

An In-time Aviation Safety Management System Concept of Operations and Modernization of the National Airspace System

Ellis, K.,^{1a} Prinzel, L.,^{1b} Vincent, M.,^{1c} Krois, P.,^{2d} Ackerson, J.,^{3e} Infeld, S.,^{1f} Brandt, S.,^{4g} Okolo, W.,^{4h} Coughlan, J.,⁴ⁱ Davies, M.,^{4j} Mah, R.,^{4k} Oza, N.,^{4l} Stephens, C.,^{1m} and Glenn-Chase, A.⁴ⁿ

¹NASA Langley Research Center, Hampton, VA

²Crown Consulting Inc., Aurora, CO

³Flight Research Aerospace, Beulah, MI

⁴NASA Ames Research Center, Moffett Field, CA

The National Airspace System (NAS) is growing in complexity of aircraft, missions, and operations. In response, many organizations have published papers and concepts of operations (ConOps) for new and enhanced safety systems. The National Academies' vision for an In-time Aviation Safety Management System (IASMS) is integral to Federal Aviation Administration (FAA) modernization efforts. The National Aeronautics and Space Administration (NASA) System-Wide Safety (SWS) project is conducting safety research, exploring solutions, and defining the safety needs of future missions, such as Advanced Air Mobility (AAM) and autonomous aircraft operating in a more connected, flexible, and dynamic airspace. IASMS enables and provides a path for bringing FAA's operational vision to fruition through increasingly automated safety systems that integrate services, functions, and capabilities (SFCs). These SFCs provide the necessary responsiveness to monitor, assess, and mitigate known hazards and emergent risks. This paper describes how safety in today's air transportation system will need to evolve, identifies key points regarding in-time safety, and explores the criticality of IASMS in the future NAS.

^a Project Manager, NASA System-Wide Safety Project, Senior AIAA Member.

^b Senior Technical Advisor (Aviation Safety), NASA System-Wide Safety Project, Senior AIAA Member.

^c Associate Project Manager, NASA System-Wide Safety Project.

^d Research Scientist, NASA System-Wide Safety Project, AIAA Member.

^e Subject Matter Expert, NASA System-Wide Safety Project.

^f Lead Systems Engineer, NASA System-Wide Safety Project, AIAA Associate Fellow.

^g Deputy Project Manager, NASA System-Wide Safety Project, AIAA Member.

^h Associate Project Manager, NASA System-Wide Safety Project, AIAA Senior Member.

ⁱ Senior Technical Advisor (Autonomy), NASA System-Wide Safety Project.

^j Senior Technical Advisor, Aviation Operations and Safety Program, AIAA Fellow.

^k Research Scientist, NASA System-Wide Safety Project.

^l Sub-Project Manager, NASA System-Wide Safety Project.

^m Sub-Project Manager, NASA System-Wide Safety Project, AIAA Member.

ⁿ Technical Specialist, NASA Aeronautics Research Institute (NARI).

I. Introduction

As the United States (US) National Airspace System (NAS) changes, it is essential to consider and plan for the integration of in-time safety management in 2040 and beyond. The emergence of novel aviation markets, enabled by new entrants and driven by highly automated systems, highlights the increasing complexity and rapid tempo of future operations. Safety is a primary challenge to enable airspace transformation. The next 15 years of NAS evolution will be highlighted by development of tools that increase options for safe, sustainable decision-making in a collaborative environment with modernization of aging infrastructure and transformation to digital, information-based operations. This collaborative, information-centric environment will enable a digital transformation for managing air traffic in airspace that is dynamic and adaptive, allowing for increased diversity, density, and complexity of operations and proactive, predictive safety management. This future airspace will be resilient and able to integrate a diverse range of aircraft quickly, such as uncrewed aircraft systems (UAS), performing new operational missions called Advanced Air Mobility (AAM).

There are over 300,000 aircraft registrations in the Federal Aviation Administration's (FAA) database, involving 11 types of aircraft, 11 types of engines, and nine airworthiness classifications with dozens of subcategories. New market entrants like commercial space launch and reentry, and electric vertical takeoff and landing (eVTOL) aircraft are growing in numbers and have become an essential part of this diversified fleet. Two eVTOL aircraft (known as powered-lift) are currently undergoing FAA certification [1, 2]. eVTOL flights are planned to be brief yet frequent and will pose a unique safety challenge, especially in densely trafficked low-altitude airspace where they will operate alongside established NAS traffic such as helicopters.

To meet aviation's future needs, the FAA has published a vision for the modernization of the NAS that aims to revolutionize the industry with new technologies and concepts of operations (ConOps), while ensuring that current levels of safety are maintained or enhanced [e.g., 3, 4, 5, 6, 7]. In anticipation, the National Academies foresaw the need to evolve today's safety management system (SMS) into an "In-time Aviation Safety Management System" (IASMS) ConOps [8]. Fundamental to the IASMS ConOps is that it monitors, assesses, and mitigates risk, and assures safety by continuously exchanging data and adapting automated monitoring with proactive and predictive risk modeling and advanced data analytics. The data and information the IASMS generate will then enable alerting and response capabilities and, through verification and validation (V&V), provide assurance of autonomy. IASMS is growing as a globally recognized concept; there is substantial industry support for its adoption to address safety challenges in the future airspace.

Today, the public considers the NAS to be safe, due in large part to the near absence of fatal accidents; there have been only three passenger fatalities on Part 121 operated aircraft in the last 15 years [9]. Safety metrics for all operator types indicate an increase in safety over the past 20 years. Although this success has raised passenger expectations, it has also lowered the public's tolerance for risk; recently there have been several high-profile incidents in which aircraft narrowly avoided collisions [10]. Significant changes, including integration of uncrewed/reduced crew aircraft and new safety data management, will have a further effect on NAS operations that researchers, operators, and policy makers have yet to fully understand. Responding to these changes will require new safety system thinking, which will require transformative approaches to designing novel aircraft and air traffic management (ATM) technologies and analyzing big, complex data sets to assure the safe management of emergent hazards and risks. As the future of air transportation evolves, stakeholders need a fuller understanding of the hazards and risks affecting system-wide safety. One major concern is capability to monitor, assess, mitigate, and ensure safety against potential hazards and risks in the context of these expected changes to the NAS. A more proactive and innovative predictive safety approach is necessary to address these issues and establish new baselines for continued

operational safety.

The National Aeronautics and Space Administration (NASA) IASMS ConOps provides a path for the FAA's vision. New safety system cutting-edge SFCs, state-of-the-art data science methods, and novel AI applications used to implement the concept will help transform the NAS. This paper will describe the current state of SMS and the impetus, driven by FAA NAS modernization goals [3, 4], that informs IASMS system-wide data and services, functions, and capabilities (SFCs) to safely usher in the future of flying and air transportation in the NAS. It focuses on modernization changes that will take place in the NAS and how the increased use of artificial intelligence (AI) and introduction of autonomous systems will benefit all. The realization of this vision will require breakthroughs in AI and data science, like machine learning (ML) and natural language processing, and will be necessary to develop more advanced autonomous capabilities for aircraft and air traffic systems. The paper will outline these future needs and describe how current SMSs must evolve to accommodate these changes. This evolution will require integrated in-time system safety analytics that leverage new technologies to improve ATM and safety. For purposes of this paper, "artificial intelligence" is used as an umbrella term that represents diverse methods and applications to include machine learning (ML), deep learning, and natural language processing (NLP).

