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16. ABSTRACT
Numerous accidents and incidents have occurred over the past decade where a contributing factor was lack of support, or even an incompatibility, between cockpit system design and the flight procedures which needed to be flown in the current airspace. Several reports reveal pilot errors where they were trying to get the automation to perform a particular procedure. Examples range from errors due to in-flight re-programming of the flight management system (FMS) to fly a complex approach or to change a runway, to the lack of automation support for performing calculations to determine whether an Air Traffic Control (ATC) clearance can be met, to difficulties in creating a user-defined waypoint due to an unusual clearance, to subtle lateral deviations in flight path caused by the discrepancy in the way the FMS performs a turn at a waypoint versus the way ATC expects the turn to be executed. With the advent of the Next Generation Air Transportation System (NextGen) and associated increasingly complex flight procedures, the risk of such pilot errors may increase. Accordingly, the goal of this effort was to develop design guidelines to mitigate anticipated pilot errors in using advanced flight deck (FD) automation to fly new, complex air navigation procedures under NextGen. The work achieved three main objectives: 1. Analysis and classification of current cockpit design and operational procedure safety data, and extrapolating those data to NextGen operations; 2. Identification and description of NextGen air space procedures that are most likely to lead to potential FD use issues; and 3. Development of design guidelines and recommendations to mitigate these issues.

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1 Introduction

Numerous accidents and incidents have occurred over the past decade where a contributing factor was lack of support, or even an incompatibility, between cockpit system design and the flight procedures which needed to be flown in the current airspace. This is illustrated in frequent accounts, both during normal operations and in reported incidents, of pilots having to do "workarounds" with the automated systems in order to fly particular procedures. Even more troubling are reports of pilot errors in trying to get the automation to perform a particular procedure. Examples range from errors in in-flight re-programming of the flight management system (FMS) to fly a complex approach or change a runway, to the lack of automation support for performing calculations to determine whether an Air Traffic Control- (ATC) requested clearance can be met or not, to difficulties in creating a user-defined waypoint due to an unusual clearance, to subtle lateral deviations in flight path caused by the discrepancy in the way the FMS performs a turn at a waypoint versus the way ATC expects the turn to be executed. It is very likely that these "design-procedure incompatibility" induced errors and problems will be exacerbated in a NextGen environment where the complexity and precision of flight procedures will increase while faster paced operations will increase the time pressure for pilots to utilize cockpit automation for execution of tactical procedures. Further, pilots will likely have more discretion in selecting the flight procedures to fly, and cockpit systems should be designed to facilitate those decisions.

1.1 Problem Statement

While NextGen airspace procedures and flight deck (FD) automation advances should help improve safety related to NextGen operations, the changes also have the potential to negatively affect safety. For example, a more complex operational environment with more highly automated FD systems will likely exacerbate the chronic issue of how to keep pilots involved and informed without overloading them with information and tasks. This is due in part to the fact that FDs are often not completely compatible with operational procedures or with the automation inherent in modern ATC systems. Further, more alerts, notifications and other types of information that compete for pilots' attention could create more distractions, interruptions, and disruptions in a very demanding multitasking environment, and it will be more and more difficult to maintain an overall quiet, dark cockpit philosophy that has been an important part of aircraft safety in the past [1].

1.2 Goal of Work

The primary goal of this work is to develop design guidelines to mitigate anticipated pilot errors in using advanced FD automation to fly new NextGen airspace procedures.

1.2.1 **FAA Objective**

The specific FAA objective of this work is to produce guidelines, including those that address:

- FD automation and pilot-automation interaction design;
- NextGen airspace procedure design.

The main FAA function identified as benefiting from these data is Certification Human Error Support. Certification of new and existing systems to support NextGen applications will require research to assist in the development of design standards and evaluation tools that identify and mitigate human errors.

The work reported here supports these NextGen Human Factors Air/Ground Integration research goals by:

- Assisting certification personnel in assessing the suitability of design methods to support human error detection and correction;
- Investigating methods to mitigate mode errors in the use of NextGen equipment;
- Completing research and modeling activities aimed at identifying, quantifying and mitigating potential human errors in the use of NextGen equipment and procedures.

1.2.2 **Contract Task Objectives**

In the context of envisioned NextGen operational procedures, the specific contract objective of this task is to reduce the risk and provide guidance for design of FD systems and airspace procedures that will enable safe and efficient flight under both normal and off-nominal conditions by:

1. Analysis and classification of current cockpit design and operational procedure safety data, and extrapolating those data to NextGen operations;
2. Identification and description of NextGen air space procedures that are most likely to lead to potential FD use issues;
3. Development of design guidelines and recommendations to mitigate these issues.

The analyses and resulting guidelines will necessarily be coarse; categorical issues and high level risk mitigations will be identified which are predicted to be overarching for the types of FD automation and NextGen airspace procedures envisioned.

1.2.3 **Background**

Guidelines for FD automation design and airspace procedure design are not new. Many excellent guidelines exist which should be as applicable to NextGen as they are to today's operations. For example, automation guidelines from Chapter 3 (Automation) of the FAA's Human Factors Design Guidelines [2] should apply to the design of NextGen automation. Although it is aimed primarily at ground automation, many of those guidelines apply to FD systems as well. Examples of particularly relevant design categories and existing guidance (paraphrased from [2]) are provided below.

Design for Intended Function

- The automation has to improve performance.

Efficiency

- Users should be able to carry out tasks efficiently so that the desired results are produced with a minimum of waste.

Consistency

- Pilot interface design should provide interaction consistency.

Control and Final Authority

- The end user needs to be in command.
- Automation should be designed to provide flexibility and allow the user to make the decision to use or not to use the automation.
- Systems should provide a means of user override. Systems should be designed so that the user can override the automation at any time unless there is not enough time for the user to make a decision.

Design for Human Use

- Automation should be human-centered, not technology-centered.
- Systems should be easy to learn, understand and use.
- System behavior should be predictable.
- The system design should be simple, logical and consistent. When possible, spatial representations of information should be used. All dynamic information should be presented in real time.
- Systems and procedures should ensure safe operations that are within human capacity. The goal of automation is to create a system that improves efficiency but allows the operator to recover the system in emergencies with manual intervention.

Access and Transparency

- Pilot interfaces should provide easy data access.
- Automation should provide sufficient information to keep the user informed of its operating mode, intent, function, and output. It should also provide information about automation failure or degradation, and potentially unsafe modes that have been selected.
- Systems should be designed with clear indication and feedback of their current mode and function. Optimal designs will provide the greatest amount of system flexibility but will minimize the number of modes. A greater number of modes will increase the potential for user error. Systems should provide the user with an easy mechanism for switching between modes. Features and functions have to be consistent across modes. Additionally, automation should alert the user to the implications of interactions between modes, especially those that lead to potentially critical and hazardous events.

Feedback

- Systems should provide a means to check input and setup data. Automation design should provide a clear and distinguishable way to determine if the system has failed or if the user actually made an error.
- Automated systems must allow the user to be actively engaged in monitoring, but should not require the user to allocate extended cognitive resources for extend periods of time. Presentation of changing and critical data (e.g., warnings, critical functions, alerts) should be presented graphically, and should occur in a consistent location to promote effective monitoring performance. Critical information should be presented independently from normal events.

Engagement

- Automation should ensure active involvement of the user so the user can respond to off-nominal events as they occur.
- Fault management should allow the user to safely and efficiently detect and resume manual control of the system. Early detection and warnings will allow the user to efficiently and correctly detect, diagnose, prognose, and compensate for the loss of automation.
- Automation should provide a clear understanding of the decisions made by the system so that the user clearly sees how the automation facilitates the efficient completion of the task.

Workload and Task Management

- Automation design should avoid increasing demands for cognitive resources.
- System design should avoid extreme workload levels.
- Automation should be designed to prevent distraction from operations.
- Automation and procedures should be designed to avoid interruption at inappropriate times.
- Decision aids are an absolute necessity as the operations become increasingly more complex in advanced FDs. They will help cue pilots to procedure operations and task work flow.

Error

- Automation should make the system error-resistant and error-tolerant. This can be accomplished through simplicity in design and clear presentation of information. It is important to mitigate the effects of human error by providing system monitoring and employing checklists to provide memory aids.

The guidelines developed here are intended to augment or further elaborate existing guidelines, not replace them.

2 Technical Approach

Figure 1 illustrates the approach used for this task. Current aviation safety data and literature on NextGen operations and procedures were reviewed to identify, analyze, categorize, and prioritize potential issues flight crews (FCs) could encounter in using FD automation to fly NextGen airspace procedures. Then guidelines addressing these issues were developed. These guidelines will hopefully be useful for both FD designers and airspace procedure developers.

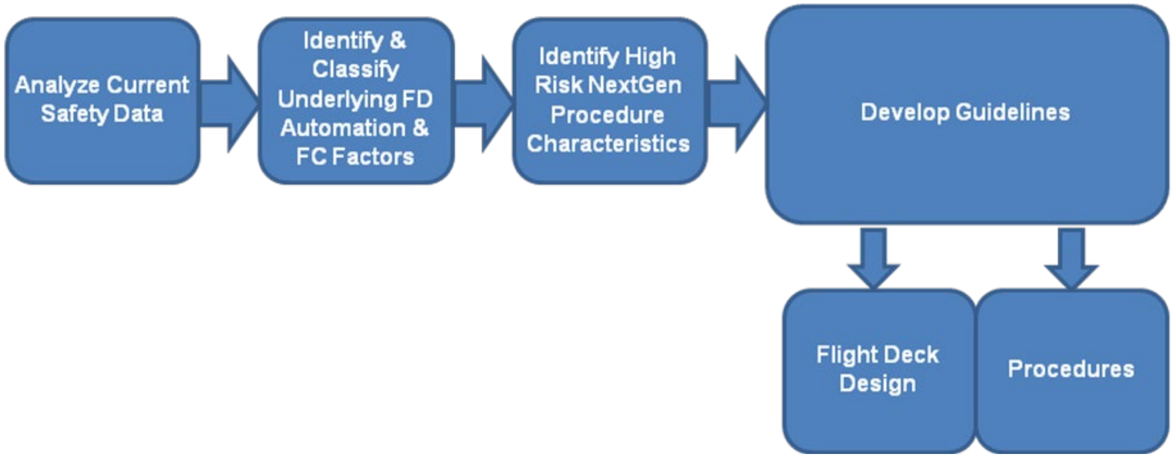

Figure 1. Technical Approach Used for This Task.

The number of specific issues that FCs may encounter in flying NextGen airspace procedures using both new and existing FD automated systems is potentially daunting. For example, Funk, Mauro, and Barshi [3] identified 94 potential automation issues alone. Since the scope of this effort was relatively small and was meant to highlight general cross-cutting concerns (and mitigations to those concerns), the approach taken here was to cull high level issues from an analysis of specific current safety issues, a review of NextGen operations, and knowledge of broad FD human factors (HF) issues.

The overall task structure was:

- Review literature and analyze safety data;
- Establish issue and guideline framework;
- Identify, categorize, and prioritize issues;
- Develop guidelines (as mitigations to issues).

