives may be incomplete, or use language that is difficult to interpret.

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[1] Most pilots submit a report to ASRS within 10 days of the event to receive immunity from disciplinary action but the reports are accepted at any time. ASRS does not record the time between the event and reporting dates.

- The narratives typically do not mention or discuss operator standard operating procedures (SOPs), so we do not know whether SOPs were followed or not.
- Determining what was related to PBN or not related was subtle, and could require making inferences or at least reconciling different reviewer interpretations.
- We tried to separate our own inferences from data in the event, but this can be challenging.
- Some reports are reflections on multiple past events, or hypothetical events that were slightly different from the actual event. We coded these separately from single, actual events.

Another important point is that ASRS reports are filed because some undesirable outcome occurred or nearly occurred. ASRS reports are not usually filed when things go right. As a result, they do not typically document benefits of PBN operations. Some of the event narratives allude to "what went right" but the information is relatively uncommon and may be hard to discern. For example, sometimes the reports described behaviors (or lack of behaviors) that did mitigate the outcome, or could have mitigated the outcome under other circumstances.

# 2 Method

We reviewed 164 public ASRS reports submitted from January 2016 to December 2017. The reports were provided to us by NASA and the FAA; the search criteria are described in Section 2.1. In Section 2.2 we describe the tools developed to analyze these reports, specifically, we describe the: (a) factor checklist and definitions, (b) review template, and (c) database of event records. The tools were developed and refined iteratively based on partial data analyses.

To begin a review, one researcher read the ASRS report and filled out the review template. Within the review template, there are fields to record the complexity factors in the event. The factors were recorded in both a table and checklist format. The table and checklist are crosschecked by the reviewer. Supporting details are noted. The factor descriptions helped to ensure that all reviewers had a common understanding. The full list of complexity factors and defining examples are in Appendix A. One example of a completed review is provided in Appendix B. After the review form was final, it was entered into the database.

## 2.1 <u>Raw Data</u>

We analyzed data from the public NASA ASRS database. It was compiled in March 2018 by NASA. Reports received in 2016 and 2017 were selected if they described events that occurred during the approach and landing phases of flight, and included any of the following specific search terms (including acronyms) in the narrative or synopsis:

- OPD
- Variations of "Optim"
- Continuous Descent Approach
- CDA[2]
- Required Navigation Performance
- RNP
- OAPM[3]

[2] CDA is the acronym for "Continuous Descent Approach" an older term for OPD.

[3] OAPM is the acronym for "Optimization of Airspace Procedures" and older term for the redesign of airspace IFPs.

- Metroplex or Metro plex
- Data Comm (and variants)
- PBN or Performance Based Nav
- RNAV

Most of the 164 reports (120) were submitted for Title 14 Code of Federal Regulations (CFR) Part 121 (scheduled air carrier) operations; 29 were submitted for Title 14 CFR Part 91 (general aviation) operations and four for Title 14 CFR Part 135 (air taxi) operations. (There were 11 reports from unknown operations.) Sometimes more than one person reported the same event (e.g., both crewmembers or a pilot and a controller). NASA combines related submissions into a single report.

## 2.2 Tools

### 2.2.1 Factor Definitions and Checklist

Table 1 lists the seven categories of operational-complexity factors in the rubric on the left and the factors within each category on the right. We also coded three other types of factors (IFP design, IFP-induced chart issues, and chart-specific issues) because they were often present and interacted with operational-complexity factors. For example, an OPD with a steep descent gradient (an IFP design issue) may be associated with unexpected behavior of the VNAV system in that it may not be able to meet the programmed constraints.

We developed the initial rubric based on the results of Chandra and Markunas (2017). We refined the rubric iteratively based on events in the ASRS dataset, adding examples and, if needed, factors, as we read the ASRS reports. We edited the rubric only with consensus from all reviewers.

Appendix A lists all the factors. This appendix shows two views of the rubric. First is the checklist view, which lists factors under bolded category names, with boxes that can be checked or unchecked quickly (see excerpt in Figure 2). This version is used in the review template. The reviewer could enter details related to the factor coding in the right column of the checklist (e.g., “FMS could not meet constraints and did not give sufficient notice to crew” as a detail about the coding of “Unexpected behavior of automated system”).

The second view of the rubric in Appendix A has a set of examples and extra pilot tasks for each factor (see excerpt in Figure 3). These examples were helpful in ensuring that all the reviewers had a common understanding of that factor. When creating the rubric, we not only defined the factor, but chose its name carefully. For example, the factor name “Unexpected behavior of automated system” deliberately does not specify whether the pilot had inadequate understanding of the system behavior, or whether the automated system behaved incorrectly. The ASRS reports do not give us enough information to determine the root cause of the problem.

As shown in Figure 3, each operational-complexity factor is associated with extra tasks for the pilot. For example, if the FMS fails to meet the programmed constraints (as mentioned above), extra pilot tasks would be to diagnose the situation (need to slow down), determine a plan to recover (decide to deploy speed brakes, execute the plan (deploy speed brakes), and manage any other consequences (deal with effects of using speed brakes on ride quality).

Table 1. Overview of operational-complexity factors from the rubric.

| Category | Factor | |
|---|---|---|
| ATC and PBN issues that affect pilots | • Interventions related to PBN<br>• Phraseology related to PBN | • Controller knowledge or training related to PBN |
| ATC issues only | • Aircraft sequencing<br>• Internal ATC coordination | • Generic ATC error |
| Flightcrew factors related to PBN | • Crew resource management (CRM) related to PBN<br>• Lack of familiarity (with terrain, local area, or local IFPs)<br>• Lack of knowledge or training related to PBN | • Confusion related to PBN<br>• Lack of flight path awareness on PBN IFP<br>• Time pressure related to PBN IFP |
| Flightcrew factors not related to PBN | • Distraction unrelated to PBN<br>• Time pressure unrelated to PBN<br>• Crew physical condition<br>• Non-normal situation unrelated to PBN<br>• Communication with ATC unrelated to PBN | • CRM unrelated to PBN<br>• Decision-making unrelated to PBN<br>• Confusion unrelated to PBN<br>• Generic crew error |
| Aircraft/Equipment factors related to PBN | • Unexpected behavior of automated system related to PBN<br>• Aircraft flight performance | • Flight Management System (FMS) or Mode Control Panel (MCP) programming or setup, or autoflight configuration/operation |
| Environment | • Terrain related to PBN IFP<br>• Terrain unrelated to PBN IFP<br>• Man-made structures unrelated to PBN IFP<br>• Man-made structures related to PBN IFP | • Airspace<br>• Airport<br>• Traffic<br>• Weather (related to PBN or not)<br>• Nighttime |
| Operator | • Dispatch<br>• Clarity of pilot roles | • Clarity of standard operating procedures |

| Factors | Notes, New Examples, Details |
|---|---|
| **Aircraft/Equipment (Related to PBN)**<br>☒ Unexpected behavior of automated system<br>☐ FMS/MCP programming/setup or autoflight configuration/operation<br>☐ Aircraft flight performance | |

Figure 2. Excerpt from the checklist of factors with checkboxes.

| Factor | Examples | Extra Pilot Tasks |
|---|---|---|
| Unexpected behavior of automated system | Altitude not captured<br>VNAV unable to meet programmed constraints<br>LNAV did not follow the route<br>GPWS unexpectedly gives warning during a PBN approach | Diagnose issue (e.g., review FMS route and mode)<br>Decide how to recover<br>Execute the plan to recover. May need to revert to manual flight<br>Manage any other consequences |
| FMS/MCP programming or autoflight configuration/ operation | Modes, mode selection<br>Data entry<br>State awareness (armed, activated) | Select IFP<br>Verify constraints<br>Configure<br>Monitor |
| Aircraft flight performance | Difficulty slowing down while descending | Reconfigure aircraft<br>Update aircraft data in FMS |

**Figure 3. Excerpt from the factor definitions and examples table for the Aircraft/Equipment (Related to PBN) category.**

### 2.2.2 Review Template

The *review template* is a 2 to 3 page text file summarizing our interpretation of the report. Two sample reviews are provided in Appendix B. One is from a Part 121 operation and the other from a Part 91 operation. Both of the samples refer to current IFPs, so we include the current charts.

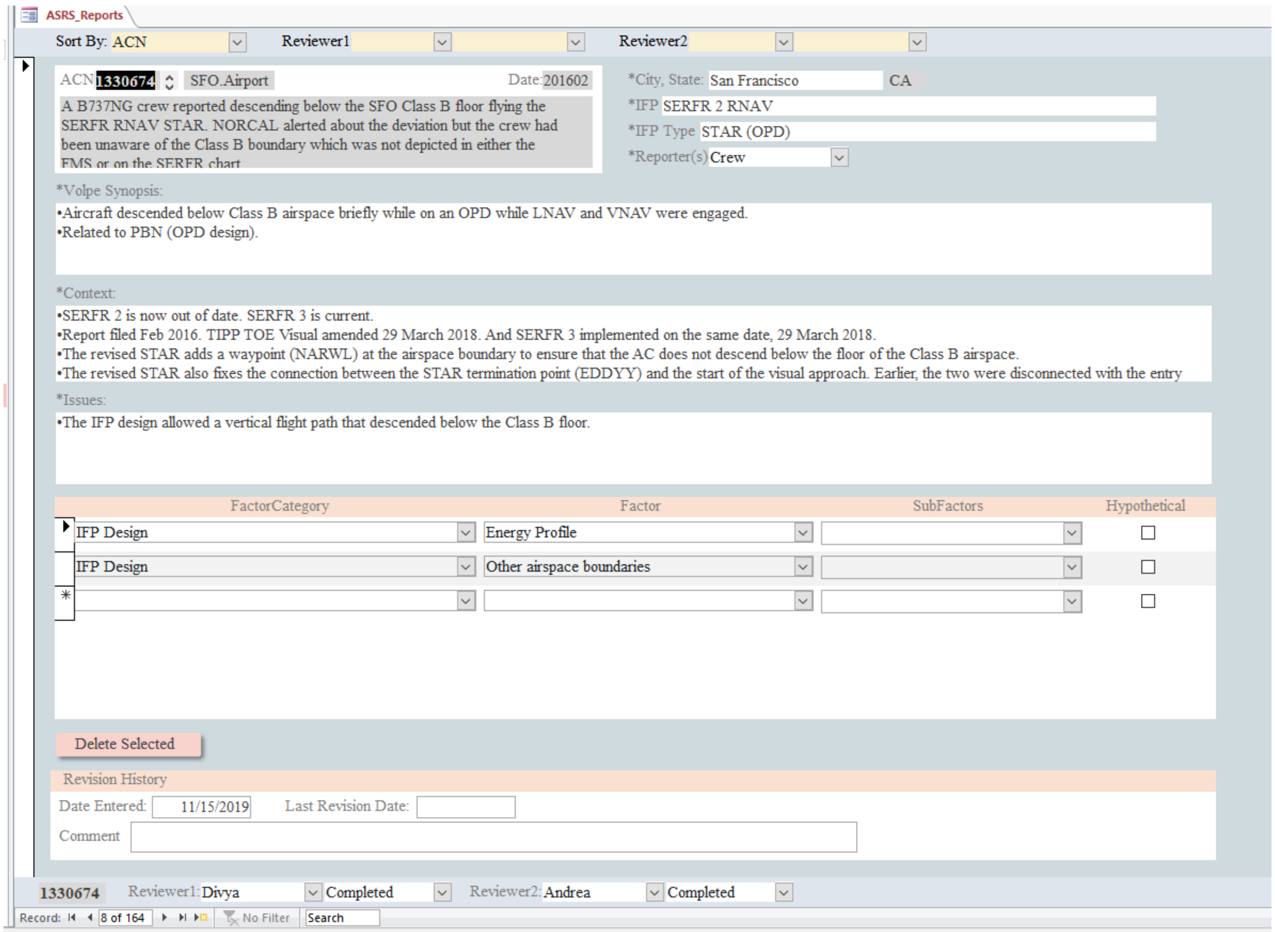
The template is used to summarize information from individual ASRS report events, per the sections described in Table 2. Factors that were discussed hypothetically in the event were marked as such, distinguishing them from factors that were actually encountered.