II. Safety in Today's NAS

The idea of a total system approach to safety evolved during the latter half of the twentieth century in several high-risk industries such as oil and gas exploration [11]. In today's aviation environment the concept of a systemic approach to safety is widely accepted. Aviation safety management has progressed through four phases [12]:

- 1) Technical Phase focused on technological failures.
- 2) Human Factors Phase focused on "man/machine interface."
- 3) Organizational Phase encompassing a systemic perspective and organizational factors.
- 4) Total System Phase which began the era of SMS implementation by service providers, national regulators, and oversight organizations such as the FAA.

The basis of an SMS starts with the International Civil Aviation Organization (ICAO) and its standards and recommended practices (SARPs) regarding SMSs and ATM. The FAA adopts and implements ICAO guidance and develops additional concepts, policies, rules, and procedures for SMSs and ATM.

A. ICAO Global ATM Operational Concept

ICAO, in its Global ATM Operational Concept Document 9854, explains that airspace integration is defined by conflict management that limits, to an acceptable level, the risk of collision between aircraft and hazards [13]. The separator can be either the airspace user or a separation provision service provider currently responsible for separating aircraft from delegated hazards.

In today's NAS, visual flight rules (VFR) and instrument flight rules (IFR) are the two types of separation provisions. VFR requires all separation provision be the responsibility of the user/pilot, with strategic methods such as VFR corridors limiting the hazards and the user/pilot responsible for detect and avoid (DAA). IFR is the responsibility of air traffic control (ATC), and strategic methods limit hazards, e.g., airspace classifications and restrictions. An uncrewed or remotely piloted AAM aircraft would need to meet all the requirements of crewed aircraft for assigned hazard separations.

However, higher density of these diverse aircraft poses a new challenge as information sharing and airspace access with other aircraft scale at pace with AAM operations. Aircraft must have digital interconnectivity to receive the same information about traffic and constraints for safe and conflict-free planning and operations [14]. An AAM service provider can support flight planning, intent sharing, aircraft deconfliction, conformance monitoring, and other traffic management functions while the pilot or AAM operator is responsible for separation management from other traffic, weather, and obstructions, managing operations safely within known constraints and without receiving voice instructions. The FAA has termed this new flight rule whereby the automated system is delegated separation responsibility as tailored flight rules (TaFR).

B. ICAO SMS Framework

ICAO Annex 19 outlines the framework of SMS and is informed by ICAO SARPs that provide the foundation for a safe global aviation system [15]. The ICAO “Safety Management Manual” (Document 9859) defines SMS as “a systematic approach to managing safety, including the necessary organizational structures, accountability, responsibilities, policies, and procedures” [12]. The SMS encompasses four components of Safety Policy and Objectives, Risk Management, Safety Assurance, and Safety Promotion. SMS components are intended to help manage commercial aviation safety risks in coordination with aviation service providers. Several terms were defined relevant to IASMS:

- 1) *Hazard* was defined as “a condition or an object with the potential to cause or contribute to an aircraft incident or accident.”
- 2) *Risk mitigation* was defined as “the process of incorporating defenses, preventive controls or recovery measures to lower the severity and/or likelihood of a hazard’s projected consequence.”
- 3) *Safety* was defined as “the state in which risks associated with aviation activities, related to, or in direct support of the operation of aircraft, are reduced and controlled to an acceptable level.”
- 4) *Safety data* were defined as “a defined set of facts or set of safety values collected from various aviation-related sources, which is used to maintain or improve safety. Note.— Such safety data is collected from proactive or reactive safety-related activities, including but not limited to:
 - a. accident or incident investigations;
 - b. safety reporting;
 - c. continuing airworthiness reporting;
 - d. operational performance monitoring;
 - e. inspections, audits, surveys; or
 - f. safety studies and reviews.”

The ICAO vision in its “Global Aviation Safety Plan” (GASP) for 2023-2025 (Document 10004) is for zero fatalities in commercial operations by 2030 and beyond [16]. The GASP identified high-risk categories of occurrences to mitigate the risk of fatalities consisting of controlled flight into terrain (CFIT), loss of control in-flight (LOC-I), mid-air collision (MAC), runway excursion (RE), and runway incursion (RI).

C. FAA State Safety Program

The FAA is the agency responsible for the US aviation safety program. In 2006, the FAA first published an advisory circular to encourage service providers to voluntarily develop SMSs. In September 2008, the agency established a policy mandating SMSs for certain lines of business including the Air Traffic Organization (ATO), Aviation Safety (AVS), Airports (ARP), and Commercial Space Transportation (AST), as well as the staff office called Next Generation (NextGen) Air Transportation System (ANG) [17]. In 2015 the agency mandated that all air carriers operating under Part 121 of Title 14 of the Code of Federal Regulations (CFR) have an SMS [18]. Part 121 air carriers include cargo operators with more than 7500 pounds of payload and those operating aircraft with more than nine seats on a scheduled basis or more than 30 seats on an on-demand basis. Part 121 air carriers transport the majority of passengers and cargo in the US.

The expansion of SMS continued in 2023, when the FAA began requiring the largest Part 139 certificated airports to implement SMSs. These airports account for over 90% of passenger enplanements in the US [19]. In 2024, the FAA further expanded mandatory SMS to Part 135 commuter and on-demand operations, Part 21 Type Certificate Holders, and Part 91.147 air tour operators. AAM operators are expected to be certified under Part 135 and will therefore be required to have an SMS [20]. As of today, Part 145 repair stations are not required to have SMSs but can join the FAA’s voluntary SMS program. Aircraft maintenance which occurs under an air carriers Part 121 certificate however will fall under the carrier’s SMS.

Compliance to the FAA’s updated SMS rules ensures the safety of the flying public. Adherence to SMSs is ubiquitous, fundamental to aircraft manufacturers, operators, maintenance organizations, airport operators, air traffic

control (ATC), FAA as the regulator, and more. While almost all areas of air travel are covered by stand-alone SMSs, there remains the need to connect them in various ways, e.g., more extensive development beyond current limited data sharing capabilities between these programs. The complexity of data sharing is underscored with “many examples of accidents and incidents showing that the interfaces between organizations have contributed to negative outcomes” [12].

In accordance with ICAO requirements, the FAA has established multiple voluntary safety reporting systems to gather data beyond what is captured in mandatory accident and incident reporting. The Aviation Safety Action Program (ASAP) allows pilots, mechanics, dispatchers, and other defined groups to report safety concerns that could create a hazard. The Voluntary Disclosure Reporting Program (VDRP) and Line Operations Safety Audit (LOSA) allow certificate holders to report errors and other safety issues to the FAA. These programs assure the reporter will not receive punitive actions from the FAA if they meet certain criteria.

An SMS relies on safety risk management (SRM) and safety assurance (SA) working together [21]. SRM in the design phase involves system analysis, identification of hazards, assessment of safety risk, and development of safety risk controls. Design safety includes showing compliance with industry standards and achieving and adhering to certification approved processes. SA in the operations phase checks that safety risk controls perform effectively to achieve their intended mitigations and the organization collects and analyzes data and information on meeting its safety objectives [21]. These relationships are shown in Figure 1.

Operational safety involves several considerations. For example, subject matter experts (SMEs) or an equivalent system provide qualitative judgment of the quantitative analysis of pre- and in-flight data provided from predictive and proactive safety systems. Also, lessons learned as industry best practices associated with reactive and proactive safety systems generated post-flight may be adopted based on operating context, relevance, and comparable risk reduction benefit to a specific context. Remaining from SRM and SA is residual or retained risk that an accountable person (e.g., executive-level) accepts.