2.1 Review Literature and Analyze Safety Data

2.1.1 NextGen Literature

NextGen documentation, industry reports, and miscellaneous data were reviewed to understand envisioned NextGen operations and airspace procedures, and to identify relevant problems from today's operations and anticipated future problems.

The FAA's Operational Improvements (OIs) [4] describe the types of envisioned operations that are addressed here. In particular, the first three solution sets (initiating Trajectory Based Operations (TBOs), increasing arrivals/departures at high density airports, and increasing flexibility in the terminal area), and the 57 OIs that are associated with them, provide a comprehensive NextGen operational context for the analyses performed here.

The eight main NextGen operational concepts reviewed for implications on design and airspace procedures were [5]:

- Trajectory based operations (TBO);
- Performance based operations (PBO);
- Assimilation of weather into FD decision making;
- Position, navigation and time (PNT);
- Network enabled information access (NCO);
- Equivalent visual operations (EVO);
- Layered adaptive security; and
- High density arrivals and departures.

Further, data on problems encountered with current implementations of advanced airspace procedures such as area navigation (RNAV) and Required Navigation Performance (RNP) were reviewed.

2.1.2 **Safety data**

The safety analysis relied primarily on data from the PARC/CAST FD Automation Working Group's (FDAWG) analysis [6]. These data covered aviation incidents and accidents since 1996 related to flight path management, focusing in part on HF and FD design issues. The critical assumption made here was that identified current issues will continue to be problematic in a NextGen environment, and in some cases, these issues may be exacerbated. Other summaries of aviation safety-human factors issues were also reviewed [7-10]. Independently, documented problems with implementations of advanced airspace procedures such as RNAV and RNP were reviewed [11-13], and the Aviation Safety Reporting System (ASRS) database was searched using several keywords and pre-defined search categories related to FD automation, HF, and advanced airspace procedures. The results of all these reviews and analyses were used to extrapolate to anticipated future issues using the framework approach described below.

2.2 Establish Issue and Guideline Framework

A key component of this effort was predicting future high level issues that could result in pilot errors and confusion when flying more advanced airspace procedures with the aid of more sophisticated FD automation; accordingly, a general framework was developed with three key elements: (1) NextGen airspace procedure characteristics that may be threats from the perspective of causing pilot errors; (2) FD design and automation characteristics that similarly could cause pilot errors in performing NextGen airspace procedures, and (3) HF issues and constructs that are known to underlie human errors.

Characteristics of airspace procedures that may be threats to FC performance were identified by first reviewing NextGen documents [4, 5, 14-16] to identify the types of procedures that are expected to be implemented in the NextGen environment. These anticipated procedures are very numerous and diverse, with some overlap in nomenclature and operational descriptions. The list below is not meant to be comprehensive, but provides a good sense of the sheer number of new procedures that may be implemented in NextGen:

1. Increased use of closely spaced parallel runway operations (esp. in low visibility, possibly with smaller separation);
2. Low visibility taxi operations (probably some need for self-separation);
3. Multiple precise departure paths (each aircraft on its own separate track);
4. Reduced separation standards (cruise) + FC responsibility for spacing;
5. Automatic re-planning for weather events (and automatically datalinked to FD);
6. Dynamic changes to oceanic route structure (based on winds and weather);
7. In –trail procedures (ITP), including oceanic in-trail climb and descent;
8. Optimized, flexible airspace entry by time and (optimized) trajectories for oceanic operations;
9. Offsets to published routes;
10. Point-in-space metering;
11. Reduced vertical separation;
12. Time based metering using RNAV and RNP;
13. Scheduled arrival times (including required time of arrivals (RTAs));
14. Arrival sequencing, reduced separations;
15. Optimized profile descents (precise vertical and lateral paths);
16. Multiple precision approach paths (and in low visibility);
17. RNP/RNAV
    a. Use of RNP and RNAV for approaches;
    b. Use of RNAV 1, RNAV 2, LNAV, and VNAV in enroute operations;
    c. Localizer Performance;
    d. Localizer Performance with Vertical Guidance;
    e. RNAV (GPS) with LNAV, VNAV, & Localizer Performance or with Vertical Guidance (LPV);
18. Curved path capability (radius to fix);
19. User preferred routes – tracks that consider pressure altitude and wind;
20. Dual or parallel routes to accommodate a greater flow of en route traffic;
21. Bypass routes for aircraft overflying high-density terminal areas;
22. Alternatives or contingency routes, either planned or unplanned;
23. Optimized locations for holding patterns;
24. More complex missed approaches;
25. Four-Dimensional Trajectories (4D)

        a. Fuel-efficient descents from cruise altitude to the meter fix;
        b. Minimum-delay weather avoidance trajectories;
        c. Wind-favorable routes;
        d. Multi-trajectory conflict detection for climbing flights;
        e. Minimum-delay conflict resolution trajectories;
26. Airborne Merging and Spacing for Terminal Arrivals (Interval Management) (including Traffic-To-Follow, Pair Dependent Speed);
27. High-Performance Trajectory-Based Operations;
28. 3D path arrival management;
29. Tailored arrivals.

Descriptions of these procedures were reviewed and potentially problematic cross-cutting characteristics were identified based on expert judgment. These characteristics were cross-checked against airspace procedural threats that were identified from current operations in the Threat and Error Management (TEM) framework [17] and FDAWG analysis [6]. The combination of characteristics was then pared down to a more manageable number by eliminating redundancies and abstracting to high level commonalties.

Next, potentially problematic FD design and automation characteristics were identified based on analysis of the relevant literature and analyses reviewed earlier. These characteristics were then organized into a smaller set of automation issue categories based on elimination of redundancies and abstraction to high level commonalties.

Finally, HF issues were identified based on analyst expertise and review of HF issues taxonomies [18-20]. The list of issues was pared down to a small general set in order to make the overall analysis more manageable.

2.3 Identify, Categorize and Prioritize Issues

A series of two dimensional matrices were developed using the list of airspace procedure threats, the list of FD automation issues, and the list of HF issues as row and column headings in a pair-wise fashion such that each list was paired with one of the other two lists (i.e., automation issues vs. airspace procedure threats, automation issues vs. HF issues, and airspace procedure threats vs. HF issues). The cells of each matrix were used to describe potential issues from several different perspectives in order to identify the combinations of HF issues, automation issues, and airspace procedure threats that were judged to be most problematic. Those combinations that were judged to be most problematic were then used to populate a Failure Modes and Effects Analysis (FMEA) [21] worksheet that was modified for purposes of this analysis (see Figure 2); the HF issues were listed as failure modes, the automation issues and airspace procedure threats were listed as causes, and potential operational impacts were listed as effects. The FMEA uses severity scores, frequency scores, and detectability scores in order to compute an overall prioritization of the issues. A team of experts provided the scoring based on knowledge gained from the reviewed literature and safety analyses. The prioritization of issues will hopefully be useful for identifying the most important future Research and Development (R&D) needs.

The primary use of the FMEA was to aid in the development of guidelines. In the "Design or Procedure Mitigation" column in the FMEA (right hand column in Figure 2), each cell was associated with a combination of failure modes (HF issues) and causes (automation issues and airspace procedure threats), and was used to describe mitigation ideas that were then translated and expanded into automation and airspace procedure design guidelines.

Potential Failure Mode	Potential Failure Effects	SEV	Potential Cause	OCC	Potential Secondary Cause	OCC	DET	RPN	Design or Procedure Mitigation
What is the failure mode in terms of underlying human factors issues or constructs?	What is the potential operational effect of the failure mode?	How critical is this effect to safety?	What is the primary cause of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	What are the secondary causes of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	How well can you detect cause or FM?	SEV * OCC * DET	What is the recommendation from a flight deck design or airspace procedure perspective to mitigate the failure mode risk?

Figure 2. FMEA Modified Template Developed for Analysis.

2.4 Develop Guidelines

As mentioned, the FMEA column titled "Design or Procedure Mitigation" was used to describe "risk mitigations" that included both FD design recommendations and airspace procedure development recommendations. These were then expanded and converted into guidelines based on analyst expertise.

3 Analysis Results

3.1 Literature Review

Review of NextGen documentation confirmed the potential for a broad range of HF issues that could negatively impact safety if not addressed via the combination of automation design, procedures, and training. These HF issues will be described further in the context of the performed analysis. However, previous studies [1, 3] provide good summaries of high level HF issues of concern, and are shown in Tables 1 and 2.

Table 1. NextGen Human Factors Issues (from [1]).

Next Gen Environment	Pilot/HF Issues
• Changing pilot roles and responsibilities	• Higher workload
• Faster paced operations	• More distractions and interruptions
• All weather operations	• More confusion over automation behavior and modes
• More precise flight paths	• More information management problems
• More air-ground collaboration	• More difficulty in keeping training-procedures-design well aligned
• More information	• More multitasking with increased roles and responsibilities
• More complex automation	• More difficulty in identifying equipage and infrastructure variations
• More efficiency pressures	• More data integrity and reliability issues
• Reduced separation standards	
• Less experiences and less trained pilots	

Table 2. NextGen Broad Human Factors Issue Categories (from [3]).

Broad Human Factors Issue Category
NextGen pilot-Air Navigation Services Provider (ANSP) collaboration processes are poorly designed, poorly defined, inefficient, and ineffective
Information on the NextGen FD is insufficient or, when available, difficult to access, inadequate, poorly presented to pilots, and often overwhelming
Pilots lack adequate awareness of automated data exchanges between NextGen ground and air subsystems
Pilots do not properly allocate their attention among information sources and tasks on the NextGen FD
Pilot authority on the NextGen FD is unclear and/or overly restricted
Many NextGen processes lack defined procedures or those procedures are poorly designed
NextGen FD automation is overly complex and hard to understand, and its logic and interfaces are poorly designed
Temporal and spatial variations in NextGen functionality and subsystems make it difficult for pilots to adapt to different circumstances

3.2 Safety Analysis

The PARC/CAST FDAWG reviewed accidents, incidents, and normal operations (through review of Line Operations Safety Audit (LOSA) data) from the last 15 years to evaluate flight path management HF issues. While the final report [6] has not been released, preliminary findings show a prevalence of incidents and accidents related to automation issues, crew issues, and airspace threats that directly translate to a NextGen environment. The categories of issues analyzed in the FDAWG study that are relevant to this study and that were present in at least 10% of the accidents or incidents reviewed are shown in Table 3.

Table 3. Prevalent Safety Issues Identified From [6].