**Table 2. Sections in the review template.**

| Section | Content |
|---|---|
| Basic information | Location, IFP name and type (STAR, SID, IAP), Reporter (crew, ATC, or both) |
| Synopsis | Description of the event outcome and an overall assessment of whether the event had contributing factors related to PBN |
| Context | Additional information to explain the event, including relevant pilot actions and changes to the IFP since the event occurred |
| Issues | Description of factors contributing to the flightcrew tasks and/or event outcome |
| Factors | Operational complexity and other factors involved in the event |
| Explanation of coding | Reasons for the coding choices (used internally) |
| Inferences (optional) | Researcher's inferences about the event (not used to determine factors) |

### 2.2.3 Database

Because it is unwieldy to work with 164 separate text files (one for each ASRS report), we developed a Microsoft Access database to store information from the review. The database does not hold all of the information from the review template, but it does have all the factors and other basic information. The database is useful for paging between different ASRS events quickly, and for filtering events with common factors. Figure 4 shows a screen image of the database entry form for one event.


ASRS_Reports
Sort By: ACN Reviewer1 Reviewer2
ACN 1330674 SFO.Airport Date 201602
A B737NG crew reported descending below the SFO Class B floor flying the SERFR RNAV STAR. NORCAL alerted about the deviation but the crew had been unaware of the Class B boundary which was not depicted in either the FMS or on the SERFR chart
*City, State: San Francisco CA
*IFP SERFR 2 RNAV
*IFP Type STAR (OPD)
*Reporter(s) Crew
*Volpe Synopsis:
•Aircraft descended below Class B airspace briefly while on an OPD while LNAV and VNAV were engaged.
•Related to PBN (OPD design).
*Context:
•SERFR 2 is now out of date. SERFR 3 is current.
•Report filed Feb 2016. TIPP TOE Visual amended 29 March 2018. And SERFR 3 implemented on the same date, 29 March 2018.
•The revised STAR adds a waypoint (NARWL) at the airspace boundary to ensure that the AC does not descend below the floor of the Class B airspace.
•The revised STAR also fixes the connection between the STAR termination point (EDDYY) and the start of the visual approach. Earlier, the two were disconnected with the entry
*Issues:
•The IFP design allowed a vertical flight path that descended below the Class B floor.

| FactorCategory | Factor | SubFactors | Hypothetical |
|---|---|---|---|
| IFP Design | Energy Profile | | ☐ |
| IFP Design | Other airspace boundaries | | ☐ |
| | | | ☐ |

Delete Selected
Revision History
Date Entered: 11/15/2019 Last Revision Date:
Comment
1330674 Reviewer1: Divya Completed Reviewer2: Andrea Completed
Record: 8 of 164 No Filter Search

Figure 4. Screenshot of database form for ASRS events.

### 2.3 Review Process

We divided the 164 ASRS reports into four sets, one for each reviewer. All reviewers have expertise in aviation human factors and/or flight experience. Each reviewer filled out the review template as the "primary" reviewer and then reviewed another set of reports as the "secondary" reviewer. The secondary reviewer reviewed the primary reviewer's initial form. If the secondary reviewer agreed with the factor coding, the review was complete. If there were questions about the coding, the two reviewers discussed and tried to reconcile the factors. If necessary, all four reviewers would discuss the factor coding. The reviewers referred to the full ASRS report as necessary, but the goal was to capture the information necessary for this analysis within the review form.

## 3 Analyses and Results

We used the ASRS data to perform four analyses. First, we examined where the events occurred, not just geographically, but in terms of the phase of flight (Section 3.1). Second, we counted how often different factors occurred, and examined which factors tended to co-occur (Section 3.2). Third, we coded deviations to understand the event outcomes (Section 3.3). Finally, we gathered some examples of resilient behaviors (Section 3.4).

## 3.1 Locations of Events

We wanted to examine the ASRS data for patterns related to the event location. We considered two types of event locations. One was the geographical region, city, or airport. The other location was where along the IFP the event occurred, for example, on a STAR or on transition from a STAR to an approach. The review templates and database had some information about event location and IFP type, but it was insufficient for this analysis. For example, those records did not have sufficient detail to identify when the event occurred along a transition. To analyze the data at the desired level of detail, we had to consider the context, so we created a separate spreadsheet to examine the number of ASRS events by location.

The 10 most common geographical locations for the 164 events are shown in Table 3. Where there was a region with multiple airports, we grouped the events in Table 3. Atlanta (ATL) featured as one of the more common reporting locations. Of the 22 events reported at ATL, 20 occurred on a STAR in November or December of 2016. The events were likely related to the major redesign of the Atlanta STARs that occurred during this period. The problematic STARs were replaced at Atlanta in October 2017. Northern California, Southern California, and Denver rounded out the most common geographical location in the dataset.

Next, we categorized the ASRS events by the type of IFP involved and where along the IFP the event transpired. Table 4 shows these descriptive statistics for all 164 events in the dataset. Seventy-four events (45%) occurred on a STAR, most of which were OPDs. Sixty events (37%) occurred on an approach, with the majority of these being RNAV (GPS) approaches, along with several RNAV (RNP) approaches. Twenty-six events (16%) occurred during a transition from a STAR to approach. Only one event was located on a SID. This is likely because events on SIDs were not selected in the search criteria for the events. In fact, in the event on a SID, the aircraft on departure had a conflict with an aircraft on arrival, which is why it appeared in the search set.

**Table 3. The ten most common geographical locations of events in full dataset.**

| Location | Number of Events in the Dataset |
|---|---|
| Atlanta, Georgia (ATL) | 22 |
| Boise, Idaho (BOI) | 4 |
| Charlotte, North Carolina (CLT) | 5 |
| Chicago, Illinois (ORD) | 4 |
| Dallas, Texas (DFW) | 5 |
| Denver, Colorado (DEN) | 13 |
| Houston, Texas (IAH and HOU) | 6 |
| Las Vegas, Nevada (LAS) | 4 |
| Northern California<br>(San Francisco, Oakland, San Jose, and others) | 21 |
| Southern California<br>(Los Angeles, San Diego, and others) | 18 |

Table 4. Location of event along the IFP by PBN IFP type.

| IFP Type/Location | Count |
|---|---|
| SID | 1 |
| STAR | 74 |
| RNAV STAR - OPD | 63 |
| RNAV STAR (unknown if OPD) | 9 |
| Conventional STAR or unknown if PBN | 2 |
| Approach | 60 |
| RNAV (GPS) | 27 |
| RNAV (RNP) | 14 |
| Visual approach with RNAV as a backup | 6 |
| RNAV Visual | 4 |
| Visual approach | 3 |
| Instrument Landing System (ILS) | 1 |
| Hybrid - RNAV transition to ILS | 1 |
| General RNAV approach (type unknown) | 2 |
| General approach (unknown if PBN) | 2 |
| Transition | 26 |
| Arrival to approach transition | 25 |
| Published feeder on RNAV IAP or runway transition from RNAV STAR | 13 |
| General RNAV transition (not enough information to determine if on a published IFP) | 5 |
| Published feeder on conventional IFP or runway transition from conventional STAR | 1 |
| Vectors to/from an RNAV IFP | 3 |
| Vectors to/from a conventional IFP | 3 |
| Enroute to arrival transition | 1 |
| General RNAV IFP (type unknown) | 1 |
| General IFP (type unknown; unknown if PBN) | 2 |
| **Grand Total** | **164** |

## 3.2 Factors

### 3.2.1 Method

We created a spreadsheet to study how often different factors occurred in the dataset. Figure 5 shows an excerpt of the spreadsheet with a variety of sample data. The leftmost column recorded the ASRS report number. Every factor and subfactor had its own column further to the right. (Only a subset of the columns are shown in Figure 5.) We coded a “1” under the factor to indicate that the factor was present, “0” to indicate that it was absent. Any mention of hypothetical events in the report were coded as 0. Hypothetical factors were mentioned as possibilities, but did not actually occur.

| | | | Aircraft/ Equipment (Related to PBN) | | | Flightcrew Factors (Not Related to PBN) | | |
|---|---|---|---|---|---|---|---|---|
| ASRS Report | Contains at Least 1 PBN-Related Factor | Total Factors | Unexpected behavior of automated system | FMS/MCP programming/ setup or autoflight configuration/operation | Aircraft flight performance | Non-normal situation unrelated to PBN | Confusion unrelated to PBN | CRM unrelated to PBN |
| 1 | Yes | 3 | 0 | 1 | 0 | 0 | 1 | 1 |
| 2 | Yes | 4 | 1 | 0 | 1 | 0 | 1 | 1 |
| 3 | No (but on PBN IFP) | 2 | 0 | 0 | 0 | 1 | 0 | 1 |
| 4 | No (all factors hypothetical) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| 5 | No (not on PBN IFP) | 0 | 0 | 0 | 0 | 0 | 0 | 0 |
| | ***Sum*** | ***9*** | ***1*** | ***1*** | ***1*** | ***1*** | ***2*** | ***3*** |

**Figure 5. Excerpt from factor tallies spreadsheet with sample data.**

After all the event data were entered, the sum of the numbers down the column for each factor (or subfactor) was a count (or tally) of how often that factor occurred. We also summed across the row to compute the total number of factors coded for each event (in the third column from the left). The number ranged from 0 to a maximum of 12 factors recorded for a single event.[4]

We entered data for the second column from the left manually, by looking across the coded factors to check if any were from a factor labeled as "related to PBN." We entered "Yes" if this was true. If none of the coded factors was related to PBN, we checked a secondary feature of the event, whether the event occurred along a PBN IFP or not, or whether the factors were hypothetical. We found that this it was more complicated to determine the relatedness to PBN than we initially anticipated. We discuss this classification further in the next section, Section 3.2.2. It was important for all the reviewers to understand how to code an individual factor as being either related or unrelated to PBN. This was the most common discussion point when reviewers were reconciling their coding.

After looking at the prevalence of the factors and factor groups, and their relatedness to PBN, we wanted to explore relationships among the individual factors and subfactors. We considered four different ways to examine these relationships:

(a) a statistical factor analysis (which could determine whether two factors describe a similar concept)
(b) correlational analyses (which quantify the degree to which one factor varies consistently with another factor)
(c) network analyses and maps (which can depict multiple interacting factors, sometimes with directionality)

[4] On average, there were four factors present in each ASRS event with a standard deviation of 2.

(d) co-occurrence data (which simply records how often pairs of factors occurred).

Because operational complexity emerges out of unpredictable elements in different combinations, it is difficult to capture underlying relationships with standard quantitative methods; this eliminated the factor analysis technique. Moreover, we do not have data on the nature of interactions, especially given the limitations of ASRS data described earlier, and we have a relatively small set of data. We attempted the correlational analysis, but found that the results were unreliable because the cells in the matrix were based on very few data points. We also attempted to use network analyses, but these did not yield new insights about our research questions. In general, network analyses were not suitable for our study because they rely on large training datasets and analysis techniques that do not work well with text data to date. If network-analysis techniques improve in the future, they may warrant further exploration. Instead, we used a simpler analysis method, computing how many times each pair of factors occurred during the same event. This allowed us to examine the co-occurrences across the factors.

### 3.2.2 Relatedness to PBN

We focused the analysis of factor prevalence on events that were related to PBN. Whether an event was related to PBN or not was not a simple yes or no question. We found degrees of relatedness to PBN for the events, as described below.