The FAA Advisory Circular (AC) 120-92D titled “Safety Management Systems for Aviation Service Providers” [18] describes the current process for conducting SRM, a key component of SMS. The ASAP, VDRP, and LOSA programs are inputs to the SRM/SA process. Other inputs include flight operational quality assurance (FOQA) with collection and analysis of digital flight data generated during aircraft operations, the Advanced Qualification Program (AQP) for validating training curriculum content, a continuing analysis and surveillance system (CASS) to monitor the performance of an air carrier’s maintenance program, and the Internal Evaluation Program (IEP) that involves inspections, audits, and evaluations. Another confidential and anonymous reporting system is NASA’s Aviation Safety Reporting System (ASRS) used by pilots and others to submit safety concerns using an independent, third-party system [22].

NASA has adapted its original IASMS ConOps to apply to several aviation domains. These domains include Parts 121 [23], 135 [24], 139 [25], and 450 [26]. The ConOps has also been adapted for upper Class E airspace [27], AAM [28], and vertiports [29]. While these individual ConOps represent multiple perspectives on IASMS, this current paper provides a comprehensive, integrated, higher-level concept for IASMS and future NAS modernization.

D. Aviation Safety Statistics

Statistically, today’s NAS is very safe, secure, and protected. Commercial aviation has experienced a significant reduction in accident rates over the last two decades, with a 45% decrease observed in aircraft accidents and an approximate 80% reduction in fatal accidents for aircraft exceeding 27,216 kg (60,000 lb.). This category encompasses aircraft equivalent to or larger than 70-seat regional jets [30]. During the interval from 2003 to 2022, international operations were characterized by 58.7 million flight hours and 26.3 million departures.

According to the International Air Transport Association (IATA), the global accident rate in 2022 was 1.21 per million sectors, accompanied by a fatality risk of 0.11, equating to a statistical probability of 1 in 25,214 years for a 100% fatal accident to occur if daily flight is taken [31]. Notably, there was a decrease in the fatality risk from 0.23 in 2021 to 0.11 in 2022, maintaining an average of 0.13 over the five-year period from 2018 to 2022. In the year 2022 alone, there was a recorded decline in the overall accident rate, with 25 incidents, including three fatal accidents.

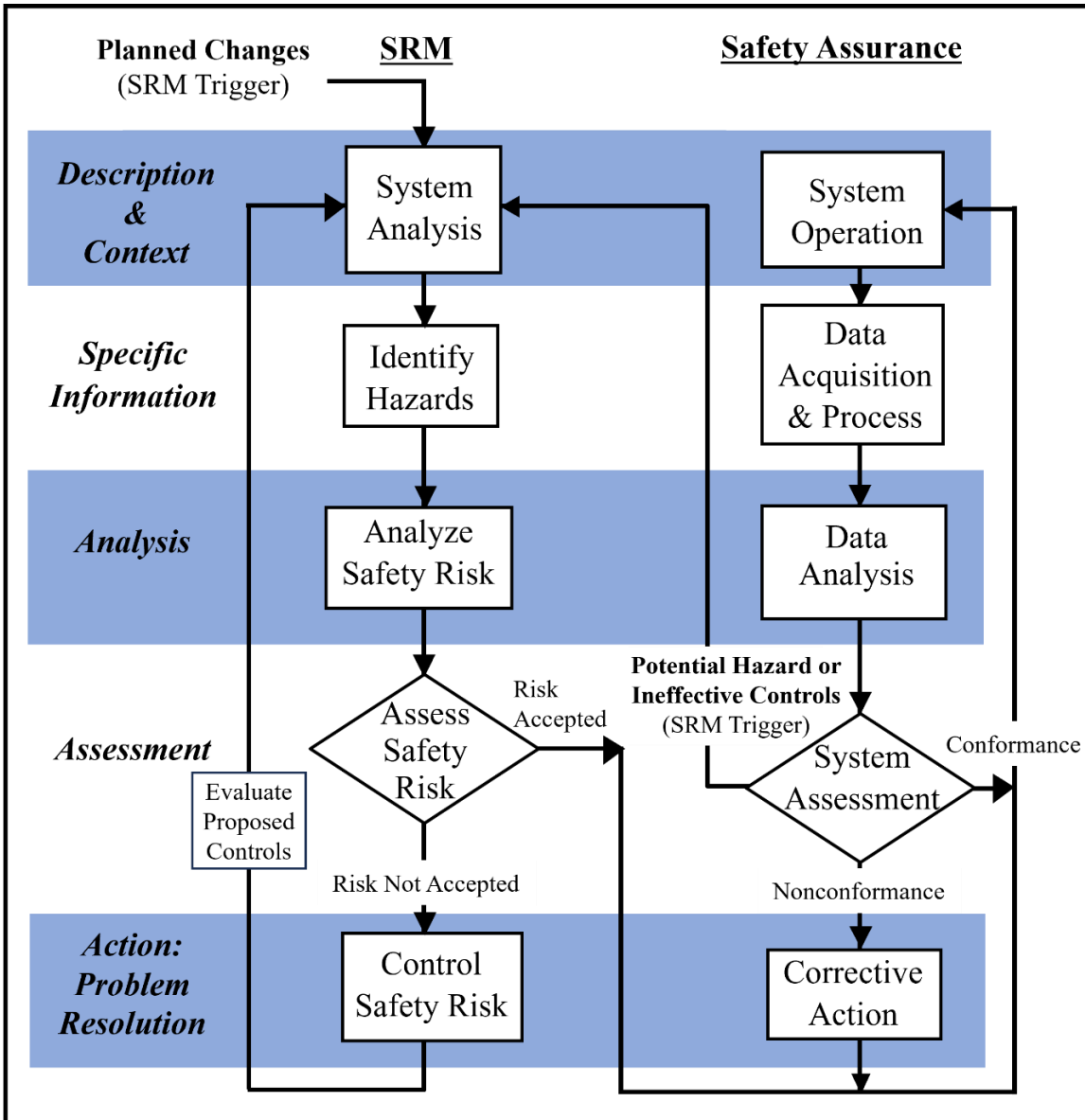


Fig. 1 FAA policy for SRM and SA [21].

According to the NTSB, Part 121 operations have continued a downward trend in fatal accidents since 2003, as shown in Figure 2[32]. In 2022, for example, the NTSB reported that US Part 121 air carrier accident rate decreased to 0.006 accidents per 100,000 flight hours. This equates to a single fatal accident for over 17.8 million flight hours in 2022. Fatal accident rates for other types of operators decreased as well. Although much higher than Part 121, the fatal accident rate for Part 135 on-demand decreased to 0.091 per 100,000 flight hours and GA decreased to 0.945 per 100,000 flight hours. (note data for 2011 is not available for Part 135 on-demand and GA).