Crew- and pilot-centered HF issues	**Automation and pilot interface design issues**	**Airspace system threats:**
Knowledge	General Physical Graphic and Interaction Design	Confusing or complex clearances
Inadequate knowledge	Insufficient display of information	Late runway changes
Inadequate pilot understanding of automation	Data entry that is difficult and time consuming	ATC-FC communication errors
Inadequate pilot predictions of states and statuses	Poorly designed pilot interfaces and displays	ATC errors
	Poor flight management system control display unit (CDU) design	ATC threats (other)
Skill	Poor mode control panel design	
Manual handling errors	Unintentional creation of new tasks and errors	
Mode selection errors		
Flight management system programming errors	Automation – Operation Incompatibility	
Input errors to other systems (e.g., radios)	Automation that lacks reasonable functionality	
	Inadequate automation support for information management	
Communication and Coordination	FD automation-ATC system incompatibilities	
Pilot-to-pilot communication issues	Manual operation that is difficult after transition from automated control	
Crew coordination issues	Automation that does not work well under unusual conditions.	
Pilot procedure errors (e.g. cross-verification callouts)		
Other crew centered issues.	Automation Opacity	
	Automation that is too complex	
Workload and Task Management	Automation that uses different control strategies than pilots	
Increased pilot information processing load	Behavior of automation that is not apparent	
Excessive monitoring requirements	Difficult automation failure assessment/recovery	
Task management difficulties		
	Automation-Induced Workload	
Automation Management	Automation that slows pilot responses	
Pilots' overconfidence in automation	Automation that demands attention	
Pilots' over-reliance on automation	Automation that is vulnerable to distractions.	
Reduced situation awareness (SA)		
Pilots out-of-the-loop		

Reports of current problems with advanced procedures were also reviewed [11-13]. In general, problems have accompanied the introduction of RNAV and RNP procedures at various airports (e.g., Las Vegas, Dallas, and Atlanta). These issues include:

- Chart complexity issues;
- Procedure complexity that requires excessive pilot monitoring;
- Issues related to differences in aircraft equipage;
- Incompatibilities with Air Traffic regulations;
- Pilot training issues;
- Pilot misunderstanding of charted procedures;
- Pilot misunderstanding of clearances;
- Improper programming of the flight management computer;
- Failure of FC to verify FMS inputs;
- Inadequate pilot briefing and review of the procedures;
- Improper execution of the procedures;
- Tactical clearance changes (e.g., late runway changes).

While most of these procedure implementation issues were resolved with experience and refinements, the lessons learned that were related to the introduction of the procedures are valuable, especially in terms of potential problems for NextGen: These problems could continue to occur or increase, with the more wide spread use of advanced airspace procedures which are complex, diverse, and will be flown by aircraft with a variety of equipage levels.

Finally, ASRS reports were reviewed and analyzed based on key word searches and use of the ASRS pre-defined HF categories listed below:

- Communication Breakdown,
- Confusion,
- Distraction,
- Fatigue,
- Human-Machine Interface,
- Physiological,
- SA,
- Time Pressure,
- Training/Qualification,
- Troubleshooting,
- Workload,
- Other.

Key words used for the ASRS searches in conjunction with the HF categories included RNAV, RNP, LNAV, VNAV, and “ambiguous clearances.”

The ASRS reviews produced results confirming the concerns over envisioned NextGen airspace procedures, FD automation, and the potential for exacerbating pilot errors.

Problems of (1) pilot SA, (2) confusion, (3) the Human Machine Interface (HMI), and (4) communication, are shown to be the most prevalent issues for the NextGen-relevant procedures and conditions that were searched (see Figure 3).

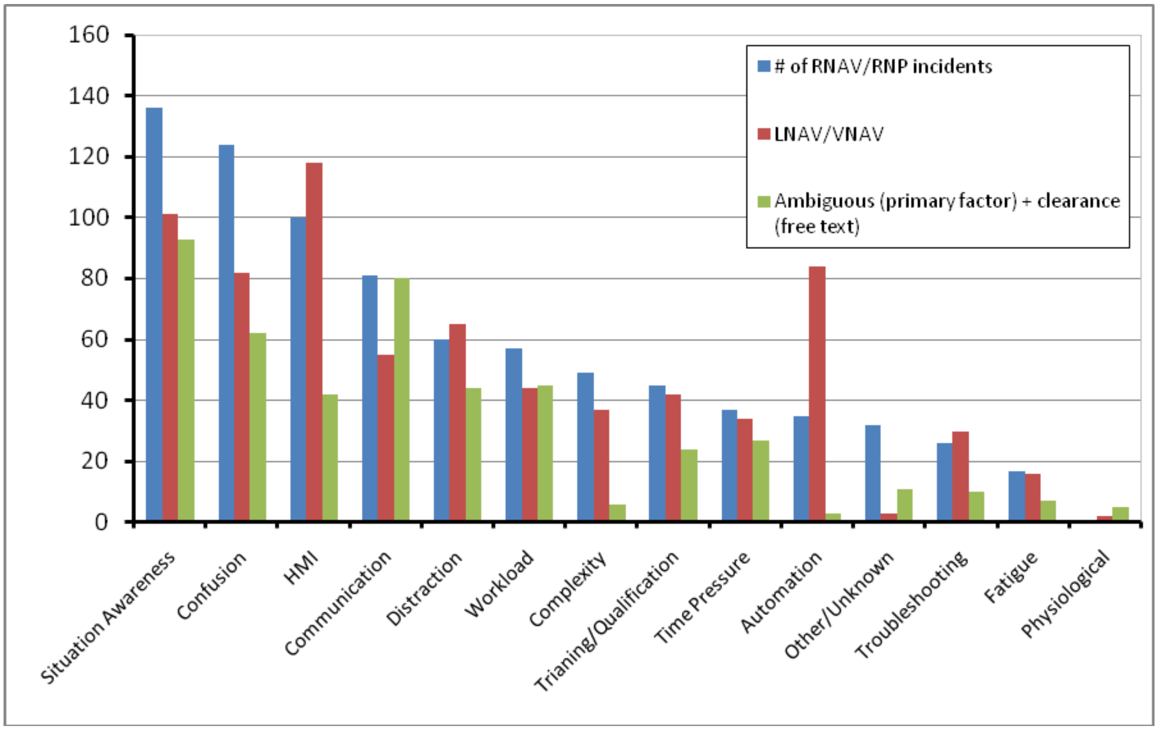

Figure 3. Frequency of ASRS Incidents Based on Human Factors Categories and Search Terms.

3.3 Issue Framework

Based on these reviews and preliminary analyses, aggregated lists of flight deck design and automation issues, HF issues, and airspace procedure threats were developed. Next, the analysis team looked for redundancies and overlaps, and then reduced the lists further based on abstraction/reduction to what were believed to be the most important high level issues and threats. This was done to make the process of identifying cross-category issues and developing guidelines more manageable. Tables 4-6 show the original detailed lists of issues in the far right columns, aligned with the pared-down lists to which they were reduced in the middle columns. It is important to note that many items from the original lists easily could have been grouped in other pared-down issue categories: The nature of these issues does not generally support strict one-to-one mappings. It should also be noted that pilot-centered HF issues (Table 5) inevitably have design, training, or procedural pre-cursors. For example, when pilots are complacent, it is often related to designs which require excessive monitoring of highly reliable automation. The airspace threats (Table 6) reflect characteristics of flight procedures in a NextGen environment (and characteristics of the environment itself) most likely to significantly degrade pilots' ability to use cockpit automation quickly and accurately to select and execute the flight procedures.

Note that an Automation Issue category not reflected in these lists was added to the subsequent analyses: namely, "higher reliability and robustness." Higher automation reliability and robustness are obviously very positive attributes, but were analyzed as an issue because of the potential negative effect on pilot over-trust and over-confidence in automation.

Table 4. Original and Pared-Down Lists of Automation-Centered Issues.

Issue Category	Pared Down List	Detailed List
Automation-centered issues	a. Poorly designed HMI	• Human Machine Interface (HMI)
		o Mode selection (uncommanded transitions are complex, modes are complex)
		o Programming/data entry is difficult
		o Cross checking is difficult
		o Behavior of automation is not apparent
		o Insufficient information is displayed
		o Too much information
		o Automation controls are poorly designed
		• Automation use slows pilot responses
	b. Inadequate automation functionality	• Automation is incompatible with the ATC system
		• Procedures assume automation
		• Automation functionality is lacking
		• Automation performance is limited
		• Workarounds are necessary
	c. Inadequate automation flexibility	• Automation does not work well under unusual conditions
	d. Inadequate automation transparency	• Failure assessment is difficult
		• Automation behavior is different than pilot expectations
		• Automation is difficult to understand/behavior is unexpected
	e. High automation complexity	• Automation is too complex
	f. Increased FC interaction requirements	• Transitions between automation levels are difficult
		• Monitoring requirements are excessive
		• Automation adversely affects workload
		• New systems to monitor for situation and for health
		o ADS-B, Cockpit Display of Traffic Information (CDTI)
		o Datacomm
		o TIS-B
		o Along track guidance
		o De-confliction guidance
		o Paired approach guidance
		o Additional alerts and notifications
	g. New failure modes	• Failure recovery is difficult
	h. Increased potential for distraction	• Automation demands attention
		• Automation can cause pilot distractions
	i. Potential for reduced crew coordination	• Task management is difficult
	k. Data inconsistencies	• Automation integration is poor
		• Abundance of, and inaccuracies in, information automation & communicated information
		o EFB information (Charts/manuals)
		o Uplinked clearances and constraints + FIS-B information
		o Dispatch paperwork/materials
		o Database information (eg, terrain, airport, etc)
	l. Inability to assess feasibility, safety, & performance	• Automation level decisions are difficult
		• Scan pattern changes are required

Table 5. Original and Pared-Down Lists of Pilot-Centered Issues.

Issue Category	Pared Down List	Detailed List
Pilot-Centered Issues	a. Pilot fails to communicate/coordinate	• Pilot-to-pilot communication issues
		• Crew coordination issues
		• Task management difficulties
		• Inadequate pilot briefing and review of the procedures
	b. Pilot has insufficient knowledge/skill	• Inadequate knowledge
		• Manual handling errors
		• FMS programming errors
		• Input errors to other systems (eg, radios)
		• Inadequate pilot understanding of automation
		• Pilot training issues
		• Improper execution of the procedures
	c. Pilot becomes complacent	• Pilot procedure errors (eg, cross-verification, callouts)
		• Pilots overconfidence in automation
		• Pilots over-reliance on automation
	d. Pilot loses SA	• Pilots are out-of-the-loop
		• Excessive monitoring requirements
		• Reduced SA
		• Inadequate pilot predictions of states and statuses
	e. Pilot is distracted	• Distraction
	f. Pilot workload is high	• Increased pilot information processing load
		• Time Pressure
		• Workload
	g. Pilot becomes confused	• Pilot misunderstanding of charted procedures
		• Pilot misunderstanding of clearances
		• Confusion
		• Troubleshooting
	h. Pilot manages the automation poorly	• Mode selection errors
	Multiple	• Fatigue
		• Other crew centered issues
		• Physiological issues

Table 6. Original and Pared-Down Lists of Airspace Threats.