1) **Event related to PBN in general.** There was a PBN IFP present in the event. The event might have occurred while on a PBN IFP, while flightcrew were setting up for a PBN, or while they were using a PBN IFP as a backup on a conventional IFP, or if we assumed a PBN IFP was involved. This is the highest level of possible relationship and the most generic. Due to the search criteria for the data we analyzed, the vast majority of events (148 out of 164, 90%) were related to PBN by this definition. This category included two subcategories:
   - **(a) Assumed related to PBN.** This is the case when we were not sure and had to make an inference that the issue is related to PBN. There were just three events that fit this description. [5]
   - **(b) There was a PBN IFP involved in the event, but no specific PBN-related factors were identified.** Thirteen reports included in the set of 148 met this definition.
2) **Event completely unrelated to PBN.** There was no reason for the report to be in the dataset, so it was excluded from the analysis of factors. There may have been a reference to a PBN term, but it was not substantive. There were very few reports of this nature in the dataset (just 13 of 164, 8%).

For the events where individual factors could be classified as being "related to PBN" or not, we asked the question: Would the situation have played out the same way if the PBN IFP in the event was a conventional IFP? If yes, then the factor was *not related to PBN*. For example, if the crew mistyped the runway number in the FMS, it did not matter whether they were on an RNAV approach. This type of data entry error could have been made for any approach. These distinctions were sometimes difficult to see at first, and required careful thought. The final determination could affect the classification of entire event if its relationship to PBN hinged on just one factor and whether that factor was related to PBN.

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[5] For example, one event mentioned that the pilots "descended via the arrival" but did not specify the arrival IFP. We inferred that use of the phrase "descended via" was a reference to an OPD, but could not verify this. In another case, ATC attempted to issue an RNAV STAR to an aircraft that was not RNAV-equipped.

To review, of the 148 events that we decided were related to PBN:

- 132 contained at least one PBN-related factor
- 13 did not contain any PBN-related factors, but occurred on or while setting up a PBN IFP.
- 3 events contained factors that might be PBN-related (i.e., relatedness to PBN was difficult to determine) and these were assumed to be related to PBN.

Therefore, 80% (132 out of 164) of the dataset reports were clearly related to PBN (due to at least one coded factor) and 10% (16 out of 164) may have been related to PBN indirectly (because a PBN IFP was involved or assumed).

### 3.2.3 Prevalence of Factor Categories

Figure 6 shows how often each of the 10 factor categories (seven for operational complexity and three for IFP/chart complexity) appeared, as a percent of the 148 PBN-related events. Although we cannot use these specific findings to infer the rate of these factor categories *in the real world* (because of the limitations of ASRS reports), we can say that these factors occur for PBN IFPs with some frequency.

Figure 6 indicates that *Flightcrew factors related to PBN* occurred most often in the dataset (occurring in 47% of the events), followed by *ATC and PBN issues that affect pilots (37%)*, *Environment factors (36%)*, *IFP design factors (35%)*, *Flightcrew factors that were not related to PBN (34%)*, and *Aircraft/equipment factors that were related to PBN (32%)*. IFP-induced chart issues, chart-specific issues, and operator issues were not commonly identified. Sometimes reporters confused IFP design issues with chart issues, but the reviewers coded these separately. Unlike the interview study from which these factor groups originated (Chandra and Markunas, 2017), we found it difficult to identify these types of factors given the ASRS report narratives. There were some ATC-only factors that were not related to PBN in our dataset, but these factors were not of primary interest.

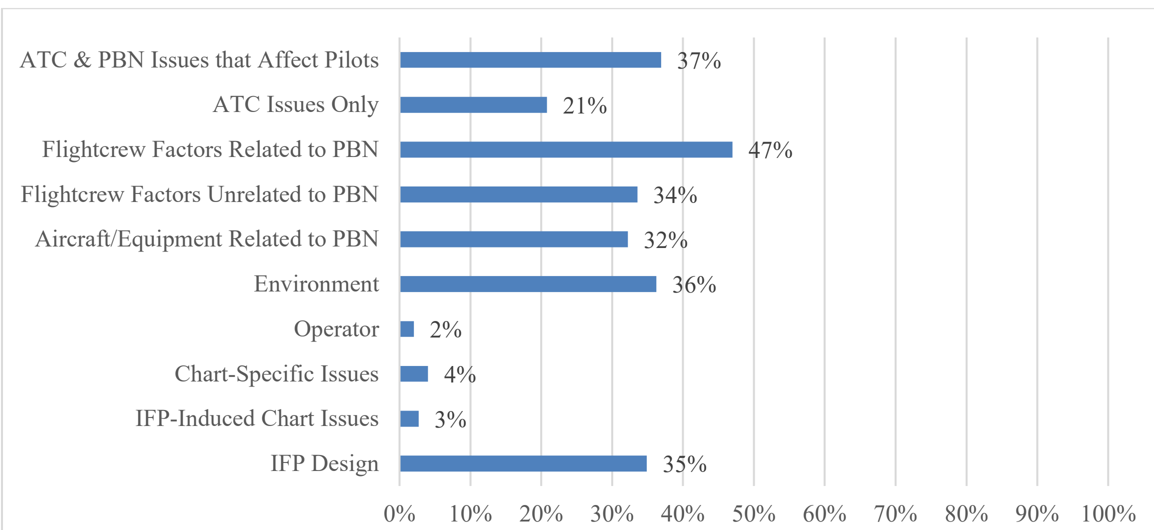


**Figure 6. Prevalence of the coded factor categories in the event dataset.**

### 3.2.4 Prevalence of Individual Factors and Co-Occurrences

We started by selecting individual factors that occurred at least 20 times across the 148 events that were related to PBN. Although this was an arbitrary criterion, it does appear to capture the most salient factors in the dataset. There were eight factors that met this criterion, which we call the "Top 8." These are listed in Table 5. One of the Top 8 factors was related to the design of the PBN IFP (*Constraints related to PBN)* and one was unrelated to PBN (*Generic flightcrew error*), but six of the Top 8 factors were operational-complexity factors related to PBN.

*ATC Interventions related to PBN IFP* was the factor that we found most often in the dataset. Two subfactors under this one also made the Top 8, *(Late) route amendment or clearance*[6] and *Revised altitude/speed restriction.* We also observed the types of errors discussed in Dismukes et al. (2018), related to acute stress, in the ASRS event narratives. These were associated with three of the Top 8 factors, specifically *CRM related to PBN*, *Unexpected behavior of the automated system related to PBN*, and *Flightcrew lack of flight path awareness of PBN IFP*.

**Table 5. Factors that occurred at least 20 times in the dataset.**

| Category | Specific Factor | Number of Occurrences |
|---|---|---|
| ATC and PBN Issues that Affect Pilots | ATC interventions related to PBN IFP<br>(Late) route amendment or clearance<br>Revised altitude/speed restriction | 40<br>25<br>20 |
| Flightcrew Factors Related to PBN | Lack of flightcrew knowledge/training related to PBN | 29 |
| Flightcrew Factors Related to PBN | CRM related to PBN | 27 |
| Aircraft/Equipment Related to PBN | Unexpected behavior of automated system related to PBN | 27 |
| Flightcrew Factors Related to PBN | Flightcrew lack of flight path awareness of PBN IFP | 25 |
| IFP Design | Constraints related to PBN IFP | 23 |
| Flightcrew Factors Related to PBN | Flightcrew confusion related to PBN IFP | 22 |
| Flightcrew Factors Not Related to PBN | Generic flightcrew error not related to PBN | 20 |

Next, we identified factors that tended to co-occur with each of the Top 8; we refer to these eight groups as "factor clusters." We did not apply a strict rule for the number of co-occurrences needed to constitute a cluster. Rather, we made a judgment based on the overall distribution of co-occurrences for each Top 8 factor. We used the Top 8 factor clusters to make observations about factor relationships. The full set of clusters are provided in Appendix C. We highlight three observations here:

1) 88% of the factors that co-occurred with a Top 8 factor were related to PBN.
2) 71% of the factors had a human component (i.e., were a flightcrew or ATC-related factor).
3) Five factors co-occurred with more than half of the Top 8 factors. These included:
    a. *Flightcrew lack of flight path awareness related to PBN IFP* (co-occurred with seven of the Top 8 factors)

[6] Note that the determination of whether the clearance amendment was "late" was subjective. It was based either on the reporter's narrative, or the reviewer's judgment.

b. *ATC Interventions related to PBN IFP* (co-occurred with seven of the Top 8 factors)
c. *Lack of flightcrew knowledge/training related to PBN* (co-occurred with five of the Top 8 factors)
d. *Flightcrew confusion related to PBN IFP* (co-occurred with five of the Top 8 factors), and
e. *FMS/MCP programming/setup or autoflight configuration/operation* (co-occurred with five of the Top 8 factors).

## 3.3 Event Outcomes

We examined the outcomes that resulted from the events, and how often those outcomes occurred, to understand the potential implications of the complexity factors. We identified five main types of outcomes: altitude deviations, speed deviations, separation issues, no deviation, and "other." Each type of outcome could also have a subtype (e.g., describing the type of altitude deviation).

Table 6 shows the list of outcomes, their subtypes, and their frequency of occurrence in the dataset. The table includes outcomes from the 148 ASRS reports that contained at least one PBN-related factor or that occurred on a PBN IFP. The total number of outcomes is greater than 148 because some of the events had more than one outcome. For example, the event could have had an altitude deviation and a speed deviation.

The most common outcome, occurring on 60 of the 148 events (41%), was an altitude deviation, most often when the flightcrew missed an altitude constraint. This agrees with findings from Butchibabu et al. (2010) that altitude deviations are more common on arrivals and approaches. In Butchibabu et al. (2010), lateral deviations were more common on departure procedures. Similarly, we found only a few (nine) lateral deviations for the arrivals and approaches in this study. *Other-Miscellaneous* deviations included, for example, encountering wake turbulence, landing without appropriate lighting, circling-to-land when not authorized, landing with a tailwind, and receiving unexpected terrain alerts.

We also identified a number of events that had no deviation, usually because the flightcrew took an action to prevent it. Of the 38 events that had *No Deviation*, at least 22 mentioned pilot actions that prevented the deviation.

**Table 6. Event outcomes**

| Outcomes | Count |
|---|---|
| *Altitude Deviation* | 60 |
| Missed crossing altitude restriction (low or high) | 35 |
| Off assigned/cleared altitude | 6 |
| Off glideslope | 3 |
| Below Minimum Safe Altitude (MSA) or other min altitude (e.g., step down fix) | 14 |
| Miscellaneous | 2 |
| *Speed Deviation* | 5 |
| Missed published speed restriction | 4 |
| Off assigned speed | 1 |
| *Separation* | 12 |
| Loss of separation | 6 |
| TCAS RA | 1 |
| Miscellaneous | 1 |
| *No Deviation* | 38 |
| Pilot said unable | 8 |
| Pilot action to prevent a deviation | 22 |
| ATC changed clearance (without pilot request) | 5 |
| Miscellaneous | 3 |
| *Other outcome* | 36 |
| Lateral Deviation | 9 |
| Miscellaneous | 27 |
| *Insufficient information* | 12 |

## 3.4 Resilient Crew Behaviors

As mentioned earlier (Section 1.3), ASRS reports do not generally document positive outcomes. However, although the data are sparse, we did find some examples of resilient pilot behaviors. Recall that resilient behaviors are associated with learning, responding, monitoring, and anticipating.

We identified resilient crew behaviors in at least 50 events. Events where the outcome was *No Deviation* typically mentioned a resilient behavior. We suspect these behaviors happened in other events too, but were not always reported. Some examples of resilient *responses* include the crew disengaging an aircraft automated system, effective CRM (e.g., splitting or reallocating tasks), notifying ATC and requesting relief from a constraint, or saying *"unable"* to an ATC request. One example of good crew *monitoring* was when a crew determined they were landing at an unintended airport by noticing that the runway lighting configuration was not what they had briefed. Crews that demonstrated good monitoring and anticipation also were able to minimize or entirely prevent altitude deviations. Crews also *anticipated* outcomes such as unstable approaches, and took an action to go-around instead of land. In some events, crews practiced the PBN IFP under visual conditions or with backup IFPs briefed and readily available, helping them *learn* what to expect. With these techniques, the pilots were both improving their understanding of the PBN IFPs, and handling any missteps or confusions in less risky conditions.