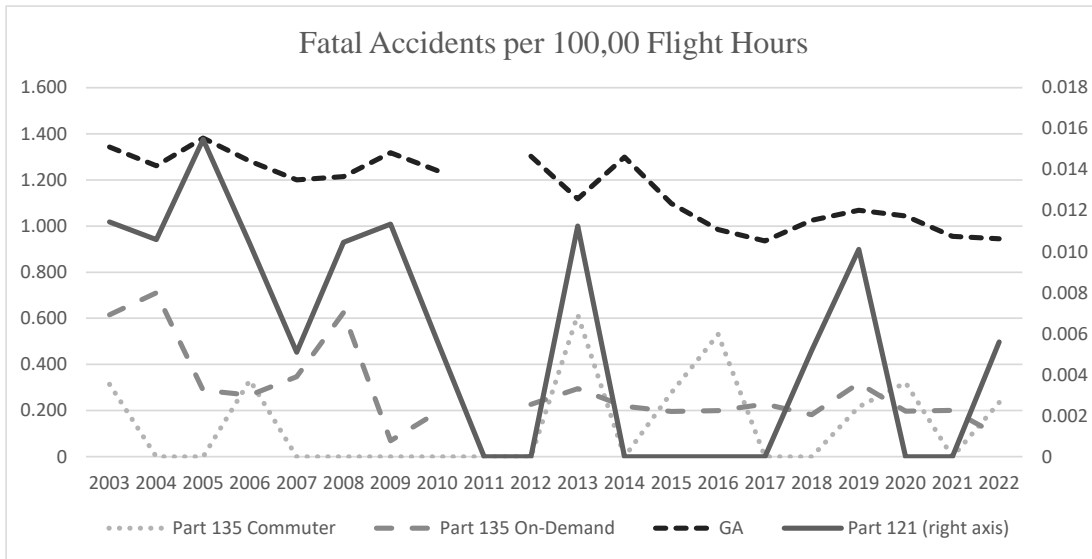


Fig. 2 US fatal accident rates [33].

Similar to the fatal accident rate, the total accident rate has declined for all types of US operators as shown in Figure 3. As with fatal accidents, the 2022 rate for all accidents is lowest for Part 121 carriers at 0.112 per 100,000 flight hours. Part 135 on-demand operators total accident rate is 1.020 per 100,000 flight hours and GA is 5.336 per 100,000 flight hours.

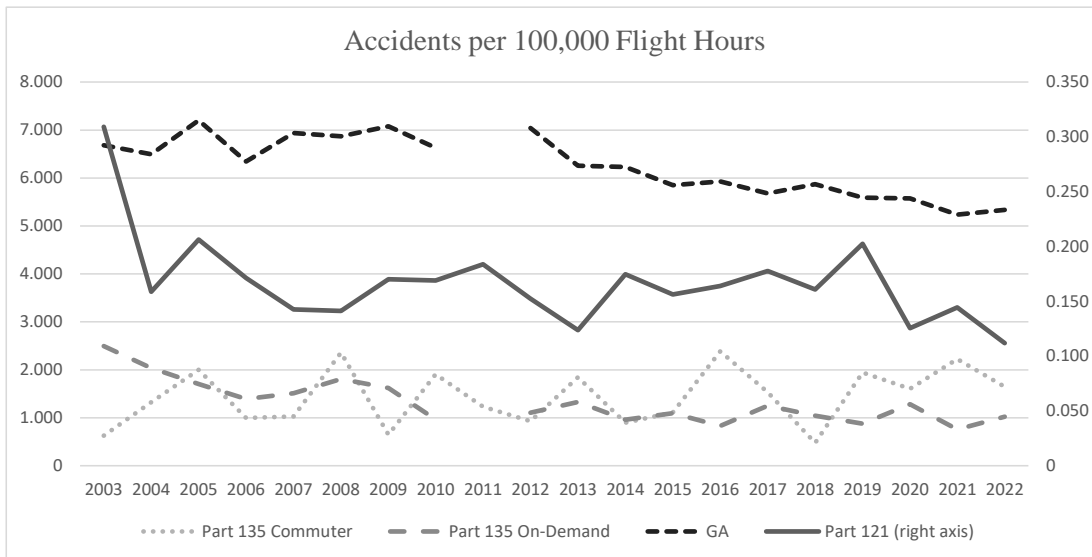


Fig. 3 US accident rates (all accidents) [33].

Aviation is characterized as a high-reliability operation with inherent risks for catastrophic outcomes. In the past two decades, US airlines have safely transported a number of passengers that exceeds the global population, with remarkably few fatal accidents. Nevertheless, the prevailing consensus within the aviation safety community acknowledges that considerable efforts are still required to enhance safety. Aviation safety cannot be defined merely by the absence of accidents and significant incidents. For instance, as of October 2023, the NTSB's Case Analysis and Reporting Online (CAROL) system lists 527 open aviation safety recommendations (accessed on May 9, 2024) and includes those with open status of initial response received, acceptable response, and unacceptable response.

The highly visible commercial aviation incidents in 2023 underscore the importance of continuing efforts to address safety risk and explore new ways to introduce change, including technology innovations, to assure aviation safety future [10, 34, 35].

Despite the long-term downward trend in accidents, other safety metrics indicate an increased level of hazards in the NAS. The number of runway incursions at the 30 busiest US airports (Core 30) increased by 21.1% in fiscal year 2023 compared to 2022, as shown in Table 1 [36]. A runway incursion is any occurrence involving the incorrect presence of an aircraft, vehicle, or person on the protected area of a surface designated for the landing and takeoff of aircraft.

Table 1 Runway incursions [36].

Core 30 Total Runway Incursions			
FY17-19 Avg	FY22	FY23	% Change
391	299	362	21.1%

Table 2 shows that losses of standard separation increased by 6.8% in fiscal year 2023 compared to 2022. Standard separation is a specified separation minima between airborne aircraft in controlled airspace. [36].

Table 2 Losses of standard separation [36].

Total Losses of Standard Separation			
FY17-19 Avg	FY22	FY23	% Change
1,221	961	1,026	6.8%

E. National Academies Report on Emerging Hazards in Commercial Aviation

The National Academies published two reports on emerging hazards affecting commercial aviation safety. The first report, published in 2022, reviewed current data and processes for identifying anomalies before they could lead to a future accident [37]. That report identified significant potential challenges and opportunities for commercial aviation safety, including new entrants developing and employing new technologies and business models without the knowledge and culture underlying today’s aviation safety. The report recognized the important processes the FAA and other organizations use for sharing safety data and analytics to identify and monitor leading indicators and precursor measures.

While cataloguing this information, researchers found no examples of measures addressing issues with software that enables automated systems. Specifically, there were no examples related to staying current with software version control or tracking records of safety-critical software behavior. For instance, there was no data on how the software responds when the aircraft reaches key limits, which could indicate software limitations and the need to review assumptions or conduct hypothesis-based testing. Another initial finding was information is incomplete about how safety programs and processes incorporate and use maintenance data, such as maintenance errors. These maintenance errors are compounded by the FAA not receiving complete information about aircraft service difficulties and performance issues for US-manufactured aircraft that are operated abroad by non-US carriers.

Data analytics span from counting exceedances as part of immediate front line air carrier operations, to big data analytics applying ML to identify precursors and inform longer-term transformative improvements to aviation through design, certification, and production of new technologies. There is a paucity of future-time-frame efforts seeking to discover new, still unidentified hazards. Methods need to be developed to detect "weak signals," which are previously unknown anomalous patterns in safety data, and to evaluate hypotheses about the relationships between system stressors and other factors. For example, stressors like operator fatigue need to be studied alongside proposed changes in technology, traffic density and distribution, and procedures. This will require a combination of predictive modeling and SME review.