Issue Category	Pared Down List	Detailed List
Airspace Threats	a. Procedure is highly complex	• Complexity
		- More complex re-routes can be datalinked because they are not constrained by limitations of voice communication
		- More difficult review and validation of these clearances
		- Higher SA demands related to dynamic oceanic route structure changes (based on weather and winds)
		- Offsets will likely be more complex
		- Curved approaches (radius to fix)
		- More complex emergency procedures (eg, go around, traffic resolution)
		• Incompatible with FD automation
		• Difficulty in meeting clearances
		• Difficulty of deviation detection
		• Complexity of FD automation required to fly airspace procedures
		• # of dimensions (4D) – addition of temporal and relative spacing requirements, 4D RTAs for metering, sequencing, etc
		• Updates based on changing condition may be subtle and hard to review
	b. Operations have high brittleness	• Brittleness (eg, when something goes wrong, the effects can ripple into connected parts of the system and can significantly disrupt overall traffic flow and safe operations)
		• More variability in potential collision geometries and traffic SA requirements
	c. There are more FC responsibilities	• Addition of self separation responsibility
		• Related workload (monitoring for traffic, weather determining ITP "passing" requirements, etc)
		• New or different or increased monitoring requirements (RNP, time)
		• New/different responsibilities (new tasks and errors can occur)
	d. Closer spacing/greater density	• Closer spacing
	e. Increased communication requirements	• Communication requirements
	f. Increased precision requirements	• Flexibility in implementation (eg, pilot discretion in how to fly)
		• Required Precision
	g. Increased "hurry" factor	• Urgency (eg, late runway changes)
		• Procedures or updates to procedure require time consuming negotiation

A second perspective was also used for assessment of pilot-centered HF issues, based on a simple generic human information processing model (acquire, analyze, decide, execute):

1. Pilot fails to acquire information;
2. Pilot fails to analyze;
3. Pilot makes poor decision;
4. Pilot executes task incorrectly.

3.4 Issue Analyses

The pared-down issue and threat lists from Table 4-6 were entered pair-wise into excel spreadsheets as shown in Tables 7-9 to provide a framework for identifying issues related to the various combinations of issues and threats.

Table 7. Airspace Procedure – Pilot Centered Issue Matrix.

	Potential Airspace Procedure Issues						
Current FC Issues	Greater complexity	Greater brittleness	Added FC responsibilities	Higher Density & Closer Spacing	Increased comm reqts	Increased Precision reqts	Increased "Hurry" Factor
Crew coordination							
Knowledge/skill							
Discipline/complacency							
Situation awareness							
Distraction							
Workload							
Confusion							
Automation mgmt							

Table 8. Flight Deck Automation – Pilot Centered Issue Matrix.

	Potential FD Automatoin Issues											
Current FC Issues	Poorly designed HMI	Inadequate automation functionality	Inadequate automation flexibility	Poor automation transparency (functionality & behavior)	Higher complexity	Increased or modified FC reqts	New failure modes	Increased potential for distraction	Potential for reduced crew coordination	Higher reliability and robustness	Data inconsist-encies	Inability to assess feasibility, safety, performance
Crew coordination												
Knowledge/skill												
Discipline												
Situation awareness												
Distraction												
Workload												
Confusion												
Automation mgmt												

Table 9. Airspace Procedure – Flight Deck Automation Matrix.

	Potential Airspace Procedure Issues						
Potential FD Automation Issues	Greater complexity	Greater brittleness	Added FC responsibilities	Higher Density & Closer Spacing	Increased comm reqts	Increased Precision reqts	Increased "Hurry" Factor
Poorly designed HMI							
Inadequate automation functionality							
Inadequate automation flexibility							
Poor automation transparency (functionality & behavior)							
Higher complexity							
Increased FC reqts							
New failure modes							
Increased potential for distraction							
Potential for reduced crew coordination							
Higher reliability and robustness							
Data inconsist-encies							
Inability to assess feasibility, safety, performance							

3.4.1 **Matrix results**

For the airspace procedure – FC HF issues and automation – FC HF issues matrices, cells for which it was judged that a prevalent issue might occur were filled out with a quantitative description of the issue. Tables 10 and 11 show portions of the completed matrices to illustrate the types of cell entries that were produced.

Table 10. Example of Cell Descriptions for Airspace Procedure Threats – Flight Crew Human Factors Issues Matrix.

	Potential Airspace Procedure Threats						
Current FC Issues	Greater complexity	Greater brittleness	Added FC responsibilities	Higher Density & Closer Spacing	Increased comm reqts	Increased Precision reqts	Increased "Hurry" Factor
Distraction	Easier to spend too much time heads down getting automation set up to fly procedure		More tasks need to be performed in parallel and can distract each other		More opportunity for interruptions (although datacomm may decrease interruptions with smart scheduling feature)	Distractions could result in deviations more quickly	More opportunities for distractions and missing something key when rushed
Workload	Higher workload if not fully automated, more intense monitoring if flying automatically	More monitoring for disruptions to traffic flow that will impact own A/C; more opportunity for "off-nominal" events related to traffic flow	Higher overall workload	Higher workload for self separation, traffic monitoring	Higher comm reqts, higher interaction workload in interacting with datacomm system and managing information	More constant monitoring reqts	More opportunities for hurries, higher multitasking workload
Confusion	Greater potential for pilot confusion, esp. when familiarity is low		More tasks and responsibilities may cause less time for in-depth assessments, resulting in confusion		Greater comm bandwidth means more potential for conflicting or confusing information		Easier to get confused when overloaded and under time pressure
Automation mgmt	More difficult to change levels of automation or compensate for anomalies if not going to according to plan	More difficult to change levels of automation or compensate for anomalies if not going to according to plan	More automation and informaiton mgmt tasks	More careful automation performance monitoring required	Greater mgmt of datacomm systems (although hopefully more automated basic functions like radio tuning	Automation level changes need to be performed more quickly	Current automation mgmt issues could be exacerbated

Table 11. Example of Cell Descriptions for Flight Deck Automation – Flight Crew Human Factors Issues Matrix.

	Potential FD Automatoin Issues							
Current FC Issues	Poorly designed HMI	Inadequate automation functionality	Inadequate automation flexibility	Poor automation transparency (functionality & behavior)	Higher complexity	Increased or modified FC reqts	New failure modes	Increased potential for distraction
Crew coordination	Design interferes with good CRM		Not easy to change who has control of automated function	Hard for crew to check behavior and health	Hard to communicate about automation behavior and functioning	Higher workload can reduce amount of communication	More demands on coordination when no checklists or procedures in place	Potential for both pilots being heads down and not communicating
Knowledge/skill	Need more training on how to operate automation and interact	Won't have skill to compensate for poor functionality, do workarounds	Maybe less knowledge/skill required	More knowledge gaps could become safety issues in non-normal, off-nominal situations	More knowledge required to understand behavior under unusual circumstances	More knowledge required	More knowledge gaps could become safety issues for failure modes	
Distraction	UI can actually distract from other things - more head down time		Doing workarounds can increase head down time					Distract from other higher priority tasks, events, and situations

For the automation issue – airspace procedure threat matrix, two versions were completed based on expert judgment; one with the cells filled out with the pared-down pilot-centered HF issues from Table 5, and one filled out with the prevalent human information processing vulnerabilities listed earlier. Tables 12 and 13 show the two versions of the completed matrix.

Table 12. Automation Issue – Airspace Procedure Threat Matrix Filled Out with Human Factors Issues.

	Potential Airspace Procedure Issues						
Potential FD Automation Issues	Greater complexity	Greater brittleness	Added FC responsibilities	Higher Density & Closer Spacing	Increased comm reqts	Increased Precision reqts	Increased "Hurry" Factor
Poorly designed HMI	Workload	Increased error potential	Workload	Distraction	Workload	Workload	Increased error potential
Inadequate automation functionality	Workload	Automation mgmt	Knowledge/skill	Distraction	Crew coordination	Workload	Increased error potential
Inadequate automation flexibility	Situation awareness	Knowledge/skill	Workload	Distraction	Crew coordination	Increased error potential	Workload
Poor automation transparency (functionality & behavior)	Situation awareness	Confusion	Situation awareness	Workload	Discipline	Situation awareness	Increased error potential
Higher complexity	Situation awareness	Increased error potential	Situation awareness	Situation awareness	Crew coordination	Discipline	Increased error potential
Increased FC reqts	Knowledge/skill	Workload	Workload	Workload	Workload	Situation awareness	Workload
New failure modes	Confusion	Automation mgmt	Workload	Increased error potential	Distraction	Situation awareness	Increased error potential
Increased potential for distraction	Situation awareness	Increased error potential	Distraction	Workload	Increased error potential	Distraction	Distraction
Potential for reduced crew coordination	Situation awareness	Crew coordination	Crew coordination	Discipline	Crew coordination	Situation awareness	Increased error potential
Higher reliability and robustness	Discipline	Knowledge/skill	Discipline	Workload		Discipline	Increased error potential
Data inconsist-encies	Situation awareness	Situation awareness	Workload	Workload	Distraction	Increased error potential	Increased error potential
Inability to assess feasibility, safety, performance	Increased error potential	Situation awareness	Increased error potential	Situation awareness	Increased error potential	Increased error potential	Confusion

Table 13. Automation Issue – Airspace Procedure Threat Matrix Filled Out with Human Information Processing Vulnerabilities.

	Potential Airspace Procedure Issues						
Potential FD Automation Issues	Greater complexity	Greater brittleness	Added FC responsibilities	Higher Density & Closer Spacing	Increased comm reqts	Increased Precision reqts	Increased "Hurry" Factor
Poorly designed HMI	Perform	Perform	Analyze	Acquire	Acquire	Analyze	Multiple
Inadequate automation functionality	Multiple	Decide	Perform	Acquire	Acquire	Perform	Perform
Inadequate automation flexibility	Perform	Perform	Multiple	Analyze	Perform	Perform	Analyze
Poor automation transparency (functionality & behavior)	Analyze	Analyze	Perform	Acquire	Perform	Analyze	Perform
Higher complexity	Analyze	Acquire	Decide	Acquire	Perform	Analyze	Perform
Increased FC reqts	Perform	Decide	Perform	Analyze	Multiple	Perform	Multiple
New failure modes	Analyze	Decide	Perform	Perform	Analyze	Analyze	Perform
Increased potential for distraction	Analyze	Acquire	Perform	Acquire	Acquire	Analyze	Perform
Potential for reduced crew coordination	Analyze	Decide	Perform	Acquire	Perform	Analyze	Decide
Higher reliability and robustness	Acquire	Multiple					Perform
Data inconsist-encies	Analyze	Analyze	Perform	Decide	Analyze	Analyze	Decide
Inability to assess feasibility, safety, performance	Analyze	Analyze	Analyze	Analyze	Analyze	Analyze	Analyze

3.4.2 **FMEA results**

Based on the pair-wise issues identified in the matrix framework, an FMEA was completed using the pared-down pilot-centered issues from Table 5 and the human information processing vulnerabilities identified earlier as failure modes, and relevant automation issues and airspace procedure threats from Tables 4 and 6 as causes. The alignment of causes with failure modes was based on the specific issues identified in the aggregate of analyses using the various matrices described above. Each of the eight pared-down pilot-centered issue categories (failure modes) was repeated in three rows in the FMEA to provide ample opportunity to associate each with various combinations of automation and airspace procedure causal combinations. Each of the human information processing stages was also listed as a failure mode. In total, this resulted in 28 failure modes with various combinations of associated automation issues and airspace procedure threats.

As previously described in Figure 2, a column in the FMEA, titled "Design or Procedure Mitigation" was used to generate mitigation ideas associated with each failure mode – causes combination, which was subsequently translated into guidelines. The completed FMEA is shown in Table 14.

Table 14. FMEA Results.