# 4 Discussion

This section includes an assessment of the complexity factor rubric (Section 4.1), recommendations to the FAA for flightcrew training related to PBN operations and operational complexity (Section 4.2), and ideas for potential future research (Section 4.3).

## 4.1 Assessment of Operational-Complexity Factor Rubric

Appendix D shows the evolution of the list of operational-complexity factors from the five general categories in Chandra and Markunas (2017) to the more detailed list developed for this study. One of the categories that changed significantly was ATC Interventions (see Figure 7). This category is now expanded and separated into two groups, one for ATC factors that affect pilots and the other for factors that only affect ATC. We recorded ATC-only issues in a general way, since they were not the primary focus of the study. Some of the internal ATC issues were discovered in reports related to the Atlanta STARs, which had issues with merging traffic streams and boundaries between the Air Route Traffic Control Center (ARTCC) and the Terminal Radar Approach Control (TRACON) facilities.

Another operational-complexity category that expanded and evolved in this way was flightcrew factors. These are now separated into two groups, flightcrew factors that were related to PBN, versus not related to PBN. We based the distinction on the differences between PBN and conventional procedures described in Section 1.1, and also considered the issues described in Section 3.2.2.

The revised rubric is comprehensive and works well. It was effective in capturing the breadth of complexity factors that occurred during the PBN IFPs in the dataset. It is based on many prior studies and could not have been developed without that foundation. The rubric could be adapted and used for analysis of other ASRS events. The most difficult part of using the rubric was training the reviewers in the factor definitions, and discussing revisions to the factor definitions or to the rubric factors. This required practice, coordination, and communication amongst the reviewers.

| Chandra and Markunas (2017) | Current Coding Rubric |
|---|---|
| **ATC Interventions**<br>• (Late) route amendments<br>• Unpublished restrictions<br>• Vectors | **ATC and PBN Issues that affect pilots**<br>☐ Interventions related to PBN IFP<br>    ☐ (Late) route amendments/clearances<br>    ☐ Revised altitude/speed restriction<br>    ☐ (Unexpected) vectors<br>☐ Phraseology related to PBN IFP<br>☐ Controller knowledge/training of PBN |
| | **ATC Issues Only**<br>☐ Aircraft sequencing<br>☐ Internal ATC coordination<br>☐ Generic ATC error (unrelated to PBN) |

Figure 7. Example of expanded list of factors related to ATC, which is separated into two groups in the new rubric.

## 4.2 Recommendations

Our main recommendation from this study is that the FAA, operators, and flightcrews should promote and cultivate a culture of "adaptive expertise" amongst pilots. Adaptive experts are able to apply knowledge effectively to novel or atypical situations (Hatano and Inagaki, 1986). They are more flexible and innovative than "routine experts" who are experts at applying known procedures/checklists for problem solving.

Our analysis showed that the most common operational-complexity factors were related to PBN, so adaptive expertise should be developed in the context of PBN operations. Pilots who are adaptive experts will be better able to apply their knowledge to the novel or atypical situations they might encounter with PBN. Such pilots may also be able to manage the effects of acute stress better, which could reduce associated errors.

How can pilots develop adaptive expertise for PBN operations? First, as a foundation, they should reinforce their basic skills and knowledge related to flying with automated systems, RNAV, and RNP. PBN operations will put these basic skills to the test, so they must be well developed.

In addition, operators should give pilots opportunities to reinforce, strengthen, and practice CRM in scenarios with PBN operations. CRM skills include task agenda management and decision making, which are especially important for PBN operations. For example, pilots need to be good at managing their task agenda for PBN operations, especially as circumstances change and the agenda has to be updated due to operational complexity (e.g., due to a clearance amendment).

Another reason that managing task agendas can be challenging while flying PBN IFPs is because the IFPs are so varied. Variable PBN IFPs require pilots to be both knowledgeable and flexible. For example, several ASRS events occurred while transitioning from a STAR to an approach. This transition can happen in a variety of ways. The pilot needs to understand how to manage the vertical flight path during transition; how the pilot does that will change based on the type of approach to be flown (e.g., RNAV STAR to an ILS approach, or to a visual approach). Pilots need to be able to plan the tasks related to the transition, and decide well in time whether the transition will be smooth or not in terms of aircraft energy state. And, if the approach clearance changes, the pilot needs to adjust accurately and efficiently.

Pilots also need to make well informed decisions based upon their analysis of required tasks for PBN operations. For example, they may need to decide when and how to intervene if an automated system does not work how they expect. If VNAV fails to meet the published constraints, should pilots revert to manual flight, or immediately contact ATC for a new clearance? What data do they need to make this decision? What monitoring tasks should they do as they are making this decision? In particular, pilots need to become more experienced in deciding when to reject an IFP from ATC, i.e., when to say "unable." For example, if ATC assigns a speed on an OPD, when is that speed acceptable, and when should it be rejected?

Another way to think about adaptive expertise is how it is associated with resilient crew behaviors (Pruchniki, et al., 2019). For example, in terms of *responding,* pilots who have developed adaptive expertise would be better at splitting up and reallocating extra tasks. Similarly, pilots with this expertise would be better able to monitor and anticipate their flight path.

Pilots could improve their adaptive expertise through additional practice with these situations (e.g., transitioning from a STAR to different types of approaches). One of the steps towards becoming an adaptive expert is to make choices and to see how they play out in situations that are safe, such as simulator training or classroom exercises. Some of these choices will not be the best option, but that is all part of learning. It is important that this learning occur when the potential negative consequences are minimized. For example, RNAV (RNP) approaches could be conducted in visual conditions for practice, as we saw in some of the events. Another way to help pilots learn to be adaptive is to identify mitigations that were successful in real events, and to remind pilots to apply these.

### 4.3 Potential Future Research

There are several logical directions that this research topic could take. One direction is to address some of the limitations of the dataset we analyzed. For example, it would be straightforward to gather more recent ASRS event data to determine whether these are different from events in 2016-2017. Based on the slow evolution of PBN, we think it is unlikely that the results would change dramatically, but some issues may flare up or die down as changes are made to IFPs and airspace designs. Another limitation of our dataset was that it did not select for events on SIDs, so that is another logical research direction to explore. Given that coding events is a labor-intensive and expertise-intensive process, it might also be useful to target data from specific geographic locations of interest, such as specific airport terminal areas. Another way to potentially learn more about operational complexity would be to review reports from the Line Operations Safety Audit (LOSA) program. LOSA is a voluntary safety program for airlines in which trained observers ride along scheduled flights to collect safety-related data on "environmental conditions, operational complexity, and flightcrew performance" (FAA AC 120-90, 2006).

Another open area for more basic research is to attempt a more sophisticated network analysis to understand factor interactions, using a larger dataset, ideally with more automated data processing. Such an analysis might give us more insight into how event outcomes are related to operational complexity factors and crew behaviors. It could also provide feedback to improve network analyses, tools, and techniques.

A third direction for research would be more applied. It would be helpful to explore pilot training opportunities and techniques to implement the general recommendations in this report. It would be important to develop these programs in a manner that would fit well with existing pilot training programs.

# 5 Summary and Conclusions

We conducted this study to understand the relationship between PBN and flight deck operational complexity in real events. Although there are many limitations of ASRS data, we gained some insights both about the how to do such an analysis and about operational complexity.

One important product of this effort is a comprehensive rubric to code ASRS events for operational complexity related to PBN. We also created a structured review process and developed tools to document the reviews. The rubric was based on a long history of research on PBN complexities from a flightcrew perspective. Because of this past research, we were able to make informed judgments to separate the impact of PBN from operational complexity in general.

We found many operational-complexity factors related to PBN in the ASRS dataset. The rubric worked well. Six of the most prevalent factors were from operational complexity related to PBN. These six were also related to flightcrew and ATC behaviors. We conclude, from the reports we analyzed, that PBN appears to magnify the effects of operational complexity. Whenever pilots have incomplete understanding, PBN operations can reveal those vulnerabilities. Because pilots are more reliant on automated systems to fly PBN IFPs, for example, it is important for them to develop a detailed mental model of how those systems work under many different PBN scenarios. Pilots should learn, for example, how to deal with anomalous system behavior. More generally, pilots should develop adaptive expertise to improve handling of operational complexity in PBN operations.

The most common outcome in the events we studied was an altitude deviation. However, we also found many cases where crew actions prevented a possible deviation, demonstrating resilience. We found examples of these behaviors even though the narratives have many limitations as noted earlier. This finding gives us hope of discovering more about how pilots increase the safety of flight operations. This result also confirms our recommendations for pilots to develop adaptive expertise. By developing adaptive expertise, they will have more practice at initiating resilient behaviors, helping to mitigate or prevent deviations.

We could not find a clear structure for operational complexity in the dataset. We searched for patterns using data about factors that co-occurred, but could not make recommendations to mitigate operational complexity based on the co-occurrence patterns. There are many possible reasons for this result. One reason may be due to the limitations of the ASRS reports we studied; they may not be a representative set of events. This is related to the fact that the frequency of events in the database cannot be assumed to represent the frequency of occurrence in actual operations. Another explanation might be that the sample of reports was too small; more events in the dataset might show a clearer structure of operational complexity. Or, it is possible we did not have sufficiently diagnostic methods for this analysis. And finally, it is possible that operational complexity is just not structured, and that even with a larger more representative set of reports, or better analysis tools, we may not discover any structure.

Our results verify what is already well known among experienced pilots. Most of the time, pilots gain expertise by simply doing their jobs, flying to different airports and using PBN every day. Well-informed pilots know, for example, that the transition from an arrival to the approach is an area of risk. STARs connect to different types of approaches in different ways and there is little room for error because the aircraft's energy profile must be managed carefully during this transition.

However, PBN operations may require a deeper understanding than pilots can develop based on line experience alone. They need to have a detailed understanding of how their automated systems will work in different situations, and a detailed understanding of the required route of flight. They need to understand how PBN is designed to work, so that when operational complexity happens, they know which resilient behaviors and actions could improve the overall outcome. Our main recommendation for the FAA, operators, and flightcrew is to work together towards the goal of building a culture of adaptive expertise, because pilots with such expertise will be better able to analyze and respond in real-time to any operational situation. For example, they will be able to evaluate what factors to consider when deciding whether to accept an ATC instruction or say *"unable."* All pilots would benefit from such training, especially for handling new and potentially unexpected situations, because NextGen PBN IFPs will continue to evolve over the years.