The second National Academies report published in 2024 focused on technology enabling transformative changes to operations. The report defined “transformative changes” as changes sufficiently novel that their impact to safety and risk exceeds today’s data analytics. New data types and sources and innovative methods would be necessary to mitigate the potential risks [38]. The report further described “emerging” hazards as new hazards emerging from novel technologies or operations, as well as existing concerns that may be exacerbated by the introduction of new risks. A framework based on the ICAO SMS components entails that SRM is integrated in the design, evaluation, certification, and approval of new technologies and operations; safety assurance monitors operations and detects any possible safety concern; and that organizational structure and culture is crucial to an organization’s ability to lead and support safety. These components flow across the lifecycle of technologies and concepts of operations.

The overarching finding highlighted that any first-generation implementation of technology or operations opens a new frontier of knowledge, where the unexpected can arise as either minor perturbations or major impacts. Even small step-changes in later generations can introduce unforeseen risks. The report identified several gaps in aviation safety management. These include the need for greater use of performance-based standards in all flight safety functions, the development of new methods to systematically design and assess transformative changes to general operating and flight rules, and the use of data analytics to identify emerging trends. Additionally, it emphasized the importance of integrating innovative data collection mechanisms into new technologies and operations to support future safety assurance processes, as well as fostering a strong safety culture and ensuring the integration of safety across organizations.

III. In-Time Safety in NAS Modernization

Air transportation safety systems are generally effective and well-equipped to meet the current NAS safety needs, despite occasional failures. These systems must continually adapt to changes within the NAS, necessitating significant advancements in preparing for anticipated demands and new operations.

Technological advancements are catalyzing transformation in the realm of transportation, offering the promise and tantalizing prospect of improving transportation safety. However, they also usher in and pose new challenges and novel quandaries. Both the FAA and NASA visions call for changes in how safety will be managed in the future and advocate for innovations that better utilize AI and increasingly autonomous technologies. These innovations aim to evolve safety management systems and improve how data is collected, fused, analyzed, and shared across the airspace system, benefiting both traditional and emerging operators. These advances afford operators substantial opportunities to improve on aviation safety’s already laudable record. However, to realize the full potential of a transformed future, the aviation community must anticipate that transformative technological advances must be accompanied by equally transformative approaches to ensuring and assuring safety.

Future visions of the NAS include FAA concepts on NAS modernization, NASA’s Sky for All, and other concepts. Some concepts intend to be broad in scope whereas others focus on particular domains. FAA future concepts include commercial space [5], Upper Class E airspace [6], Urban Air Mobility (UAM) ConOps v2.0 [7], and AAM Implementation Plan (Innovate 28) [20]. While all underscore the importance of safety in the design of aircraft and their operations, in-time safety provides the responsiveness necessary to keep pace with the rising tempo of increasingly automated and autonomous operations.

A. FAA NAS Modernization Concepts

The FAA’s NAS modernization vision proposes substantial changes to the future air transportation system that significantly impact aviation safety. The FAA’s “Charting Aviation’s Future: Operations in an Info-Centric National Airspace System” document [3] describes a vision of an information-centric NAS (ICN) that foresees increasing demands for new emergent operators. It presents three pivotal transformational attributes—operations, infrastructure support, and comprehensive integrated safety management. ICN includes the concept of in-time integrated safety management that involves the management and oversight of the integrated system, introducing tailored safety measures, ensuring interoperability and compatibility, and providing for in-time safety assurance.

The FAA provides a path for the future NAS to better align with the evolving technological landscape and the increasing demands of modern aviation. The overarching goal is to become a more seamless airspace, one that leverages technological advancements to enhance ATM and safety. To achieve this aim, the FAA plans to integrate new technologies that increase the performance, efficiency, and safety of airspace operations [3, 4]. Figure 4 is a depiction of the diversity and complexity of aircraft, airspace, and operations in this envisaged future. Figure 5 shows services and enablers.

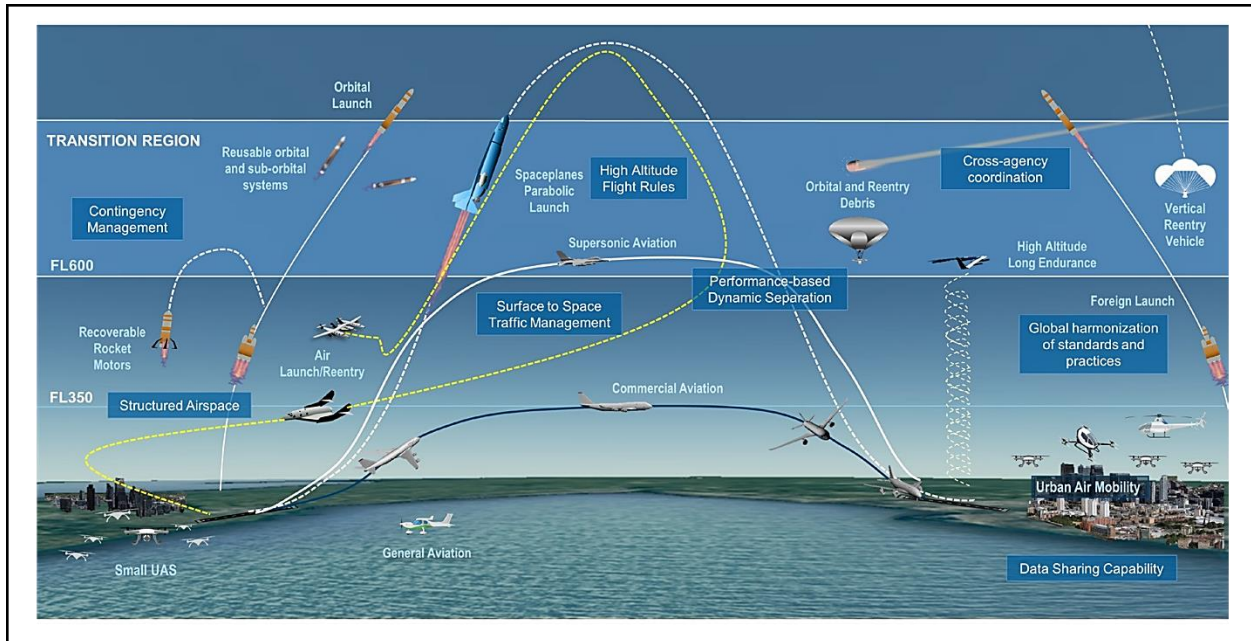


Fig.4 Complexity of future aircraft and NAS operations [3].



Fig. 5 NAS modernization services and enablers [3].

The FAA delineates three key areas of transformation of operations, infrastructure support, and comprehensive integrated safety management as shown in Table 3 [3].

Table 3 Representative transformations of the NAS.

Integrated Safety Management	Operations	Infrastructure
Tailored Safety Processes	Collaboration Among Diverse Service Providers	Ubiquitous Services
Interoperability	Fully Integrated Information Environment	System Resiliency
In-Time Safety Assurance	Agile Systems and Services	System Evolves On-Pace with Technology

The concepts outlined in the FAA ICN ConOps reimagine the approach to safety by integrating real-time management and oversight capabilities within the NAS. The concept emphasizes the development of customized safety measures tailored to specific operational contexts, ensuring seamless interoperability and compatibility across different segments of airspace management and providing timely, effective safety assurances.

FAA's modernization efforts rely on integrating new technologies and processes that support continuous monitoring and management of the airspace. These capabilities can mitigate risk before they escalate by quickly adapting to any issues or changes in the operating environment. These proactive and predictive approaches to safety are expected to revolutionize the way airspace is managed, making it safer and more efficient for new operators entering the market with advanced, potentially disruptive technologies.