Potential Failure Mode	Potential Failure Effects	S E V	Potential Cause	O C C	Potential Exacerbating Factor	O C C	D E T	R P N	Design or Procedure Mitigation
What is the failure mode in terms of underlying human factors issues or constructs?	What is the potential operational effect of the failure mode?	How critical is this effect to safety?	What is the primary cause of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	What are the secondary causes of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	How well can you detect cause or FM?	SEV * OCC * DET	What is the recommendation from a flight deck design or airspace procedure perspective to mitigate the failure mode risk?
Pilot fails to analyze	Deviation	5	Inability to asess feasibility, safety, & performance	5	Procedure is highly complex	9	9	2025	Ways to make procedure simple to understand; method to easily compare performance against procedure; way to predict future performance against goals; method to check clearance against safety and efficiency goals and aircraft performance.
Pilot loses situation awareness	Delayed or slow response	3	High automation complexity	9	Increased potential for distraction	5	9	1215	Reminders when action isn't take in timely fashion; simplification of information automation; look at NextDeck guidelines; Graphic techniques for visualization of clearances.
Pilot fails to acquire information	Mode confusion	3	Closer spacing/greater density	9	Increased potential for distraction	5	9	1215	Pilot task aids (to help with new tasks for which they have responsibility); Summary displays; graphical displays; Simplified modes; Simplified methods for transitioning between different automated ways to fly the aircraft.
Pilot becomes confused	Manual reversion error	9	New failure modes	1	Procedure is highly complex	9	9	729	Annunciation of automation anomalies, esp. if root cause can be identified; identification of pilot errors in terms of entries that lead to logical inconsistencies or disconnects; guideline for automation use philosophy - how to scale back from fully automated to less automated (real time vs training); guideline addressing procedure complexity - key is to sacrifice some efficiency if it signficantly reduces pilot errors in flying them.
Pilot loses situation awareness	Manual reversion error	9	Procedure is highly complex	9	New failure modes	1	9	729	Redundant with one above
Pilot has insufficient knowledge/skill	Manual reversion error	9	Inadequate automation flexibility	5	Operations have high brittleness	3	5	675	Need aids for non-normal and off-nominal situations; design to provide pilots with several ways to fly procedure; if pilots deviate or things change, have tactical aids that help get back to plan and recover
Pilot is distracted	Error in managing unusual events	5	Poorly designed HMI	5	Increased coomunication requirements	9	3	675	Information automation design; automation flexibility in handling different situations, both strategic and tactical; Provide shorthand (playbook) for conveying complicated procedures to keep communication load manageable - limit options for simplicity
Pilot loses situation awareness	Mode confusion	3	Inadequate automation transparency	5	There are more FC responsibilities	5	9	675	Explain automation intentions and behavior - not only what it is doing, but why; Simplify modes;
Pilot becomes complacent, demonstrates inadequate discipline	Mode confusion	3	Inadequate automation transparency	5	Increased coomunication requirements	9	5	675	For NextGen airspace procedures, crew procedures and VVM will be even more critical in order to catch errors early. Automation design and procedure design can help with features that allow checks of actual performance against plan. Automated checkers apply to datacomm too, to keep required comm due to discrepancies to a minimum. Guideline for CRM that includes automation interaction.
Pilot becomes complacent, demonstrates inadequate discipline	Error in managing unusual events	5	Higher automation reliability and robustness	5	Inability to asess feasibility, safety, & performance	5	5	625	Guideline about what if automation scenarios, training that distinguishes between automation reliability and frequency of problems if automation is directed to do wrong thing - reliably right means reliably wrong if given wrong plan or input. Guideline on checking assumptions about automation behavior, etc.
Pilot has insufficient knowledge/skill	Error in managing unusual events	5	Inadequate automation functionality	3	There are more FC responsibilities	5	5	375	More aids, especially information aids, help aids for thinking through unusual situations; also, guidelines for real time assistance with automation management, including limitations of automation and how to switch levels or modes.
Pilot is distracted	Safety margins compromised	5	Increased "hurry" factor	5	There are more FC responsibilities	5	3	375	Way to quickly assess ability to make clearance; better HMI to speed up the ability to re-program; easy back up modes; guidelines for ATC for lead time required for different types of clearances based on required pilot tasking to comply
Pilot workload is high	Error in managing unusual events	5	There are more FC responsibilities	5	Inadequate automation flexibility	5	3	375	Coordination between ability of automation to be set up to fly procedures and design of procedures - assure there is compatibility with what has to be flown and how the aircraft automation needs to be set up to fly the procedures. Design procedures so they can be flown in flexible ways, design the automation so that procedures can be flown by different automation and manual methods.
Pilot manages the automation poorly	Can't perform airspace procedure	5	Inadequate automation flexibility	5	Increased "hurry" factor	5	3	375	Same automation management guidelines as above. Must include simple ways to interact and monitor automation - include signposts of potential threat or deviations?

Potential Failure Mode	Potential Failure Effects	SEV	Potential Cause	OCC	Potential Exacerbating Factor	OCC	DET	RPN	Design or Procedure Mitigation
What is the failure mode in terms of underlying human factors issues or constructs?	What is the potential operational effect of the failure mode?	How critical is this effect to safety?	What is the primary cause of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	What are the secondary causes of the failure mode in terms of automation design or airspace procedure design?	How often does cause or FM occur?	How well can you detect cause or FM?	SEV * OCC * DET	What is the recommendation from a flight deck design or airspace procedure perspective to mitigate the failure mode risk?
Pilot makes poor decision	Safety margins compromised	5	Operations have high brittleness	3	Increased "hurry" factor	5	5	375	Decision aids, including best way to utilize automatoin for procedure plus back ups. Also decisions about when not to accept clearance to fly procedure, and what alternatives might be available that won't disrupt traffic flow - sort of an AOP aid.
Pilot has insufficient knowledge/skill	Mis-programming or input error	1	Increased FC interaction requirements	3	Procedure is highly complex	9	9	243	Design of user interface guidelines - more graphical, object oriented. Add in multi-modal (touch, speech, CCD, etc.). CCL-like guideline - make interaction (and procedures) compatable with the way pilots think.
Pilot workload is high	Can't perform airspace procedure	5	Increased FC interaction requirements	3	Increased "hurry" factor	5	3	225	Procedures must be able to be flown with a variety of equipage. This is not only based on technical limitations of FMS, but also practical limitation in ability of crew to quickly and efficienlty program the automation. Guidleine (mentioned previously) to identify what kinds of clearances need what kind of lead time for flight deck set up.
Pilot is distracted	Delayed or slow response	3	Increased potential for distraction	5	Data inconsistencies	3	5	225	Guideline about comparing data sources and flags or alerts for discrepancies. In particular, need way to compare charts nav database, terrain database, and airspace procedures - either automatic function or pilot procedure.
Pilot manages the automation poorly	Error in managing unusual events	5	Inadequate automation functionality	3	Poorly designed HMI	5	3	225	Aids for managing automation, including easy query system, simiple design that provide easy transitions between levels of automation. Guidance on when to use what level, etc.
Pilot becomes confused	Mis-programming or input error	1	Inability to asess feasibility, safety, & performance	5	Increased "hurry" factor	5	9	225	UI design, also automation options and modes compatability with procedure elements that need to be entered into system.
Pilot becomes complacent, demonstrates inadequate discipline	Mis-programming or input error	1	High automation complexity	9	Potential for reduced crew coordination	5	5	225	Automation that enables easy checks and verification of entries and resulting automation behavior and predicted path characteristics. Procedures that lend themselves to easy verificaiton and monitoring steps.
Pilot becomes confused	Delayed or slow response	3	Operations have high brittleness	3	Data inconsistencies	3	5	135	Nothing new - mentioned before.
Pilot workload is high	Mis-programming or input error	1	Poorly designed HMI	5	Procedure is highly complex	9	3	135	Compatability of HCI with airspace procedures; that is, the ability to easily enter and manipulate procedure parameters. Reduction of complexity of procedure for workload/error reasons, even if some efficiency is lost.
Pilot fails to communicate/coordinate	Error in managing unusual events	5	Inability to asess feasibility, safety, & performance	5	There are more FC responsibilities	5	1	125	Same as communication guidelines below.
Pilot manages the automation poorly	Manual reversion error	9	New failure modes	1	Operations have high brittleness	3	3	81	Covered in other rows.
Pilot executes task incorrectly	Error in managing unusual events	5	Inadequate automation functionality	3	There are more FC responsibilities	5	1	75	Error detection and alerting guidelines. Way to automatically check predicted path based on entry against clearance.
Pilot fails to communicate/coordinate	Delayed or slow response	3	Potential for reduced crew coordination	5	Inadequate automation functionality	3	1	45	Guidelines on crew role in communication - that is, when is automation-automation ok, when does pilot need to assess/approve, when is flight crew-ATC human to human communication required.
Pilot fails to communicate/coordinate	Mis-programming or input error	1	Increased coomunication requirements	9	Inadequate automation flexibility	5	1	45	Same as above

4 Guidelines

From the various notes and descriptions of mitigations derived from the FMEA (design or procedure mitigation column), FD design and airspace procedure guidelines were developed. These guidelines were then organized post-hoc into groups based on a card sorting exercise conducted by the analysts. The draft guidelines are listed below, with supporting narrative.

FD design guidelines

These guidelines have relevance to many existing regulations and advisory circulars; the mapping is shown in Appendix A.

Information Content (IC) – Development of new information content to support better flight planning, execution, and monitoring

> IC 1. Flight planning information should make it easy to compare trajectory status against strategic safety and efficiency goals, including predicted trajectory (based on settings and entered flight plan) against future goals.

This information should include a method by which to check both the predicted trajectory and the clearance or procedure against safety and efficiency constraints and aircraft performance. Safety checks could include information from data bases (e.g., terrain, obstacles), sensed information (e.g., weather radar, traffic, winds) and datalinked information.

> IC 2. Flight planning information should be provided to allow the flight crew to quickly assess the ability to execute a clearance based on aircraft performance models, current settings, and environmental conditions.

Pilots appear to have a bias toward accepting clearances, yet it is often difficult for them to quickly determine whether the aircraft has the capability to make a requested clearance, particularly in time-constrained or tactical situations. If an automation aid could quickly check the aircraft's ability to meet a requested clearance based on performance, current modes and settings, and so on, it could help pilots make the decision to reject the clearance when appropriate. This will likely be more important as 4D trajectories are implemented.

> IC 3. Flight crews should be provided with a graphic situation display that provides integrated strategic summary information relating to the conduct of current and upcoming airspace procedures, including constraints, limitations, potential risks, and other key elements that require monitoring.

Since there will be more aspects of airspace procedures for pilots to monitor, including more complex constraints, risks, and contingency plans, an easy-to-interpret summary display that supports pilot situation awareness of current and predicted status will help pilots stay ahead of the aircraft.

> IC 4. Flight crew automation aids should explain automation intentions and behavior - not only what it is doing, but why, what its assumptions are, what it plans on doing next, and so on.

This is not necessarily specific to NextGen airspace procedures – more self-explanative automation systems could eliminate much of the mode confusion and automation behavior misunderstanding that pilots experience today. But as the automation and the operational environment continue to increase in complexity, the ability of the automation to explain its behavior, plans, and assumptions will become more critical to safe operations and the ability of pilots to anticipate potential problems.