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# Appendix A: Complexity Factors

## Checklist of Complexity Factors for Reviews

This checklist includes all the factors that were considered for each event. After the factors were coded, the reviewer deleted portions of the checklist that were not used in the review, to improve the readability of the summary.

| Factors | Notes, New Examples, Details |
|---|---|
| **ATC and PBN Issues that affect pilots**<br>☐ Interventions related to PBN IFP<br>    ☐ (Late) route amendments/clearances<br>    ☐ Revised altitude/speed restriction<br>    ☐ (Unexpected) vectors<br>☐ Phraseology related to PBN IFP<br>☐ Controller knowledge/training of PBN | |
| **ATC Issues Only**<br>☐ Aircraft sequencing<br>☐ Internal ATC coordination<br>☐ Generic ATC error (unrelated to PBN) | |
| **Flightcrew Factors (related to PBN)**<br>☐ CRM (related to PBN)<br>☐ Lack of familiarity<br>    ☐ Terrain<br>    ☐ Local area<br>    ☐ Local PBN IFPs<br>☐ Lack of knowledge/training related to PBN<br>    ☐ PBN IFP designs<br>    ☐ Aircraft autoflight systems<br>    ☐ Decision making<br>☐ Confusion related to PBN IFP<br>☐ Lack of flight path awareness of PBN IFP<br>☐ Time pressure related to PBN | |
| **Flightcrew Factors (not related to PBN)**<br>☐ Distraction unrelated to PBN<br>☐ Time pressure unrelated to PBN<br>☐ Crew physical condition<br>☐ Non-normal situation unrelated to PBN<br>☐ Communication with ATC unrelated to PBN<br>☐ CRM unrelated to PBN<br>☐ Decision making unrelated to PBN<br>☐ Confusion unrelated to PBN<br>☐ Generic crew error | |

| Factors | Notes, New Examples, Details |
| --- | --- |
| **Aircraft/Equipment (Related to PBN)**<br>☐ Unexpected behavior of automated system<br>☐ FMS/MCP programming/setup or autoflight configuration/operation<br>☐ Aircraft flight performance | |
| **Environment**<br>☐ Terrain related to PBN IFP<br>☐ Other terrain (unrelated to PBN IFP)<br>☐ Man-made structures related to PBN IFP<br>☐ Other man-made structures (unrelated to PBN IFP)<br>☐ Airspace<br>    ☐ Prohibited<br>    ☐ Recent design changes/redesign<br>    ☐ Other boundaries<br>☐ Airport<br>☐ Traffic<br>☐ Weather (all types) (unrelated to PBN)<br>☐ Nighttime (unrelated to PBN) | |
| **IFP Design**<br>☐ Ambiguity<br>☐ Route variability<br>☐ Number of transitions<br>☐ Holds<br>☐ Waypoint names<br>☐ Number and content of notes<br>☐ Vectors<br>☐ Restricted Airspace<br>☐ Constraints<br>☐ Restricted Airspace<br>☐ Energy Profile<br>☐ Satellite airports<br>☐ Other airspace boundaries | |
| **IFP Induced Chart Issues**<br>☐ Visually noncontiguous paths (e.g., inset boxes)<br>☐ Depiction of IFP design<br>☐ Nonstandard layout | |
| **Chart-Specific Issues**<br>☐ Arrangement of Data<br>☐ Placement of sections<br>☐ Placement of elements within sections<br>☐ Depiction inconsistencies<br>☐ Nonstandard/custom notes<br>☐ Arrangement of Data<br>☐ Electronic Flight Bag (EFB) zoom/pan | |

| Factors | Notes, New Examples, Details |
| --- | --- |
| **Operator**<br>☐ Dispatch<br>☐ Clarity of pilot roles<br>☐ Clarity of SOPs | |

## Complexity Factor Descriptions, Examples, and Related Definitions

In this section, we show one table for each of the seven groups of operational-complexity factors. The group's name is the title of the table, e.g., "ATC and PBN Issues that Affect Pilots." Each of the tables has its list of factors from the full checklist on the left side. Subfactors, if present, are shown in the next column, followed by examples of that factor, related extra tasks for the pilot, and finally, a related definition.

We did not have formal definitions for each complexity factor when we began. Instead, our understanding of each factor evolved as we reviewed the ASRS reports. Essentially, the factors were defined by the examples we found in the dataset. If we found examples of operational complexity that did not fit within the existing factors, the reviewers decided together whether to create a new factor or expand the meaning of an existing factor to incorporate the new item. We updated the rubric only after reaching consensus among the reviewers. This also allowed us to maintain a common understanding. For example, through the consensus process, we decided that when pilots mentioned high "workload" or many tasks to be done, we would code that under the CRM factor.

To confirm that our factor definitions were consistent with other aviation human factors taxonomies, we gathered related definitions from the following documents. We include this related material in the table, both as a check on our internal team definitions, and as a guide for refining the definitions if desired in the future.


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The last part of this appendix provides further information on the IFP design and chart complexity factors. We do not provide definitions for these factors, since they are not general concepts. For further information and examples of these, refer to Chandra and Markunas (2017).

## *I. ATC and PBN Related Factors that Affect Pilots*

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
| --- | --- | --- | --- | --- |
| **Interventions related to PBN IFP** | (Late) route amendments (or clearance) | Change of IFP<br>Change of transition<br>Delayed clearance to descend<br>Multiple IFP changes | Decide whether the clearance can be accepted.<br>Re-view, re-brief, reprogram, and re-verify the new route<br><br>Revise strategy for meeting constraints if necessary (change automated system settings, fly manually, change airplane configuration) | A late amendment to a route is one that does not allow the flightcrew adequate time to comply (adapted from FAA Order JO 7110.65Y Para 4-2-5). |
| | Revised Altitude/Speed restriction | Add, delete, or modify altitude or speed constraint | Decide whether the constraint can be accepted.<br><br>Revise strategy for meeting constraints if necessary (change automated system settings, fly manually, change airplane configuration) | An amendment to a speed and/or altitude that is not part of a published procedure or is a change from an existing clearance (adapted from FAA Order JO 7110.65Y Para 4-2-5). |
| | (Unexpected) Vectors | Taken off an IFP and asked to rejoin the same or another IFP later | Disengage autoflight systems and transition to manual flight | A clearance that is not part of the previously cleared route and/or varies from the published procedure. |
| **Phraseology related to PBN IFP** | | Descend via phraseology confusion<br>Maintain phraseology confusion | Interpret the phraseology. Verify.<br>Check autoflight systems configured as required. | ATC communications that allow aircraft operations to be safely conducted with approved reduced separation for aircraft established on a PBN segment of a published instrument flight procedure (adapted from FAA Order JO 7110.65Y Pilot/Controller Glossary). |
| **Controller knowledge/ training of PBN** | | Whether to issue climb/descend via<br>Awareness of current IFP design | Extra communications with ATC to ensure clearance is understood | The training required for Air Traffic Controllers on PBN as stated in FAA JO 7100.41A and content in FAA Order 8260.58A. |

## 2. *ATC Issues Only*

| Factor | Examples | Related Definition |
|---|---|---|
| **Aircraft Sequencing** | Sequencing from different sectors<br>*Descend via* conflict with traffic on underlying arrival | The procedure to transfer control of an aircraft from a “transferring controller” to a “receiving controller” via a “handoff (adapted from FAA Order JO 7110.65Y Para 2-1-15). |
| **Internal ATC Coordination** | Descent profile transitions Center to TRACON boundaries<br>Handoffs<br>Non-towered airports<br>Lack of monitoring Common Traffic Advisory Frequency (CTAF) when aircraft on instrument approach in IMC.<br>Factors related to the transfer of information among air traffic controllers and related to the movement of aircraft or the use of airspace (CICTT). | The coordination from ARTCCs to receiving Air Traffic Service (ATS) facilities (adapted from FAA Order JO 7110.65Y Para 8-2-1). Coordination includes tasks such as handoffs, position relief briefings, point-outs, information exchange, coordination between ground and local controllers, and sector/team coordination (CCIT Air Traffic Causal and Contributory Factors). |
| **Generic ATC error (unrelated to PBN)** | Wrong call sign<br>Issued inappropriate clearance to aircraft | Non-intentional behaviors such as incorrect action selection, incorrect or inadequate action performance, incorrect action sequence, delayed action, lack of action, forgotten action/omission, incomplete action, or unnecessary action. Note this factor can relate to a range of behaviors such as misspeaking (e.g., “air traffic controller misspoke aircraft callsign”) and should be used if a behavior is not specifically referenced in the other procedural factors (CICTT Air Traffic Causal and Contributory Factors). |

### 3. *Flightcrew Factors (Related to PBN)*

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|---|
| **CRM (related to PBN)** | | Lack of attention to lateral and vertical flight path during approach briefing. | Coordinating plans for flying an IFP<br>Task management and coordination | The effective use of all available resources to manage flight operations in PBN. |
| **Lack of Familiarity** | Terrain | | Be aware of terrain in the vicinity of PBN IFP | The lack of awareness regarding terrain as specified on the procedure charts. |
| | Local area | | Be aware of local jargon and ATC preferences for the PBN IFP | Lack of awareness regarding local procedures in effect by letter of agreement or merely local knowledge. |
| | Local PBN IFPs | Constraints<br>Names/spellings of available STARs/SIDs in the area | Be able to find the local IFPs in the FMS database | Lack of information management skills needed to navigate information resources. |
| **Lack of Knowledge/Training related to PBN** | PBN IFP designs | Waypoint names<br>Notices to Airmen (NOTAMs) | If new designs, need to resolve any ambiguities and determine required flight path (see IFP Design Above) | Flightcrew lack of knowledge regarding PBN IFP designs. |
| | Aircraft Autoflight systems | How to use automated systems and avionics in normal and unexpected situations | Know/learn commonly used techniques and how to problem solve/debug issues | Lack of automation management skills. |
| | Decision making | When to say "unable" for a PBN IFP (i.e., reject a clearance) | Gathering data, planning tasks | The ability to process available information, and how it is applied in the decision-making process and assessment of risk regarding PBN (CICTT Human Factors). |

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|---|
| **Confusion related to PBN IFP** | | How to fly a Descend via<br>IFP ambiguity<br>IFP route variability | Managing autoflight systems for PBN IFPs<br>Interpreting IFP design and/or chart<br>Diagnose and recover, possibly with help from ATC | Confusion regarding PBN IFP flight path or lack of flight path monitoring. Flight path monitoring means the observation and interpretation of the flight path data, aircraft-configuration status, automation modes and on-board systems appropriate to the phase of flight. It involves a cognitive comparison of real-time data against the expected values, modes and procedures. It also includes observation of the other pilot and timely intervention in the event of a deviation. (Dismukes and Berman, 2010) |
| **Lack of flight path awareness on PBN IFP** | | Unaware of crossing restriction<br>Unaware of airspace<br>Lost Situation Awareness (SA) about position | Diagnose and recover, possibly with help from ATC | Lack of awareness of the PBN IFP compared to actual flight path. Flight path monitoring means the observation and interpretation of the flight path data, aircraft-configuration status, automation modes and on-board systems appropriate to the phase of flight. It involves a cognitive comparison of real-time data against the expected values, modes and procedures. It also includes observation of the other pilot and timely intervention in the event of a deviation. (Dismukes and Berman, 2010) |
| **Time pressure related to PBN** | | Multiple clearance changes | Manage task agenda, prioritize correctly | A real- or perceived-time constraint affecting PBN workload management. Workload Management is used for task scheduling, task load shedding, task allocation, and task overload (CICTT Human Factors). |

### 4. *Flightcrew Factors (Unrelated to PBN)*

| Factor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|
| **Distraction unrelated to PBN** | Maneuvering around weather<br>Flight attendants<br>Passengers | Manage task agenda, prioritize correctly | Attention/Distraction are factors related to the flightcrews' ability to maintain attention or to be distracted from their operation or task. It includes attention, channelized attention, and distraction from tasks. Examples include failure to pay attention, lack of focus on tasks, individual ability to remain on task and likelihood to become distracted (CICTT Human Factors). |
| **Time pressure unrelated to PBN** | Weather moving in requires shortcut to the runway | Manage task agenda, prioritize correctly | A real- or perceived-time constraint affecting workload management. Workload Management is used for task scheduling, task load shedding, task allocation, and task overload (CICTT Human Factors). |
| **Crew physical condition** | Vertigo<br>Fatigue | Identify and recover | Impairment/Incapacitation includes factors due to illness, injury, alcohol, illicit drugs, prescription medication, over the counter medication, hypoxia/anoxia, hyperventilation, carbon monoxide, neurological, cardiovascular, toxic fumes, motion sickness, decompression/diving, or other loss of consciousness. Fatigue/Alertness refers to factors such as lack of sleep, disruption in circadian rhythm, jetlag, or rest/duty periods. This factor includes both mental fatigue as well as physical symptoms of fatigue (CICTT Human Factors). |
| **Non-normal situation unrelated to PBN** | Airport diversion<br>Equipment malfunction unrelated to PBN | Reprogramming flight path<br>Working around malfunctioning equipment<br>Extra checklists | The task management to include workload and decision-making associated with non-normal occurrences. |
| **Communication with ATC unrelated to PBN** | Hear back/read back error | Clarify communication with ATC | Factors related to communication between crewmembers and other groups not related to PBN operation (adapted from CICTT Human Factors). |
| **CRM unrelated to PBN** | Planning for a weather diversion | Communication, weather checks, etc. | The effective use of all available resources to manage flight operations. |
| **Decision making unrelated to PBN** | Canceling Instrument Flight Rules | Switching to alternative navigation method | The ability to process available information, and how it is applied in the decision-making process and assessment of risk (CICTT Human Factors). |
| **Generic crew error** | Confirmation bias/expectations<br>Data entry error (e.g., slip)<br>Unintentional noncompliance with flight deck procedure (e.g., Minimum Equipment List)<br>Incorrect altimeter setting | Identify and recover | Situations in which a flight crewmember failed to follow a procedure, plan, or coordinate with others or made an unintentional error in aircraft handling and technique (CICTT Human Factors). |