The vision outlined in the FAA's Charting Aviation's Future represents a framework for a radically transformed airspace system that is safer, more efficient, and more inclusive [3]. Through strategic innovation and collaboration, both NASA and FAA visions aim to redefine the boundaries of what is possible in air transportation, setting the stage for a new era of aviation by the mid-21st century. These initiatives underscore a commitment to a future where aviation continues to thrive, driven by advances in technology and an overarching emphasis on safety and efficiency.

B. NASA Sky for All Modernization Concept

NASA's Sky for All vision [39] similarly anticipates a cooperative airspace ecosystem characterized by highly automated and distributed systems. Sky for All is complementary to FAA's modernization vision and is reflected in thrust five of NASA Aeronautics' Strategic Implementation Plan [40], "In-Time System-Wide Safety Assurance." Critical elements for system-wide safety involve:

- 1) Give more users better access to safety-relevant data to allow for system-wide monitoring and enable predictive technologies. Integration of heterogeneous data from the entire system will allow for a more comprehensive understanding of risks, including in-time detection and alerting capabilities available to operators across the NAS (2020-2035).
- 2) Introduction of an IASMS that continuously monitors the NAS – and sub-elements within the NAS – to collect data on the status of all elements and operators within the NAS. The IASMS will accommodate new operations and new capabilities as they are introduced into the system, detecting new risks as they emerge (2035-2045).
- 3) Adaptive in-time safety threat management will incorporate increasingly autonomous human-machine decision support to enable proactive prediction and mitigation of risk in complex operations and support NAS-wide safety assurance (Beyond 2045).

In-time safety mechanisms, leveraging substantial big data resources, enable the proactive and predictive detection of indicators, precursors, and anomalies. Predictive detection will reduce risk to the NAS by notifying stakeholders of hazards and threats in time to address them. NASA's Sky for All and FAA's ICN ConOps highlight the synergy between visions underscore the technological and operational shifts necessary to advance aviation safety and achieve this future state.

Sky for All's vision identifies several fundamental paradigm shifts that will transform today's NAS into a seamless airspace ecosystem and assure safety as operations diversify and grow in complexity. To assure safety in-time, safety systems must shift from reactive to proactive and predictive. Until now, all NAS modernization efforts have evolved in slower paced, incremental ways, preserving and building on tried-and-true methods and procedures; the transformation from reactive to predictive safety management will fundamentally change ATM and aviation safety principles forever. Moreover, the transition to an info-centric and highly automated NAS requires a broad reevaluation of current regulations, standards, and practices to accommodate new technologies and operational paradigms. This sea change requires collaboration from all stakeholders in the aviation industry—regulatory bodies, technology providers, airspace operators, and academia—to forge a unified path forward. Success hinges on the ability to foster an innovative ecosystem that can sustainably support the anticipated growth and complexity of future aviation needs.

The FAA and NASA anticipate that the future NAS will introduce technological innovations that will ease integration challenges for new entrants such as UAS, UAM, and other innovative air traffic services (ATS) and operational concepts. Advances in data/decision fusion techniques, data exchange and information sharing platforms, automation/autonomy, and AI, including ML and natural language processing are expected to significantly enhance decision-making processes and operational efficiency; key benefits include improving route optimization, traffic flow, and environmental performance to name a few. Real-time data exchange and analytics enable dynamic management of airspace, thereby reducing delays, optimizing flight paths, and minimizing environmental impacts.

C. Industry Modernization Concepts

Several aviation industry entities have published concepts for modernization and many share similar themes and areas of emphasis.

Civil Air Navigation Services Organisation (CANSO)

CANSO and other entities comprising the Complete Air Traffic Services (CATS) Global Council presented to ICAO a transportation system vision for 2045 [41]. In line with FAA and NASA, CANSO's future system recognizes that the needs, missions, and risks are changing for crewed and uncrewed aviation, as well as service and technology providers. Advancements in technology and services design innovations support seamless, safe, fair, intelligent, interoperable airspace. To develop a detailed roadmap, the CATS Global Council first defined building blocks; the resulting roadmap involves over 70 milestones and 100 activities [42]. Aligned with the ICAO GASP, the CATS safety and regulation building block emphasizes proactive risk management practices for new models of strategic and tactical service delivery and promotes a strong safety and quality culture. The roadmap includes improved performance through automation with harmonized service delivery, digital collaboration, integrated airspace, secured communications, and high performing teams.

Boeing and Airbus

Boeing and Airbus, in a rare collaboration, called for a new digital era of airspace and traffic management, specifically UTM [43]. UTM will evolve as a distributed system of interconnected microservices (surveillance, weather, and airspace information). UTM service providers will share responsibility for safety risk management, dynamic airspace management, and contingency management. Interoperability between service providers, different aircraft and operators, and existing ATM systems will be cross-cutting, and scalability and flexibility for both current operators and new airspace users are paramount. Safety assurance must be built-in from initial design to implementation, operation, and continued evolution.

Boeing and Wisk

Boeing and Wisk developed a comprehensive vision in version 2 of its ConOps for uncrewed UAM [44]. Their plan envisions safely launching UAM passenger operations in the NAS by the end of this decade, via a procedural methodology that integrates UAM without requiring changes to existing ATM systems. In the following years, this will scale to high-throughput operations. UAM-specific flight plans will provide strategic separation, procedural deconfliction, and conformance monitoring that uses UAM Required Navigation Performance (RNP) Routes for flow management. Detect and avoid (DAA) and landing hazard avoidance (LHA) systems, which may be onboard and/or ground based, will provide tactical conflict management.

Association for Uncrewed Vehicle Systems International (AUVSI)

The AUVSI in its "Blueprint for Autonomy," noted the diversity of future autonomous aviation spanning across small UAS (sUAS) and larger passenger-carrying aircraft necessitates in-time scalable and tailorable solutions [45]. The Blueprint emphasizes technology, airworthiness, operations, and integration as foundational to safely scaling autonomous operations for diverse aircraft and missions. This scaling ranges from lower-risk autonomous operations, including beyond visual line of sight (BVLOS) and UTM, to higher-risk autonomous operations by larger aircraft. Equipage is expected to include certifiable and more adaptive AI-based autonomy executives such as based on a

statistically driven certification methodology. SMS should address autonomy including use of a feedback loop to leverage best practices and lessons learned in autonomy design and implementation.

International Air Transport Association (IATA)

IATA developed a high-level concept paper on changes for a new operational environment [14]. At low altitudes, small to medium-sized UAS will perform missions such as inspection, surveillance, and deliveries. A mixed-mode operating environment will have different airspace users sharing the same airspace, each with varying levels of on-board automation. A mixed-mode operating environment will have airspace users with varying levels of on-board automation sharing the same airspace, some of which will be more congested than today. Within a digitally connected environment, ATM and UTM are integrated, providing information sharing and airspace access so each aircraft can simultaneously access the same information about surrounding traffic and constraints. This digital interconnectivity between operating aircraft will trigger a shift in the role of ATC to managing by exception. The vision also considers upper airspace, at altitudes of 50,000 feet and above. There, aircraft will have significantly different performance levels in terms of maneuverability and speed. Due to some vehicles' vulnerability to wake turbulence and environmental conditions, aircraft may require a larger buffer of airspace to operate and maintain safe separation [27].