IC 5. Automation should enable error checking of pilot inputs and display automation behavior and predicted path characteristics resulting from entries that are considered questionable but are not identified as definite errors.

Future automation should have the ability to go beyond simple error checkers and provide feedback based on logical inconsistencies between different pilot entries or different parameter settings. Even if a potential error cannot be definitively detected, if there a potential discrepancy or inconsistency detected, information can be provided to the pilot that highlights the concern and its implications.

Alerting and Notification (AN) – Design of alerting and notification systems for early pilot detection of errors, discrepancies, and potential flight path issues

AN 1. When possible, flight crews should be alerted if flight path-related pilot inputs are determined to contain inconsistencies, discrepancies, or disparities relative to other entries, settings, statuses, or conditions.

More sophisticated pilot input error checking should be possible with future FD systems that are more integrated. Inputs that may be legitimate in terms of parameter ranges or allowed settings, but that are illogical from the perspective of overall aircraft configuration and other inputs or system settings, can be brought to the pilot's attention in order to detect potential problems earlier.

AN 2. If the system determines that a pilot input or other pilot action is required, then pilots should be alerted when action is not taken in timely fashion.

With time-based NextGen airspace procedures, pilot delays in responding could be more disruptive than in today's operations. If systems can detect that a pilot response is needed, particularly when a delay in that response could jeopardize successful completion of a procedure, alerting or reminding the pilot that a response or input is expected could avoid the subsequent need to revise or modify the procedure or clearance.

AN 3. If off-nominal events or automation anomalies occur which put the ability to comply with a particular airspace procedure in doubt, the flight crew should be notified. Explanation of the problem and its effect on the aircraft's flight path should be displayed.

Real time events can occur which may impact the ability to successfully complete a particular airspace procedure. If the situation is not clear cut, it requires the FC to make a decision as to whether to continue with the procedure or request a new or modified clearance. Bringing information to the attention of the pilots that can support an informed decision could reduce the potential safety risks and traffic flow disruptions of such a situation.

AN 4. Automation functions should be available that compare data from different sources (e.g., navigation databases, electronic charts, published procedures, terrain data bases, etc.) that have discrepancies or conflicting information. These discrepancies or information conflicts should be brought to the attention of the flight crew.

Since the number of sources of information could drastically increase with net-centric information systems envisioned for NextGen, and more on-board sensors and database systems, the potential for discrepancies among those data sources could also increase. Automated aids that cross-check these sources and notify the pilots of discrepancies relevant to the current situation could help avoid subtle problems that could cascade into potentially dangerous events.

AN 5. The flight crew should be notified if FD systems detect that a datalinked clearance conflicts with published procedures, chart data, terrain data, or has other identified safety risks.

A very important advantage of integrated avionics systems with electronic databases and charts is that they are capable of doing extensive consistency checks between pending or future flight paths and stored data relevant to the safety of those flight paths very quickly and reliably. This will provide detection of potential problems much earlier, avoiding time-critical or tactical re-planning or hazard avoidance.

AN 6. Aircraft flight path performance predictions that suggest a deviation from the cleared procedure might occur should be brought to the flight crew's attention as soon as possible.

This predictive alerting must be evaluated in terms of the potential benefit versus the risk of false alarms, but it could avoid flight path deviations that would occur if alerting is only based on a threshold that has been exceeded indicating that a deviation has occurred.

<u>Information Automation (IA) – Design of information automation to assist pilots flying NextGen airspace procedures in the context of new responsibilities</u>

IA 1. Given new pilot responsibilities such as self separation and increased clearance negotiation, task aids should be developed to reduce the workload associated with these new responsibilities.

Since flying NextGen airspace procedures are likely to include new responsibilities such as self- or delegated-separation and clearance negotiation, flight path management aids could address more than the technical aspects of compliance with a procedure; assisting the pilot with performance of the related responsibilities so that his or her overall workload is manageable would provide a more comprehensive approach to flight path management aiding.

IA 2. Automation aids to assist with recovery from off-nominal situations should be developed.

NextGen airspace procedures may have increased brittleness and greater potential for traffic flow disruptions when off-nominal events occur (i.e., events unrelated to ownship performance, but that could require re-planning). These aids could assist with assessing the safety and efficiency of contingency plans, communicating those plans, and providing information on the most efficient use of FD automation to quickly execute the contingency plans.

IA 3. Flight crew aids for managing information and information automation should be designed, including assistance with information query and search protocols, and with automation interaction strategies.

The prevalence of information automation on the FD increases the amount of information available to the FC and that needs to be processed by the FC. Fortunately, the ability for information automation to assist pilots in utilization of the increased amount of information exists, and interaction features that provide facile, agile ways for pilot to find, process, and utilize the right information for the situation are feasible.

IA 4. If a flight path deviation occurs, tactical flight crew aids should be available that help with safe recovery and management of various effects (e.g., impacts on safety, passenger comfort, communication requirements, schedule, and flight efficiency).

Deviations and perturbations to plans will occur. It is often difficult to determine how to recover from these events while minimizing impacts to safety and efficiency goals. Tactical aids that can help with planning and execution of a recovery that minimizes negative impacts could help increase safety and decrease traffic flow disruptions.

IA 5. Information automation should be designed that focuses on simplifying pilot information processing through display and information presentation features such as integration, abstraction, categorization, prioritization, formatting, de-cluttering, and highlighting.

Information automation, by definition, supplies information to aid pilots in cognitive tasks such as situation assessment and decision making. It is very important that utilization of information automation by the pilot doesn't increase his or her workload; so it is essential to exploit features and functions that minimize required pilot information processing.

IA 6. Flight crew decision aids to help pilots assess whether or not to accept a clearance should be designed. These should provide information about what alternatives might be negotiated that would have a high probability of being accepted by ATC by considering their impact on traffic flow and potential traffic conflicts.

In contrast to guideline IC-2, which is focused on information about the ability to make a clearance based on aircraft performance, this guideline focuses on information assistance to help pilots decide whether to accept a clearance and support for proposing an alternative clearance based on efficiency goals and strategic traffic flow and separation information.

Display Formats (DF) – Design of new display formats and symbology to assist pilots with flying NextGen airspace procedures

DF 1. Graphic displays such as perspective synthetic vision displays, combined synthetic vision and enhanced vision displays, moving map displays, and vertical situation displays should be used for visualization of current and proposed clearances.

As technologies provide more and more capability to present real world visual information on displays (e.g., synthetic and enhanced vision), and even go beyond real world visual information with augmented symbology that enhances the real world information, the potential for improving pilot visualization of complex procedures and clearances is enormous. Features such as rotating graphic depictions and using time-based animations could help pilots acquire and maintain situation awareness involving the spatio-temporal dynamics of complex airspace procedures.

DF 2. Smart de-cluttering methods should be used so that the graphical depictions of clearances and airspace procedures (e.g., on map displays or electronic charts) can be viewed without irrelevant information that can distract the pilots.

The amount of information on multifunction displays is already daunting in terms of pilot monitoring and processing. This problem is likely to worsen with envisioned NextGen airspace procedures, but the ability to filter information and de-clutter displays based on aircraft and procedure relevancy could be exploited much more than it is today. Historically, charts, maps, and other display depictions provided information required for a set of situations (e.g., different aircraft classes, different approaches, etc.), because there was no way to present only information relevant to a particular flight or aircraft. Display tailoring is now possible, so presentation of information that has no relevance to a particular aircraft or airspace procedure is no longer necessary.

> DF 3. Standard symbology should be used for graphical depiction of specific standard elements of advanced airspace procedures such as "follow me" aircraft, and time or spatial constraints (e.g., at or above, at or below, arrive before or after, etc.).

These standards should be developed for NextGen clearance, flight path, and airspace procedure symbology that is appropriate for Primary Flight Displays, Multifunction Displays, Head-Up Displays, Near-to-Eye Displays, and Electronic Flight Bags.
As the diversity and amount of information required to successfully perform NextGen airspace procedures increase, there is the risk of a proliferation of symbology, abbreviations, and other unique display elements that can create confusion, particularly related to aircraft differences training and pilot progressions to different aircraft. As procedures are standardized, the formats and symbology by which required and supporting information are displayed on the FD should be standardized to avoid unnecessary confusion and pilot errors.

<u>Pilot Input Methods (PIM) – Design of pilot input methods to increase input accuracy and reduce time required to enter clearances and flight path information</u>

> PIM 1. Shorthand pilot input methods should be developed for inputting complicated procedures to the automated systems in order to minimize head down time.

Pilot input of information continues to be one of the most workload-intensive and error prone activities on the FD. Improved input methods could be achieved through a combination of limiting options, decomposing options into standard input elements, and decomposing complicated procedures into intuitive playbook interaction techniques for entering those elements. Effective ways to increase the speed and accuracy of free text entry should also be considered.

> PIM 2. Automated techniques for completing and checking pilot entries should be used to speed up re-programming of flight plans and entering new clearances.

Auto-checking and auto-loading are methods to improve the speed and accuracy of pilot inputs. These could include smarter auto-completion and "allowable entry" filters, error and consistency checkers, and other context-sensitive methods for limiting and checking pilot inputs.

> PIM 3. Multiple information input devices should be designed in order to provide options to pilots that could help balance or reduce workload.

Viable input methods include keyboards, touch panels, cursor control devices, speech recognition, and gesture recognition. Direct manipulation of graphical depictions of clearances and airspace procedures offers a particularly intuitive way of making proposed flight path modifications. Different input methods offer speed and accuracy benefits for different types of inputs (e.g., touch panels for direct manipulation of graphic images, and keyboards for entry of free text), so availability of multiple methods of inputting information would allow these benefits to be exploited more fully.

> PIM 4. Pilot-automation interactions should mimic the language and syntax of pilot – controller communication.

This could include use of specific clearance language for entering data, or use of pilot-ATC conventions and assumptions as metaphors for graphical user interfaces on the FD. The key is to make inputs to FD automation compatible with the way pilots think [22].

Automation Management Aids (AMA) – Design of automation management aids to improve pilot-automation performance related to flying new airspace procedures

> AMA 1. Flight Crew aids should be designed that describe effective methods for using the automation to fly various procedures as well as transitioning between different methods of automation use.

In particular, assistance with effective ways to scale back from fully automated to less automated methods of flying the procedure may be useful, including information on circumstances which may require back up methods of flying the aircraft. Overall FD design should support easy transitions among different ways of using the automation.

> AMA 2. Automation management aids should be available that provide real time assistance with proper usage of automated flight planning, guidance, and control systems, including explanation of automation capabilities and limitations relative to specific operational conditions and aircraft system states.

There are many incidents today where pilots don't understand what the automation is doing or what its limitations are. This confusion could be exacerbated by expected increases in the amount and complexity of flight planning, guidance, and control automation on future FDs. Systems that can explain their behavior and limitations can help pilots make better decisions on how to use automation and when to use different modes or levels of automation.

Communication Management (CM) – Design of FD communication management features to support faster and more accurate communication and negotiation of flight path changes

> CM 1. Shorthand pilot input methods similar to those described in guideline PIM1 should be used for conveying complicated procedures through FD datacomm systems.