### 5. *Aircraft/Equipment (Related to PBN)*

| Factor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|
| **Unexpected behavior of automated system** | Altitude not captured<br>VNAV unable to meet programmed constraints<br>LNAV unable to follow the route<br>GPWS unexpectedly gives a warning during a PBN approach | Diagnose issue (e.g., review FMS program and mode)<br>Decide how to recover.<br>Execute the plan to recover. May need to revert to manual flight.<br>Manage any other consequences. | Any unexpected or non-normal action or inaction of an automated system. |
| **FMS/MCP programming or autoflight configuration/operation** | Modes, mode selection<br>Data entry<br>State awareness (armed, activated) | Selecting IFP<br>Verifying constraints<br>Configuration<br>Monitoring | The interaction between the flightcrew and the operation of the automated equipment to include operator interface. |
| **Aircraft flight performance** | Difficulty slowing down while descending | Reconfigure aircraft.<br>Update aircraft data in the FMS. | The expected performance of the aircraft based on the programming of the automated functions, limitations, and any non-normal condition. |

### 6. *Environment*

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|---|
| **Temporary Restriction** | | GPS outage<br>NOTAM change | Request alternate clearance<br>Modify flight path to adhere to NOTAM or extra communication with ATC if failed to adhere to NOTAM | A time-limited and/or uncharted change to an IFP. |
| **Terrain (related to PBN IFP)** | | Ridge line | Be aware of minimum altitudes<br>Monitor weather that may be related to terrain (e.g., mountain winds).<br>Potential for more constraints on IFP and related tasks. | Terrain associated with the design parameters for a PBN IFP. |
| **Other Terrain (unrelated to PBN IFP)** | | Flat terrain | n/a | n/a |

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|---|
| **Man-made structures (related to PBN IFP)** | | Tower | Be aware of minimum altitudes<br>Be aware of notes on IFP related to operations near cities. | Man-made structures associated with the design parameters for a PBN IFP. |
| **Other Man-made structures** | | Solar farm | n/a | n/a |
| **Airspace** | Prohibited | Areas avoided | Be aware of boundaries and flight deck procedures to avoid | Special Use Airspace or airspace otherwise charted or in a NOTAM. |
| | Recent redesign/ changes | Updates to multiple IFPs | Review airport information<br>Review IFPS even if familiar | IFP changes since last revision cycle. |
| | Other boundaries | Class B<br>VFR corridors (under IFP design if related to that)<br>Closely spaced STARs and SIDs | Be aware of boundaries and potential related speed/altitude constraints | Static airspace conditions and airspace procedures in effect during flight. |
| **Airport** | | Inoperable ground equipment<br>Closely spaced parallel runways<br>Airport configuration change | Identify alternatives and set up backups<br>Monitor and be prepared for immediate actions (e.g., go-around)<br>Follow additional ATC instructions | Airport means an area of land or water that is used or intended to be used for the landing and takeoff of aircraft, and includes its buildings and facilities, if any (14 CFR 1). |
| **Traffic** | | NORDO traffic at non-towered airport<br>Military operations<br>Wake Turbulence<br>VFR traffic | Visual search for nearby traffic<br>Be aware of potential for merging traffic streams | Other aircraft (to include Unmanned Aerial Systems) associated with the flight. |

| Factor | Subfactor | Examples | Extra Pilot Tasks | Related Definition |
|---|---|---|---|---|
| **Weather-All Types (unrelated to PBN)** | | Thunderstorms (convective weather)<br>Wind shear<br>Turbulence<br>Low Instrument Meteorological Conditions (IMC)<br>Precipitation<br>Strong winds<br>Changing weather conditions | Monitor speeds, vertical constraints<br>Monitor weather radar<br>Reroute around weather<br>Difficulty entering data on flight deck systems<br>Be aware of weather minimums and related flight deck procedures<br>Be aware of potential for changing conditions<br>Monitor conditions, especially if rapid deterioration | The environmental conditions encountered during flight. |
| **Nighttime (unrelated to PBN)** | | Nighttime, but no special IFP-related tasks | Be aware of runway and other airport lighting<br>Be aware of potential for visual illusions, fatigue | Night means the time between the end of evening civil twilight and the beginning of morning civil twilight, as published in the Air Almanac, converted to local time (14 CFR 1). |

## *7. Operator*

| Factor | Examples | Extra Pilot Tasks | Related Information |
|---|---|---|---|
| **Dispatch** | Rerouting; weather updates | Communication and coordination with Dispatch | The dispatcher has joint responsibility with the captain for the safety and operation control of flights to include weather, fuel, flight plans, and unsafe conditions. |
| **Clarity of pilot roles** | Which pilot is verifying the programmed route | Ensuring that all tasks are completed.<br>Coordinating and communication decisions regarding route if ambiguous. | Each operator specifies crewmember roles and responsibilities, but there is also routine variation in how roles are divided based on the immediate situation. |
| **Clarity of SOPs** | Recommended configurations | Be aware of special operating procedures | Policies and procedures can be very detailed. They can be presented to the crewmembers via different means. Crewmembers' understanding and knowledge of SOPs may vary. |

## 8. *IFP Design*

| Factor | Example | Extra Pilot Tasks |
|---|---|---|
| **Ambiguity** | If unclear on the IFP instructions, can result in pilot confusion | Have to resolve the ambiguity (Interpret the instructions—What flight path is actually required?)<br>May have to seek additional information |
| **Route variability** | Overlapped arrivals (e.g., same waypoint used in multiple IFPs, have to know and program correct IFP) can result in pilot confusion | More careful review<br>More verification steps |
| **Number of transitions** | The number and type of transitions for the IFP. | More careful review (e.g., picking the correct transition) |
| **Holds** | Holding patterns associated with IFP. | Join and leave the hold correctly (e.g., matching energy profile) |
| **Waypoint names** | Hard to pronounce during briefing<br>Similar sounding names | More careful review |
| **Number and content of notes** | Speed below Class B not provided | More careful review and more reading<br>Might be missing information |
| **Vectors** | Segments on an IFP controlled by ATC | Transition from FMS programmed route systems to flying using MCP |
| **Restricted Airspace** | P-56 in Washington, District of Columbia, near White House | More careful review/awareness |
| **Constraints** | At or above altitudes, or window altitudes | Managing/setting up automated systems<br>Monitoring automated systems<br>Monitoring and deciding whether to change aircraft configuration<br>Manual flying when automated system is unable |
| **Energy Profile** | Mismatched connection between STAR and approach<br>Steep gradient between waypoints<br>Incompatible speed assigned on OPD | Monitoring<br>Managing aircraft configuration<br>Manual flying when automated system is unable |
| **Satellite airports** | Conflicting or arrivals | More careful review (e.g., picking the correct flight path) |
| **Other airspace boundaries** | ARTCC/TRACON boundaries<br>VFR traffic corridor<br>Floor of Class B | These can result in additional constraints for pilots to manage. |

### *9. IFP Induced Chart Issues*

Factors

- Visually noncontiguous paths
- Depiction of IFP design
- Nonstandard layout

Examples

- Inset boxes for transitions
- RNAV to ILS transition on panels
- Multiple pages

Extra pilot tasks

- Figure out the full path
- Interpret the IFP instructions
- Manage data across unfamiliar format

### *10. Chart-Specific Issues*

Factors

- Arrangement of Data
- Placement of sections
- Placement of elements within sections
- Depiction inconsistencies
- Nonstandard/custom notes
- EFB zoom/pan

Examples

- Difficult identifying final approach fix on plan view
- Difficulty finding a constraint or note

Extra pilot tasks

- Figure out how to read the chart if unfamiliar
- Be sure to search for all the important data

# Appendix B: Sample Reviews

Two sample reviews are provided. The first event (1463450) was for a Part 121 operation, and the second (1440838) was a Part 91 operator. Both events occurred on current IPFs, so charts for these are included.

## Report 1463450 from ASRS

### Basic Info

| | |
|---|---|
| **City** | Sacramento |
| **IFP** | SUUTR 2 |
| **IFP Type** | STAR (OPD) |
| **Reporter** | Crew, Part 121 |

### Synopsis

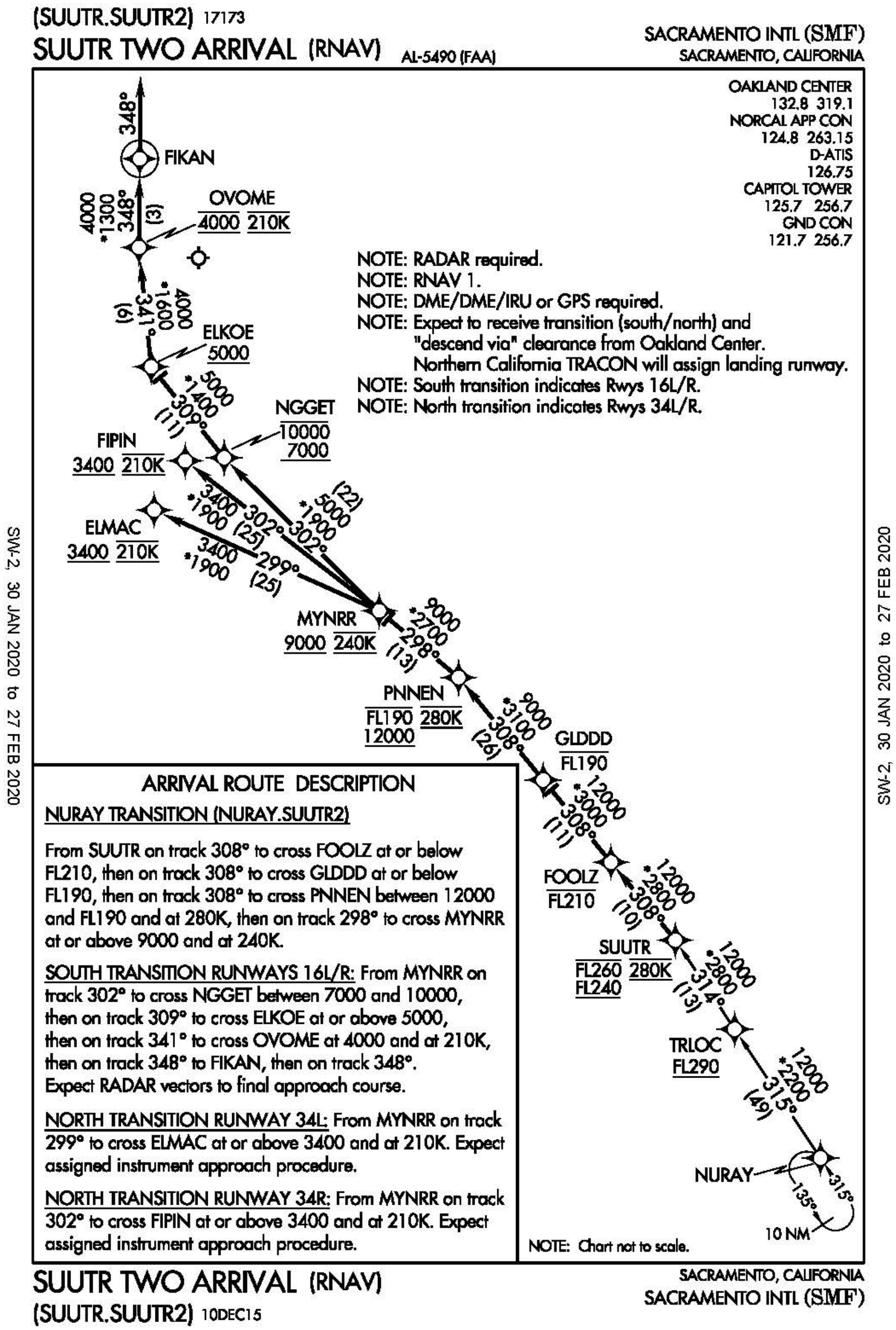
- A B-737 aircraft did not meet the altitude constraints on an OPD while following a "descend via" clearance. The aircraft was on the SUUTR TWO STAR at Sacramento International Airport, which is current.
- Related to PBN