D. Higher Level Considerations

The FAA will exercise its regulatory authority to set and approve new performance and interoperability standards, flight rules, and the metrics used that inform design, operations, and information sharing. Operators will be required to adhere to these regulations and complete necessary SMS analysis to ensure safe integration and adaptation to the evolving environment.

New operational principles, as described in the FAA ICN ConOps document [3, 4], include maintaining and improving safety, security, and resilience as part of contingency management while incorporating performance-based standards throughout the enterprise. Collaboration with and among affected stakeholders, such as operators and service suppliers, includes operating practices for strategic conflict management, collision avoidance, and balancing airspace user and system objectives. These new collaborative methods will allow for increased user input into flow management decisions and appropriate access to new and existing missions. In addition, the system will ensure that operators cannot optimize their own operations to the detriment of sub-optimizing an Extensible Traffic Management (xTM) environment or the NAS as a whole.

Airspace will be structured where necessary and flexible when possible, including in mixed-use airspace. Scalability will be integral to rapidly expand capabilities to overcome challenges with growth in the number and complexity of operations while ensuring the adaptability and agility necessary to keep pace with unanticipated changes. A flight or aircraft will operate according to a single set of flight rules (e.g., IFR, VFR, or TaFR), although it may operate under different flight rules over the duration of its operation. Flight data will be exchanged to facilitate cooperative separation in xTM environments and conflict management provided by ATS in a trajectory-based operations (TBO) environment. Operational information will be accessible on-demand by ATS and continuously among xTM providers to facilitate situational awareness with globally harmonized services and operations.

NAS operators, FAA, third-party suppliers, and other participants and airspace users will support Cooperative Operating Practices (COPs), and other stakeholders inclusive of any perspective such as standards bodies, academic institutions, OEMs, equipment suppliers, and airport and vertiport operators, along with space launch and reentry operators. Stakeholders with public interest, as recognized by governing entities like the FAA and established COPs, will have access to xTM operations data. These ATM data will be available through specific portals or are directly distributed by service providers to public safety organizations and selectively to appropriate stakeholders.

For operations, FAA's new modernization efforts will enhance services for traditional aircraft and facilitate the safe integration of diverse new aircraft and missions within the NAS. By capitalizing on technological advancements, aircraft will accurately predict and communicate their future locations. This capability, supported by the necessary infrastructure, will enhance strategic planning and demand-capacity management, and will offer traditional aviation more opportunities to contribute to flow management decisions that affect their operations. These advancements will ensure that the introduction of diverse new aircraft to the NAS does not adversely affect the delivery of ATS.

Operations will receive ATM services either through FAA-managed ATS or through self-provisioned xTM services by operators or third-party providers.

The FAA's approach organizes operations into those managed through ATS and those managed through xTM services and examines their interoperability as flights traverse between these domains. Information sharing will improve planning for ATS-managed operations by integrating data, which will improve decision-making and facilitate collaborative performance-based flow management. Scenarios for operations managed through xTM services will include continuous planning and SRM with connected aircraft and smart systems, Upper Class E traffic management (ETM) cooperative separation, interaction between visual flight rules and xTM aircraft at low altitudes, agile and resilient services with self-healing systems that address failure conditions, and scaling for equitable access with dynamic and evolving service.

To achieve the benefits of the innovations, as envisioned by the FAA NAS modernization [3, 4], it is essential to establish clear policies, governance, and a performance-based strategy. SRM is central to driving the use of information and technology within this future system. As operations diversify, the way services are delivered to NAS users will evolve, as new service suppliers are introduced. Additionally, processes will strengthen for the review and approval of standards, rules, and regulations, as well as the oversight of xTM services and providers.

New processes will be required – such as standards, policies, or guidance – to review, approve, and monitor COPs for xTM and ATS. These systems will need to operate alongside diverse users, operations, aircraft, and collaborating traffic management systems. Cybersecurity advances protect information integrity, while enhanced network diversity guarantees the reliability and continuity of services for all operations.

Any required changes will need to be assessed for airspace design and allocation for performance-based operations. Collaboration and agreement among appropriate stakeholders, including ATM and xTM service suppliers, is necessary to measure, value, prioritize, and balance operations based on performance-based outcomes (e.g., access, capacity, efficiency, and equity). The relationship of performance-based outcomes to operational objectives and distributed decision-making will enable operators to optimize their own operations without adversely affecting the NAS system-level performance. Established processes are necessary to define TaFR for diverse operations with a data-driven process to oversee and monitor TaFR compliance. Lastly, new data-driven processes will measure the performance of xTM operations and services.

Infrastructure evolution to a service-based architecture with modular integrated capabilities and organized distributed services managed by various public and private entities will require updated standards for data management, use, access, and exchange. This infrastructure relies more and more on data within an integrated information environment and will need data analytics powered by appropriate architecture, information management, and automation. ATM service delivery and data provisions will require standards, policy, and regulations including a framework to determine which services require certification.

To transform safety management into a more comprehensive safety assurance process, ATS and xTM elements must work together, keeping up with the growing diversity in aircraft, missions, and operational environments. A system-wide SRM analysis is essential to determine when total risk in the NAS becomes unacceptable. Additionally, the FAA and operators need a process to tailor safety requirements for diverse operations and new technologies, supported by automation that enables a data-driven, integrated safety assurance framework shared among stakeholders. Automated, data-driven processes are crucial for making timely decisions in response to changes, such as new aircraft certification, system enhancements and upgrades, and the introduction of new technologies and methods, to support such diverse operations and meet all NAS users' needs.

TBO is integral to the FAA's vision for the future. Integration across UAS, UAM, and the assured ATM framework will require adaptive traffic management strategies that seamlessly merge new entrants and operations into the NAS. In-time safety mechanisms will leverage massive data sources and will have the capacity to integrate resources. These mechanisms will proactively and predictively discover indicators, precursors, and anomalies and immediately alert the relevant stakeholders through set protocols to prevent hazards and threats that introduce risk to the NAS.

FAA's NAS modernization vision [3, 4] will require the following:

- 1) Collaborative decision-making between and within diverse ATM services and non-FAA service providers
- 2) More comprehensive SMS for integrated, collaborative aircraft-centered and novel missions and operations
- 3) Shifting traditional ATM players to more research roles
- 4) Infrastructure changes to empower a fully integrated information environment for scalable, accessible, and resilient SFCs, and
- 5) Safety assurance that establishes agile systems and services to respond promptly to changes with customized safety.

Figure 6 depicts the FAA objective for NAS ATM that will consist of: a) ATS that includes both ATC and traffic flow management (TFM) services provided by the FAA, and b) xTM services for operations such as UTM, UAM traffic management services, and ETM [3].