Faster input methods are needed in order to keep head down time and clearance negotiation time manageable when pilots are using datacomm systems. This could be done through a combination of limiting options, decomposing options into standard input elements, and use of standard playbook techniques for entering those elements into the datacomm system.

CM 2. Standard protocols should be developed that identify under what conditions ground automation – to – FD automation communication (without pilot involvement) is acceptable, under what conditions pilots need to assess/approve automation – to – automation communication, and under what conditions flight crew – to – ATC human-to-human communication is required.

The issue of what flight path-impacting information can be auto-loaded in FD flight planning systems, versus what information needs to be approved by the FC, versus what information should be manually input or manipulated by the FC, is a key area requiring more research. But it is clear that there are potential human performance trade-offs: for example, there are risks associated with ground-based errors (auto-generated or remote human-generated) not being detected if clearances are auto-loaded without pilot review; there are complacency risks if pilots simply acknowledge/accept clearances that are almost always error-free; and there are workload risks if pilots are kept more involved by developing procedures that require them to perform more thorough reviews of datalinked clearances.

CM 3. Standard flight crew procedures and conventions for efficient clearance negotiation, and pilot interfaces to support them should be developed, including standardization of the way clearances are parsed, and the order and number of clearance elements that can be negotiated in single messages.

While datacomm message sets are currently being standardized, additional standardization of aspects such as the order and number of clearance parameters or components that can be concatenated and the order in which negotiation parameters are presented, should be developed based on human cognitive characteristics such as short term memory.

CM 4. Flight Deck design should support standardized procedures and conventions aimed at when to use voice communication versus datacomm for air-ground communication functions.

While there is a widely-held view that voice communication will continue to be used for time-critical communications, more prescriptive procedures and guidelines are needed to address under what other conditions voice communication might be appropriate. As the types of communications and standard message sets allowed for datacomm expand, identification of communications, such as complicated clearance negotiations and exchange of information requiring extensive entry of free text, that might be better handled with voice communication (even when there is not time pressure) could reduce the risk of errors and high pilot workload.

Automation Functionality (AF) – Design of automation functionality to assure compatibility with NextGen airspace procedures

AF 1. Flight Deck flight planning system functionality and pilot interfaces should be explicitly designed to be compatible with design of new NextGen airspace procedures, including design of extensibility features to assure future compatibility with yet-to-be developed airspace procedures.

Clearly, this guideline needs to be fleshed out in more detail or be de-composed into a set of more detailed guidelines that include how this compatibility can be achieved. This addresses the core issue motivating this work. Fundamentally, FD system designers need to be aware of how airspace procedures are designed as well as how pilots will need to use the automation to successfully fly them under different scenarios. This guideline needs to go hand-in-hand with guideline AP-8, which approaches the same issue from the opposite direction, that is, design of airspace procedures based on understanding of design of FD systems.

Pilot – Automation Interaction Style (PAIS) – Design of pilot-automation interaction style features to support better flight path management

PAIS 1. Flight Deck pilot-automation interaction features should support Crew Resource Management (CRM) principles among the crew members and between crew members and the automated systems.

CRM as a way to catch and correct subtle errors as early as possible will likely become more critical as the precision and complexity of airspace procedures increase. Enhancements could include automated systems that are explanative and can query and challenges crew members to encourage crew member – crew member – automation "verbalize, verify, and monitor" (VVM) practices.

Airspace Procedure (AP) Guidelines

AP 1. The design of airspace procedures should account for complexity from a Flight Deck automation and pilot input/programming perspective.

Ways to make procedures simple to program and understand while preserving the airspace and traffic flow benefits should be explored. Sacrificing some capacity benefits in order to assure accurate and timely programming by the pilot should be considered.

AP 2. Procedures should be designed to have safe, easy-to-remember and easy-to-execute recovery, abort, and emergency contingencies.

An important part of airspace procedure design is accounting for events where the procedure has to be abandoned and an emergency declared, an evasive maneuver performed, or a contingency plan exercised. With closer spacing and higher precision and complexity, these types of situations could be even more time-critical and demanding for the FC than they are today, so procedures must address the need for quick pilot responses no matter when during the procedure the event occurs.

AP 3. Procedures should be designed to allow flight crews to have flexibility in the way they use automated flight planning, guidance, and control systems to fly them.

On any particular aircraft, pilots normally can utilize the FD systems and automation in a variety of ways to fly a particular procedure. Those options may be decreased as airspace procedures become more complex and precise, because semi-automated or more manual modes may not be practical for safely and efficiently flying the procedure. To the extent that airspace procedures can be designed in a way that provides the FC with several different options on how to fly them and still meet the precision requirements and other constraints, the more likely disruptions can be avoided because pilots will have the flexibility to manage unforeseen circumstances and situations in different ways.

AP 4. Design of procedures should allow for the ability to be flown with a variety of equipage. Not only should aircraft system functionality be considered, but pilot interface features and ease of entering new procedures and clearances into the automated systems should be considered as well.

Aircraft with advanced equipage, as well as decades-old aircraft with original equipage will need to fly the same airspace procedures. Even if some operations require some level of minimum equipage, there will be variations in that equipage and the pilot interfaces for the key FD systems. Design of airspace procedures should account for these differences even if it means that some hypothetical traffic flow efficiencies are reduced.

AP 5. Procedures should be designed to allow easy use of datacomm systems to send and receive them, and to decompose them easily for purposes of negotiation.

Design of procedures that can be easily communicated should lead to more efficient negotiation and decreased pilot head down time. A "simplicity" check for airspace procedure designers during early procedure iterations would be to try to communicate the procedure to pilots or air traffic controllers and collect data on how long it takes to communicate it, and what types of misunderstandings occur.

AP 6. For NextGen airspace procedures, crew procedures and VVM will be even more critical in order to catch errors early. Procedure design should provide features that allow checks of actual performance against plan; that is, procedures that lend themselves to easy verification and monitoring steps.

This guideline goes hand-in-hand with AP 5. Design of procedures that can be decomposed into elements that can be easily verified and tracked by the FC should lead to more effective error detection and correction. These elements could be aspects such as aircraft parameters (e.g., altitudes, speeds), constraints, or time or space segments.

AP 7. Standards should be developed for recommended lead time for communication to flight crews for different types of procedures based on the required amount of pilot-automation interaction to comply.

There may be a range of pilot inputs and interactions required for each type of airspace procedure, and design of the procedures should take into account that range, and worst cases in particular. These standards could include guidance on what kinds of clearances need what kind of lead time for typical pilot programming and lead times and interaction requirements for typical clearance negotiations.

AP 8. Design of airspace procedures should be coordinated with design of FD systems and flight crew procedures.

Like guideline AF 1, more specific details associated with this guideline need to be developed. But there are many elements of FD design and crew procedures that should be considered in airspace procedure design. For example, depending on the complexity of the airspace procedure, they should allow for FC procedures with adequate allotted time and steps for pilots to review and brief the procedure.

5Conclusions and R&D needs

Lessons learned from implementation of advanced procedures such as RNAV and RNP, as well as the results of the safety analyses, suggests that a combination of improved FD automation design, airspace procedure design, and pilot training and procedures, can help reduce the potential risks of pilot errors in NextGen operations. Both current safety analyses and the prioritization that was performed here suggest that pilot situation awareness, confusion, and inadequate knowledge associated with highly complex procedures and complex automation, are key issues to resolve for NextGen. These issues are critical during the information acquisition and analysis stages of information processing, which is particularly problematic because it is difficult to trap these cognitive problems until explicit actions are taken. While error detection, resolution, and tolerance are important, the high priority issues that can arise early in human information processing stages highlight the need for error prevention solutions, which many of the guidelines proposed here address, and which should be considered as key topics for further R&D.

Several other areas of further research were identified:

- Issues and guidelines at the level of detail of specific FD systems or specific NextGen airspace procedures were not addressed, but analyses at these more detailed levels of description should be the next step to validate the higher level findings established here. Further, more details around guidelines AF 1 and AP 8 are urgently needed; that is, how to assure design of airspace procedures and flight deck systems are coordinated and complementary.
- The causes for failure modes used in the FMEA comprise only a partial list, and were over-simplified for the purposes of this analysis. Much more work needs to be performed to analyze human factors issue causes in detail.
- Guidelines inevitably require trade-offs to be made during design. These guidelines should be evaluated to identify the key trade-offs and potential resolutions for conflicting guidelines.
- Appendix A describes the mapping of the developed guidelines to Part 25 regulations and advisory circulars, but the relevance of the guidelines to Operational Procedures – Part 91, Part 135, and Part 121, and airline Standard Operating Procedures also need to be explored. Perhaps more importantly, the impact of the NextGen operational environment and the guidelines developed here need to be assessed for relevance to Part 23 operations.
- The advantages of concepts such as adaptive automation and predictive alerting should be considered to reduce information overload and search time by providing situationally-relevant information. These systems could filter and present information based on the state of the aircraft, environmental factors, system statuses, and so on. The adaptive features could include how to best use the flexibility of the automated systems for the particular situation. However, adaptive systems and predictive alerting can also cause false alarms, nuisance alerts, and unintended pilot distractions, so these trade-offs need much more investigation.
- The role of the pilot in ground-aircraft automation-to-automation communication needs further investigation. As stated under guideline CM 2, further research is needed to identify the role of the pilots for different datacomm protocols; these protocols may vary depending on the situation and the criticality of the information being transmitted.
- It was also noted that the FMEA scoring based on failure criticality, frequency, and detectability should be expanded to address the importance of ease of error resolution.

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7Acronym List

4D – Four-Dimensional
ADS-B – Automatic Dependent Surveillance-Broadcast
AF – Automaton Functionality
AMA – Automation Management Aids
AN – Alerting and Notification
ANSP – Air Navigation Service Provider
AP – Airspace Procedures
ASRS – Aviation Safety Reporting System
ATC – Air Traffic Control
ATM – Air Traffic Management
CAST – Commercial Aviation Safety Team
CDTI – Cockpit Display of Traffic Information
CDU – Control Display Unit
CM – Communication Management
CRM – Crew Resource Management
Datacomm – Data Communication
DF – Display Format
EFB – Electronic Flight Bag
EVO – Equivalent Visual Operations
FAA – Federal Aviation Administration
FC – Flight Crew
FD – Flight Deck
FDAWG – Automation Working Group
FMEA – Failure Modes and Effects Analysis
FMS – Flight Management System
GPS – Global Positioning System
HF – Human Factors
HMI – Human Machine Interaction
IA – Information Automation
IC – Information Content
ITP – In-Trail Procedures
LNAV – Lateral Navigation
LOSA – Line Operations Safety Audit
LPV – Localizer Performance with Vertical Guidance
NCO – Net-Centric Operations
NextGen – Next Generation Air Transportation System
OI – Operational Improvement
PAIS – Pilot – Automation Interaction Style
PARC – Performance-based operations Aviation Rulemaking Committee
PBO – Performance-Based Operations
PIM – Pilot Input Methods
PNT – Position, Navigation, and Time
R&D – Research and Development
RNAV – Area Navigation

RNP – Required Navigation Performance
RTA – Required Time of Arrival
SA – Situation Awareness
TBO – Trajectory-Based Operations
TEM – Threat and Error Management
TIS-B – Traffic Information Services - Broadcast
TTF – Traffic-To-Follow
VVM – Verbalize-Verify-Monitor
VNAV – Vertical Navigation

8Appendix A.
Mapping of proposed flight deck design guidelines to existing Part 25 regulations and advisory circulars.