### Context

- After the aircraft crossed TRLOC at FL290, the FMS unexpectedly switched out of VNAV PATH mode and defaulted into VSPD mode, so it crossed the next waypoint 1200 ft high. The crew felt they might have made the altitude constraint (or at least come closer to it) if they had known about the FMS issue ahead of time, because they would have started the descent earlier.
- TRLOC has an "at or above FL290" constraint. The next constraint is 13 miles ahead at SUUTR ("between FL260 and FL240, at 280 KIAS"), which requires a descent of 3000 to 5000 ft over 13 miles. After SUUTR, the next constraint is 10 miles ahead at FOOLZ ("at or below FL210"). Depending on what altitude it crossed at SUUTR, the aircraft would have to descend another 3000 to 5000 ft in 10 miles. *(Typical descents require approximately 3 miles for every 1000 ft change in altitude, so a 5000 ft altitude change would generally need 15 miles.)*
- The crew said their briefing page mentions general issues with this procedure, but not specifically this issue.

### Issue

- *Combination of IFP design and Aircraft/equipment*
- The OPD allowed the crew to be in position for a steep descent.
- The FMS could not deliver the required descent and did not give the crew enough warning to make adjustments to mitigate the altitude deviation.


(SUUTR.SUUTR2) 17173
SUUTR TWO ARRIVAL (RNAV)
AL-5490 (FAA)
SACRAMENTO INTL (SMF)
SACRAMENTO, CALIFORNIA
OAKLAND CENTER
132.8 319.1
NORCAL APP CON
124.8 263.15
D-ATIS
126.75
CAPITOL TOWER
125.7 256.7
GND CON
121.7 256.7
NOTE: RADAR required.
NOTE: RNAV 1.
NOTE: DME/DME/IRU or GPS required.
NOTE: Expect to receive transition (south/north) and "descend via" clearance from Oakland Center. Northern California TRACON will assign landing runway.
NOTE: South transition indicates Rwys 16L/R.
NOTE: North transition indicates Rwys 34L/R.
FIKAN
OVOME
4000 210K
ELKOE
5000
NGGET
10000
7000
FIPIN
3400 210K
ELMAC
3400 210K
MYNRR
9000 240K
PNNEN
FL190 280K
12000
GLDDD
FL190
FOOLZ
FL210
SUUTR
FL260 280K
FL240
TRLOC
FL290
NURAY
10 NM
NOTE: Chart not to scale.
SW-2, 30 JAN 2020 to 27 FEB 2020
ARRIVAL ROUTE DESCRIPTION
NURAY TRANSITION (NURAY.SUUTR2)
From SUUTR on track 308° to cross FOOLZ at or below FL210, then on track 308° to cross GLDDD at or below FL190, then on track 308° to cross PNNEN between 12000 and FL190 and at 280K, then on track 298° to cross MYNRR at or above 9000 and at 240K.
SOUTH TRANSITION RUNWAYS 16L/R: From MYNRR on track 302° to cross NGGET between 7000 and 10000, then on track 309° to cross ELKOE at or above 5000, then on track 341° to cross OVOME at 4000 and at 210K, then on track 348° to FIKAN, then on track 348°. Expect RADAR vectors to final approach course.
NORTH TRANSITION RUNWAY 34L: From MYNRR on track 299° to cross ELMAC at or above 3400 and at 210K. Expect assigned instrument approach procedure.
NORTH TRANSITION RUNWAY 34R: From MYNRR on track 302° to cross FIPIN at or above 3400 and at 210K. Expect assigned instrument approach procedure.
SUUTR TWO ARRIVAL (RNAV)
(SUUTR.SUUTR2) 10DEC15
SACRAMENTO, CALIFORNIA
SACRAMENTO INTL (SMF)

### Factors

| Main Factor | Subfactor | Detail |
|---|---|---|
| Aircraft/equipment | Unexpected behavior of FMS | Could not meet programmed constraint |
| IFP design | Energy profile | Steep gradient |
| IFP design | Constraints | |

### Explanation of Coding

- Crew felt they could have made adjustments had they known earlier that the FMS wouldn't meet the constraints.

| Factors | Notes/Examples |
|---|---|
| **Aircraft/Equipment (Related to PBN)**<br>☒ Unexpected behavior of automated system<br>☐ FMS/MCP programming/setup or autoflight configuration/operation<br>☐ Aircraft flight performance | FMS could not meet constraints and did not give sufficient notice to crew |
| **IFP Design**<br>☐ Ambiguity<br>☐ Route variability<br>☐ Number of transitions<br>☐ Waypoint names<br>☐ Number and content of notes<br>☐ Vectors<br>☐ Restricted Airspace<br>☒ Constraints<br>☐ Restricted Airspace<br>☒ Energy Profile<br>☐ Satellite airports<br>☐ Other airspace boundaries | |

## Report 1440838 from ASRS

### Basic Information

| | |
|---|---|
| **City** | Centennial Airport, Denver, CO |
| **IFP** | PUFFR 4 RNAV |
| **IFP Type** | STAR (OPD) |
| **Reporter** | Pilot Monitoring (PM) (Captain), Pt 91 (corporate) |

### Synopsis

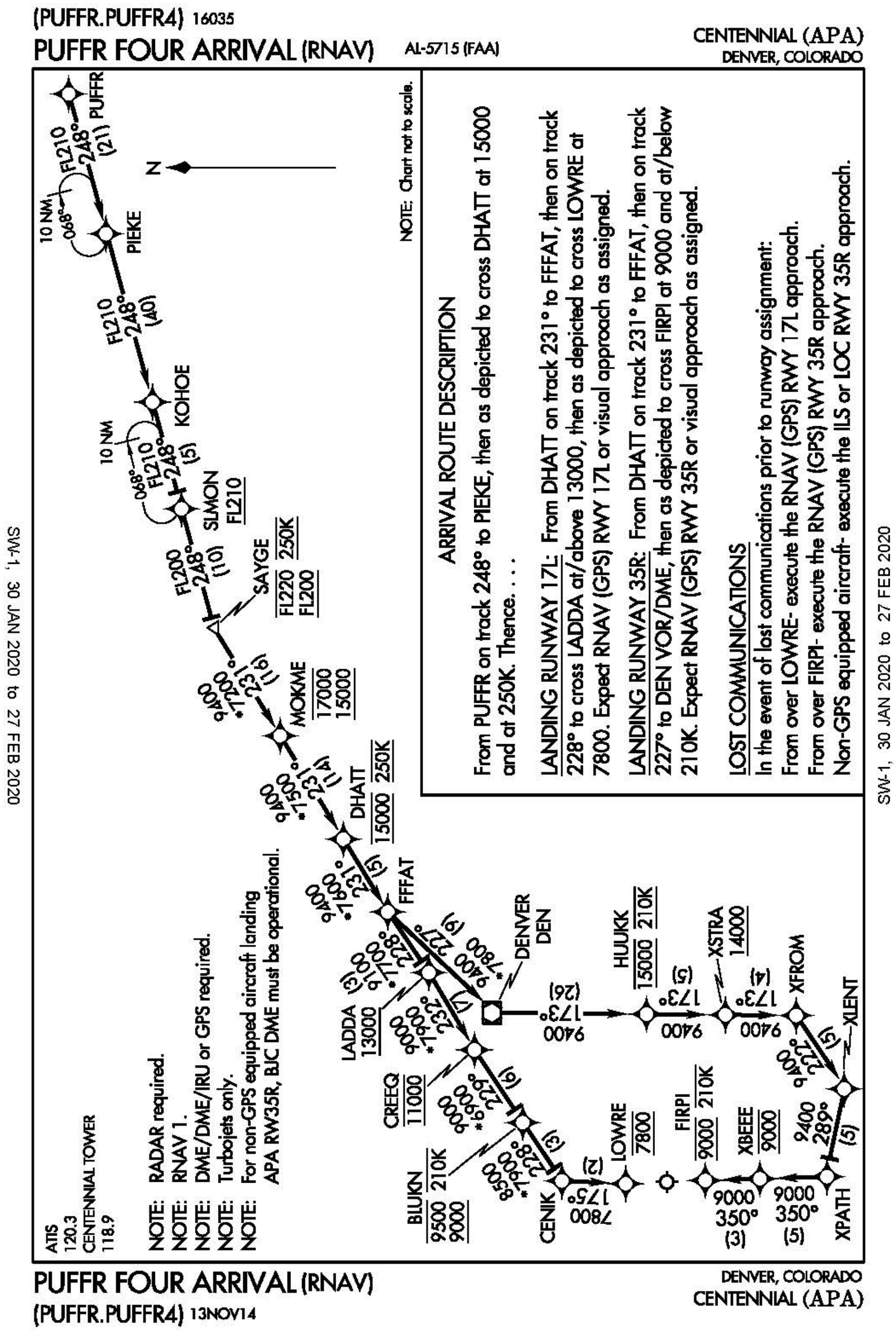
- A multi-engine-aircraft corporate pilot descended below an altitude constraint on the PUFFR 4 OPD approach transition to runway 17L.
- Related to PBN (bi-directional OPD).

### Context

- The aircraft descended below the altitude constraint at LADDA. The PM was familiar with the arrival, and was trying to help the other crewmember who was not familiar. The PM mistakenly thought they were at LADDA, which has an altitude constraint (“at or above 1300 ft”), when they were really at the waypoint before it (FFFAT), which does not have a constraint. Thinking they were at LADDA, the pilots tried to get down fast to meet what they thought was their next altitude constraint (mandatory 1100 ft at CREEQ), and ended up descending below 13000 ft when crossing LADDA.
- The PM knew that the STAR has a high-energy profile when landing south, and flightcrews do not have much time to manage the descent. The PM explained that he/she felt the STAR was overly complex and that waypoints without altitude or speed constraints should be removed to simplify it.
- ATC did not alert the pilot of impending altitude miss. Did not code this. It could have been a mitigating factor, but was not. The controller at Denver later told the pilot that there are many issues with this procedure.
- The FMS was older and could not show altitude restriction on the map display. Another potential mitigation that was not available.
- Pilot describes himself/herself as a “seasoned” “career aviator” who flies for a living.
- This STAR is still current.

### Issues

- The STAR has a high-energy descent profile, which was especially hard to manage given the number of waypoints and constraints to track. Landing north (opposite direction), there is too much time.
- The pilot suggested a variety of procedure design changes to make this STAR easier for pilots, and if those are not possible, he/she suggested making the STAR specific to landing south, rather than being bidirectional.