Flight Deck Design Guidelines for NextGen
14 CFR Part 25 Harmonization

Information Content (IC) – Development of new information content to support better flight planning, execution, and monitoring

Guideline	Part 25 Harmonization
IC 1. Flight planning information should make it easy to compare trajectory status against strategic safety and efficiency goals, including predicted trajectory (based on settings and entered flight plan) against future goals.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1501(b) Operating Limitations and Information AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1581-1 Airplane Flight Manual, Appendix 1 – Computerized Airplane Flight Manual

IC 2. Flight planning information should allow the flight crew to quickly assess the ability to execute a clearance based on aircraft performance models, current settings, and environmental conditions.	14 CFR § 25.1501(b) Operating Limitations and Information 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1581-1 Airplane Flight Manual, Appendix 1 – Computerized Airplane Flight Manual
IC 3. Flight crews should be provided with a graphic situation display that provides integrated strategic summary information relating to the conduct of current and upcoming airspace procedures, including constraints, limitations, potential risks, and other key elements that require monitoring.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1501(b) Operating Limitations and Information AC 25-11A Electronic Flight Deck Displays AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1581-1 Airplane Flight Manual, Appendix 1 – Computerized Airplane Flight Manual
IC 4. Flight crew automation aids should explain automation intentions and behavior - not only what it is doing, but why, what its assumptions are, what it plans on doing next, and so on.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems

IC 5. Automation should enable error checking of pilot inputs and display the resulting automation behavior and predicted path characteristics resulting from entries that are considered questionable but are not identified as definite errors.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

Alerting and Notification (AN) – Design of alerting and notification systems for early detection of errors, discrepancies, and potential flight path issues

Guideline	Part 25 Harmonization
AN 1. When possible, flight crews should be alerted if flight path-related pilot inputs are determined to contain inconsistencies, discrepancies, or disparities relative to other entries, settings, statuses, or conditions.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1309(c) Equipment, Systems, and Installations 14 CFR § 25.1322 Flightcrew Alerting 14 CFR § 25.1329(f)(i) Flight Guidance System AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting AC 25.1329-1B Approval of Flight Guidance Systems
AN 2. If the system determines that a pilot input or other pilot action is required, pilots should be alerted when action is not taken in timely fashion.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1322 Flightcrew Alerting AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting

AN 3. If off-nominal events or automation anomalies occur which put the ability to comply with a particular airspace procedure in doubt, the flight crew should be notified. Explanation of the problem and its effect on the aircraft's flight path should be displayed.	14 CFR § 25.143 Controllability and Maneuverability: General 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1309(c) Equipment, Systems, and Installations 14 CFR § 25.1322 Flightcrew Alerting 14 CFR § 25.1329(f)(i) Flight Guidance System AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting AC 25.1329-1B Approval of Flight Guidance Systems
AN 4. Automation functions should be available that compare data from different sources (e.g., navigation databases, electronic charts, published procedures, terrain data bases, etc.) that have discrepancies or conflicting information. These discrepancies or conflicting information should be brought to the attention of the flight crew.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1322 Flightcrew Alerting AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting

AN 5. The flight crew should be notified if FD systems detect that a datalinked clearance conflicts with published procedures, chart data, terrain data, or has other identified safety risks.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1322 Flightcrew Alerting AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting
AN 6. Aircraft flight path performance predictions that suggest a deviation from the cleared procedure might occur should be brought to the flight crew's attention as soon as possible.	14 CFR § 25.143 Controllability and Maneuverability: General 14 CFR § 25.771(a)(e) Pilot Compartment 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1309(c) Equipment, Systems, and Installations 14 CFR § 25.1322(d) Flightcrew Alerting 14 CFR § 25.1329(f)(i) Flight Guidance System AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1322-1 Flightcrew Alerting AC 25.1329-1B Approval of Flight Guidance Systems

Information Automation (IA) – Design of information automation to assist pilots flying NextGen airspace procedures and with related new responsibilities

Guideline	Part 25 Harmonization
IA 1. Given new pilot responsibilities such as self separation and increased clearance negotiation, task aids should be developed to reduce the workload associated with these new responsibilities.	14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1523-1 Minimum Flightcrew
IA 2. Automation aids to assist with recovery from off-nominal situations should be developed.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1309(c) Equipment, Systems, and Installations AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew
IA 3. Flight crew aids for managing information and information automation should be designed, including assistance with information query and search protocols, and with automation interaction strategies.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1555(a) Control Markings AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

IA 4. If a flight path deviation occurs, tactical flight crew aids should be available that help with safe recovery and management of various effects (e.g., impacts on safety, passenger comfort, communication requirements, schedule, and flight efficiency).	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329 Flight Guidance System AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems
IA 5. Information automation should be designed that focuses on simplifying pilot information processing through display and information presentation features such as integration, abstraction, categorization, prioritization, formatting, de-cluttering, and highlighting.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR § 25.1555(a) Control Markings 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1523-1 Minimum Flightcrew
IA 6. Flight crew decision aids to help pilots assess whether or not to accept a clearance should be designed which provide information about what alternatives might be negotiated that would have a high probability of being accepted by ATC because of minimum impact to traffic flow and potential traffic conflicts.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

Display Formats (DF) – Design of new display formats and symbology to assist pilots with flying NextGen airspace procedures

Guideline	Part 25 Harmonization
DF 1. Graphic displays such as perspective synthetic vision displays, combined synthetic vision and enhanced vision displays, moving map displays, and vertical situation displays should be used for visualization of current and proposed clearances.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-11A Electronic Flight Deck Displays AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew
DF 2. Smart de-cluttering methods should be used so that the graphical depictions of clearances and airspace procedures (e.g., on map displays or electronic charts) can be viewed without the concern of pilots being distracted by irrelevant information.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-11A Electronic Flight Deck Displays AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew
DF 3. Standard symbology should be used for graphical depiction of specific standard components of procedures such as “follow me” aircraft, and time or spatial constraints (e.g., at or above, at or below, arrive before or after, etc.).	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-11A Electronic Flight Deck Displays AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

Pilot Input Methods (PIM) – Design of pilot input methods to increase input accuracy and reduce time required to enter clearances and flight path information

Guideline	Part 25 Harmonization
PIM 1. Shorthand pilot input methods should be developed for inputting complicated procedures to the automated systems in order minimize head down time manageable.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1523-1 Minimum Flightcrew
PIM 2. Automated techniques for completing and checking pilot entries should be used to speed up re-programming of flight plans and entering new clearances.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25-15 Approval of Flight Management Systems in Transport Category Airplanes AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

PIM 3. Multiple information input devices should be designed in order to provide options to pilots that could help balance or reduce workload.	14 CFR § 25.777(a)(b)(c) Cockpit Controls 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR § 25.1555(a) Control Markings 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1523-1 Minimum Flightcrew
PIM 4. Pilot-automation interactions should mimic the language and syntax of pilot – controller communication.	14 CFR § 25.1301(a) Equipment: Function and Installation 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems

Automation Management Aids (AMA) – Design of automation management aids to improve pilot-automation performance related to flying new airspace procedures

Guideline	Part 25 Harmonization
AMA 1. Flight Crew aids should be designed that describe effective methods for using the automation to fly various procedures as well as transitioning between different methods of automation use.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1523 Minimum Flight Crew 14 CFR § 25.1555(a) Control Markings 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1523-1 Minimum Flightcrew

AMA 2. Automation management aids should be available that provide real time assistance with proper usage of automated flight planning, guidance, and control systems, including explanation of automation capabilities and limitations relative to specific operational conditions and aircraft system states.	14 CFR § 25.143 Controllability and Maneuverability: General 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1501(b) Operating Limitations and Information AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1581-1 Airplane Flight Manual, Appendix 1 – Computerized Airplane Flight Manual

Communication Management (CM) – Design of flight deck communication management features to support faster and more accurate communication and negotiation of flight path changes

Guideline	Part 25 Harmonization
CM 1. Shorthand pilot input methods similar to those described in guideline PIM1 should be used for conveying complicated procedures through FD datacomm systems.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1523 Minimum Flight Crew 14 CFR § 25.1555(a) Control Markings 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1523-1 Minimum Flightcrew

CM 2. Standard protocols should be developed that identify under what conditions ground automation – to – FD automation communication (without pilot involvement) is acceptable, under what conditions pilots need to assess/approve automation – to – automation communication, and under what conditions flight crew – to – ATC human-to-human communication is required.	14 CFR § 25.1523 Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1523-1 Minimum Flightcrew
CM 3. Standard flight crew procedures and conventions for efficient clearance negotiation, and pilot interfaces to support them should be developed, including standardization of the way clearances are parsed, and the order and number of clearance elements that can be negotiated in single messages.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1523-1 Minimum Flightcrew
CM 4. FD design should support standardized procedures and conventions aimed at when to use voice communication versus datacomm for air-ground communication functions.	14 CFR § 25.1301(a) Equipment: Function and Installation 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew

Automation Functionality (AF) – Design of automation functionality to assure compatibility with NextGen airspace procedures

Guideline	Part 25 Harmonization
AF 1. FD flight planning system functionality and pilot interfaces should be explicitly designed to be compatible with design of new NextGen airspace procedures, including design of extensibility features to assure future compatibility with yet-to-be developed airspace procedures.	14 CFR § 25.1301(a) Equipment: Function and Installation 14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1523(a) Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1523-1 Minimum Flightcrew

Pilot-Automation Interaction Style (PAIS) – Design of pilot-automation interaction style features to support better flight path management

Guideline	Part 25 Harmonization
PAIS 1. FD pilot-automation interaction features should support Crew Resource Management (CRM) principles among the crew members and between crew members and the automated systems.	14 CFR § 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew 14 CFR § 25.1329(f)(i) Flight Guidance System 14 CFR § 25.1523 Minimum Flight Crew 14 CFR 25 Appendix D (a)(b)(c) Criteria for Determining Minimum Flight Crew AC 25.1302 (In Press) Installed Systems and Equipment for use by the Flightcrew AC 25.1329-1B Approval of Flight Guidance Systems AC 25.1523-1 Minimum Flightcrew

Regulations and Advisory Circulars more broadly linked to NextGen Flight Deck Design Guidance

14 CFR § 25.773 Pilot Compartment View
14 CFR § 25.1321(a) Equipment: Arrangement and Visibility
14 CFR § 25.1381 Instrument Lights
14 CFR § 25.1543 Instrument Markings: General
AC 25-7B Flight Test Guide for Certification of Transport Category Airplanes, Chapter 6 – Equipment
AC 25-23 Airworthiness Criteria for the Installation Approval of a Terrain Awareness and Warning System (TAWS) for Part 25 Airplanes
AC 25.703-1 Takeoff Configuration Warning Systems
AC 25.773-1 Pilot Compartment View Design Considerations
AC 25.1309-1A System Design and Analysis