(PUFFR.PUFFR4) 16035
PUFFR FOUR ARRIVAL (RNAV)
AL-5715 (FAA)
CENTENNIAL (APA)
DENVER, COLORADO
ATIS 120.3
CENTENNIAL TOWER 118.9
NOTE: RADAR required.
NOTE: RNAV 1.
NOTE: DME/DME/IRU or GPS required.
NOTE: Turbojets only.
NOTE: For non-GPS equipped aircraft landing APA RW35R, BJC DME must be operational.
NOTE: Chart not to scale.
PUFFR
PIEKE
KOHOE
SLMON FL210
SAYGE FL220 FL200 250K
MOKME 17000 15000
DHATT 15000 250K
FFFAT
LADDA 13000
CREEQ 11000
BLUKN 9500 9000 210K
CENIK
LOWRE 7800
FIRPI 9000 210K
XBEEE 9000
XPATH
XLENT
XFROM
XSTRA 14000
HUUKK 15000 210K
DENVER DEN
10 NM
ARRIVAL ROUTE DESCRIPTION
From PUFFR on track 248° to PIEKE, then as depicted to cross DHATT at 15000 and at 250K. Thence. . . .
LANDING RUNWAY 17L: From DHATT on track 231° to FFFAT, then on track 228° to cross LADDA at/above 13000, then as depicted to cross LOWRE at 7800. Expect RNAV (GPS) RWY 17L or visual approach as assigned.
LANDING RUNWAY 35R: From DHATT on track 231° to FFFAT, then on track 227° to DEN VOR/DME, then as depicted to cross FIRPI at 9000 and at/below 210K. Expect RNAV (GPS) RWY 35R or visual approach as assigned.
LOST COMMUNICATIONS
In the event of last communications prior to runway assignment:
From over LOWRE- execute the RNAV (GPS) RWY 17L approach.
From over FIRPI- execute the RNAV (GPS) RWY 35R approach.
Non-GPS equipped aircraft- execute the ILS or LOC RWY 35R approach.
PUFFR FOUR ARRIVAL (RNAV)
(PUFFR.PUFFR4) 13NOV14
DENVER, COLORADO
CENTENNIAL (APA)

### Factors

| Main Factor | Subfactor | Detail |
|---|---|---|
| IFP Design | Energy Profile | |
| IFP Design | Constraints | |
| Crew | Distraction unrelated to PBN | Training |
| Crew | Confusion related to PBN | Lost SA about position |
| Crew | Lack of flight path awareness of PBN IFP | |
| Crew | Time pressure related to PBN | |

### Explanation of Coding

- The PM was training the other pilot and doing checklists etc. Mentions multiple other tasks, some of which might be called Distractions, some of which were necessary (approach checklist).
- The ASRS report mentions the chart as a factor, but the pilot does not mention the chart, just a complex set of constraints.
- The reporter was very familiar with this procedure.

### Inferences

- None

| Factors | Notes, New Examples, Details |
|---|---|
| **Flightcrew Factors (related to PBN)**<br>☐ CRM (related to PBN)<br>☐ Lack of familiarity<br>    ☐ Terrain<br>    ☐ Local area<br>    ☐ Local PBN IFPs<br>☐ Lack of knowledge/training related to PBN<br>    ☐ PBN IFP designs<br>    ☐ Aircraft autoflight systems<br>    ☐ Decision making<br>☒ Confusion related to PBN IFP<br>☒ Lack of flight path awareness of PBN IFP<br>☒ Time pressure related to PBN | Perceived time pressure due to confusion about aircraft position. |

| Factors | Notes, New Examples, Details |
|---|---|
| **Flightcrew Factors (not related to PBN)**<br>☒ Distraction unrelated to PBN<br>☐ Time pressure unrelated to PBN<br>☐ Crew physical condition<br>☐ Non-normal situation unrelated to PBN<br>☐ Communication with ATC unrelated to PBN<br>☐ CRM unrelated to PBN<br>☐ Decision making unrelated to PBN<br>☐ Confusion unrelated to PBN<br>☐ Generic crew error | Training the other crewmember |
| **IFP Design**<br>☐ Ambiguity<br>☐ Route variability<br>☐ Number of transitions<br>☐ Waypoint names<br>☐ Number and content of notes<br>☐ Vectors<br>☐ Restricted Airspace<br>☒ Constraints<br>☐ Restricted Airspace<br>☒ Energy Profile<br>☐ Satellite airports<br>☐ Other airspace boundaries | |

# Appendix C: Complexity-Factor Clusters

Factors that occurred in at least 20 of the events in the dataset are listed on the left column of the table below, along with factors that co-occurred in the right column. Together the two columns represent a "cluster" of factors that tended to appear together in the dataset.

| Factor that Occurred in at least 20 Events | Factors that Co-occurred |
|---|---|
| ATC interventions related to PBN | • Flightcrew time pressure related to PBN<br>• CRM related to PBN<br>• Constraints related to PBN IFP<br>• Unexpected behavior of the automated system related to PBN<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• Flightcrew confusion related to PBN IFP<br>• Flightcrew lack of knowledge/training related to PBN<br>• Weather – all types (related and unrelated to PBN)<br>• FMS/MCP programming/setup or autoflight configuration/operation related to PBN |
| Lack of knowledge/training related to PBN | • Flightcrew confusion related to PBN IFP<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• Generic flightcrew error not related to PBN<br>• FMS/MCP programming/setup or autoflight configuration/operation related to PBN<br>• ATC interventions related to PBN IFP |
| CRM related to PBN | • ATC interventions related to PBN IFP<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• FMS/MCP programming/setup or autoflight configuration/operation related to PBN<br>• Flightcrew confusion related to PBN IFP<br>• Flightcrew time pressure related to PBN |
| Unexpected behavior of the automated system | • ATC Interventions related to PBN IFP<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• Weather – all types (related and unrelated to PBN)<br>• Flightcrew distraction unrelated to PBN<br>• Energy profile related to PBN IFP<br>• Flightcrew lack of knowledge/training related to PBN<br>• ATC interventions related to PBN IFP |
| Lack of flight path awareness of PBN IFP | • Flightcrew lack of knowledge/training related to PBN<br>• Flightcrew confusion related to PBN IFP<br>• CRM related to PBN<br>• ATC interventions related to PBN IFP<br>• Unexpected behavior of automated system related to PBN<br>• FMS/MCP programming/setup or autoflight configuration/operation related to PBN |

| Factor that Occurred in at least 20 Events | Factors that Co-occurred |
|---|---|
| IFP design constraints | • ATC interventions related to PBN IFP<br>• Energy profile related to PBN IFP<br>• Other airspace boundaries related to PBN IFP design<br>• Internal ATC coordination not related to IFP<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• Unexpected behavior of automated system related to PBN |
| Flightcrew confusion related to PBN IFP | • Flightcrew lack of knowledge/training related to PBN<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• CRM related to PBN<br>• ATC interventions related to PBN IFP<br>• Flightcrew time pressure related to PBN<br>• Generic flightcrew error not related to PBN |
| Generic flightcrew error | • Flightcrew lack of knowledge/training related to PBN<br>• FMS/MCP programming/setup or autoflight configuration/operation related to PBN<br>• Flightcrew confusion related to PBN IFP<br>• Flightcrew lack of flight path awareness of PBN IFP<br>• CRM related to PBN |

# Appendix D: Evolution of Complexity Factors

The tables below show the list of complexity factor from an earlier report by Chandra and Markunas (2017) on the left and the current list of complexity factors on the right. The new list is more detailed and comprehensive, particularly in terms of ATC interventions, flightcrew factors, and environment factors. The main focus of the 2017 study was IFP and chart-related complexity. Those factors are generally unchanged; just one item, related to EFBs, was added.

## Operational-complexity factors

| Chandra and Markunas (2017) | Current Coding Rubric |
|---|---|
| **ATC Interventions**<br>• (Late) route amendments<br>• Unpublished restrictions<br>• Vectors | **ATC and PBN Issues that affect pilots**<br>☐ Interventions related to PBN IFP<br>    ☐ (Late) route amendments/clearances<br>    ☐ Revised altitude/speed restriction<br>    ☐ (Unexpected) vectors<br>☐ Phraseology related to PBN IFP<br>☐ Controller knowledge/training of PBN |
| | **ATC Issues Only**<br>☐ Aircraft sequencing<br>☐ Internal ATC coordination<br>☐ Generic ATC error (unrelated to PBN) |
| **Flightcrew Factors** | **Flightcrew Factors (related to PBN)** |
| • (Standard) expectations<br>• Fatigue<br>• Communication style<br>• Distractions<br>• Local area familiarity<br>• Familiarity with different types of IFPs | ☐ CRM (related to PBN)<br>☐ Lack of familiarity<br>    ☐ Terrain<br>    ☐ Local area<br>    ☐ Local PBN IFPs<br>☐ Lack of knowledge/training related to PBN<br>    ☐ PBN IFP designs<br>    ☐ Aircraft autoflight systems<br>    ☐ Decision making<br>☐ Confusion related to PBN IFP<br>☐ Lack of flight path awareness of PBN IFP<br>☐ Time pressure related to PBN |
| | **Flightcrew Factors (not related to PBN)** |
| | ☐ Distraction unrelated to PBN<br>☐ Time pressure unrelated to PBN<br>☐ Crew physical condition<br>☐ Non-normal situation unrelated to PBN<br>☐ Communication with ATC unrelated to PBN<br>☐ CRM unrelated to PBN<br>☐ Decision making unrelated to PBN<br>☐ Confusion unrelated to PBN<br>☐ Generic crew error |

| Chandra and Markunas (2017) | Current Coding Rubric |
|---|---|
| **Aircraft/Equipment**<br>• Lack or unreliability of automated systems<br>• Performance characteristics | **Aircraft/Equipment (Related to PBN)**<br>☐ Unexpected behavior of automated system<br>☐ FMS/MCP programming/setup or autoflight configuration/operation<br>☐ Aircraft flight performance |
| **Environment**<br>• Terrain<br>• Traffic<br>• Weather (Wind or IMC)<br>• Prohibited airspace | **Environment**<br>☐ Terrain related to PBN IFP<br>☐ Other terrain (unrelated to PBN IFP)<br>☐ Man-made structures related to PBN IFP<br>☐ Other man-made structures (unrelated to PBN IFP)<br>☐ Airspace<br>  ☐ Prohibited<br>  ☐ Recent design changes/redesign<br>  ☐ Other boundaries<br>☐ Airport<br>☐ Traffic<br>☐ Weather (all types) (unrelated to PBN)<br>☐ Nighttime (unrelated to PBN) |
| **Operator**<br>• Independence vs. dependence on Dispatch<br>• Clarity and consistency of Pilot-flying (PF)/PM roles in reviewing IFPs | **Operator**<br>☐ Dispatch<br>☐ Clarity of pilot roles<br>☐ Clarity of SOPs |

## IFP Design and Chart Factors

| Chandra and Markunas (2017) | Current Coding Rubric |
|---|---|
| **IFP Design**<br>• Ambiguity<br>• Route variability<br>• Number of transitions<br>• Holds<br>• Waypoint names<br>• Number and content of notes<br>• Vectors<br>• Restricted Airspace<br>• Constraints<br>• Restricted Airspace<br>• Energy Profile<br>• Satellite airports<br>• Other airspace boundaries | Unchanged |
| **IFP Induced Chart Issues**<br>• Visually noncontiguous paths (e.g., inset boxes)<br>• Depiction of IFP design<br>• Nonstandard layout | Unchanged |

| Chandra and Markunas (2017) | Current Coding Rubric |
|---|---|
| **Chart-Specific Issues**<br>• Arrangement of Data<br>• Placement of sections<br>• Placement of elements within sections<br>• Depiction inconsistencies<br>• Nonstandard/custom notes<br>• Arrangement of Data | Added<br>☐ EFB zoom/pan |

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DOT-VNTSC-FAA-20-02