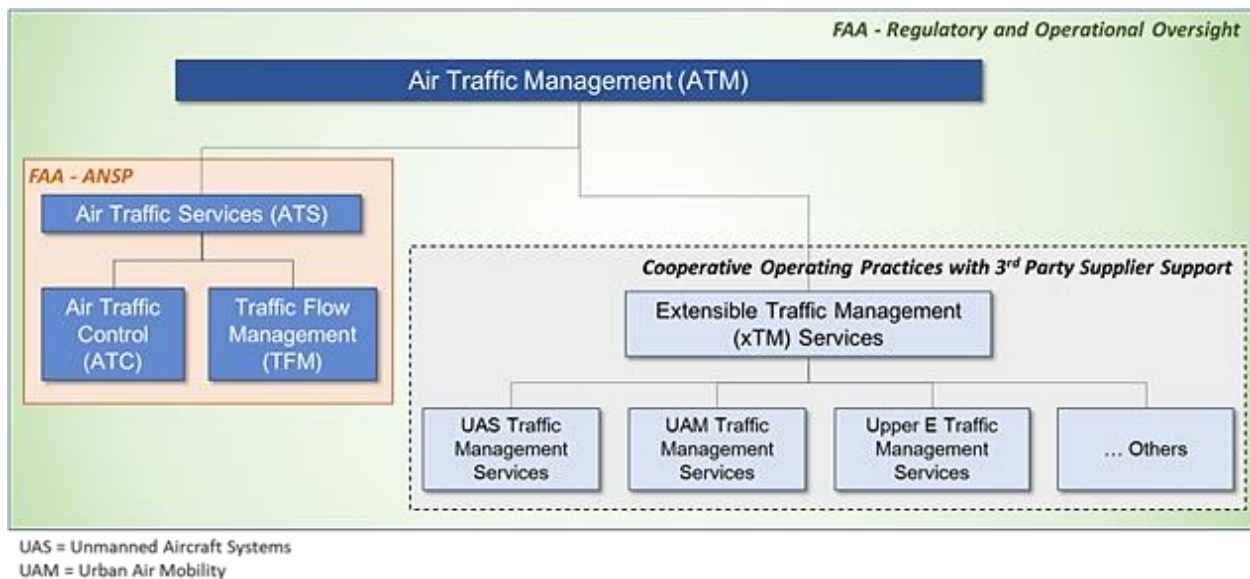


Fig. 6 ATM in the future NAS [3].

These changes to the NAS, along with enhanced human competencies and new/enhanced system SFCs, must match the growing complexity and scope of future operations. Safety challenges to a transformed NAS include, but are not limited to:

- 1) Multi-aircraft control (i.e., m:N) operations and reduced/and uncrewed operations
- 2) Changing roles of humans in safety systems (in the loop, on the loop, over the loop)
- 3) Certification of new technologies, such as autonomy
- 4) Incorporating data analytics for non-forensic, predictive methods
- 5) Developing new distributed safety mechanisms
- 6) Safeguarding against drifts into failure and unexpected, unknown emergent behavior
- 7) Developing data and cybersecurity standards (e.g., access, protection, and sharing of data, etc.)

Figure 7 shows the notional integrated flow of communication, navigation, and surveillance information in the future system.

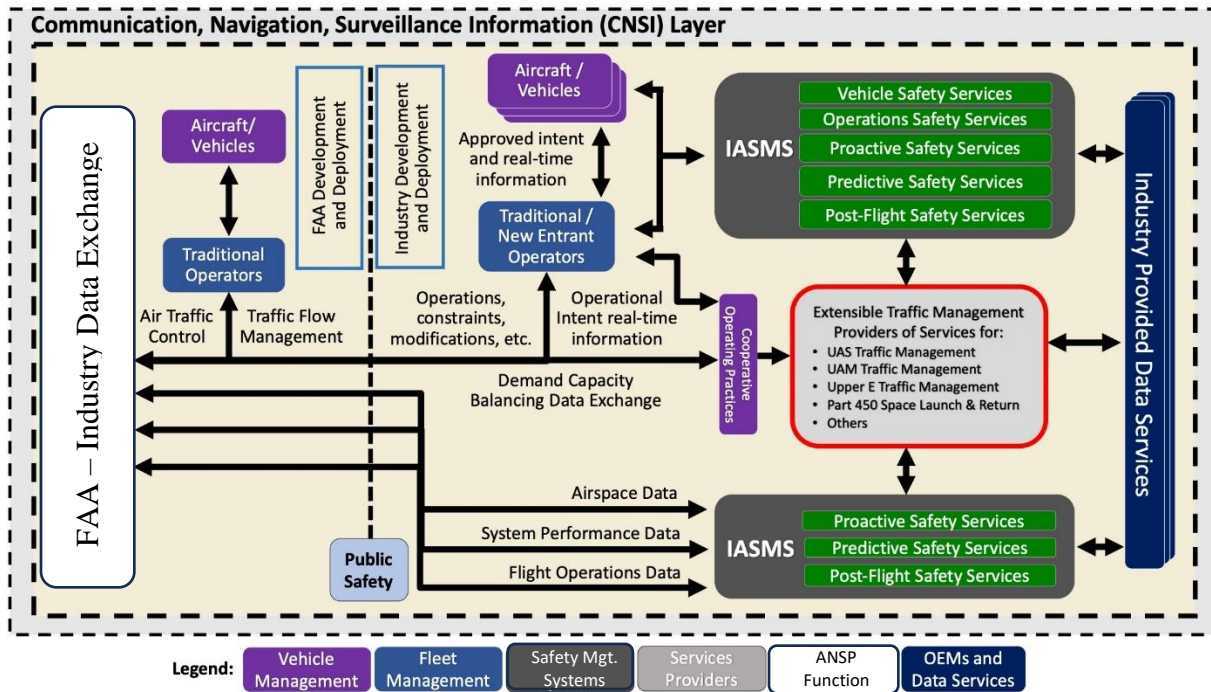


Fig. 7 Notional integrated operation information flows in the future system.

It is critical to address these safety challenges which will require research and development (R&D) for new and better ways to monitor, assess, mitigate, and assure safety, and methods to certify new autonomous systems, safety systems, and their associated SFCs. R&D is critical to NASA's SWS project's work to better monitor, assess, mitigate, and assure NAS safety and certify new autonomous systems in the future. One high-payoff path is to evolve current SMSs. As explained earlier, Part 121 commercial air carriers, Part 135 commuter or on-demand operations, Part 21 Type Certificate Holders, and Part 139 airports are required to have SMSs, and this mandate may be extended to other operators in the future, including maintenance organizations and new and emergent operations. The FAA's vision outlines necessary changes in safety and regulation versus traditional compliance methods. It proposes developing a performance-based regulatory framework designed to adapt to the diverse mix of operations and technologies in the modernized NAS. This approach promotes a multilayered safety management strategy that employs data-driven methods to identify and mitigate risks before they escalate into accidents. Performance standards are crucial, ensuring that new technologies and operations meet safety requirements without hindering innovation or compromising existing system safety. However, integrating complex new systems and operational concepts into the NAS presents numerous challenges, including issues related to compatibility, interoperability, privacy, and security. The future vision emphasizes the need for collaborative efforts, outlining a path towards transforming the NAS into a more agile, productive, and efficient system through ongoing engagement with industry, academia, government partners, and stakeholders. A dynamic approach to introducing and implementing new concepts and technologies is essential, while maintaining strict adherence to safety and performance standards.

IV. Need to Evolve Safety Management Systems

NAS operations and ATM will become increasingly more complex with the integration of high-volume AAM aircraft, vertiports, new commercial aircraft types (e.g., supersonic airplanes), autonomous cargo, regional air mobility, sophisticated general aviation types, and commercial space launch systems. These advances are juxtaposed with the public's low tolerance for risk in aviation. Today's SMS is already workload-intensive with limited ability to scale. To make possible the kind of safety system that the future NAS requires, the FAA, operators, original equipment manufacturers (OEMs), and others must expedite the transition to a digitally integrated NAS. This transformation to

digital data includes addressing challenges with access and inconsistent data quality. The anticipated surge in demand for digital data and its applications will define the future NAS enabling a renewed focus on safety innovation. To meet future demand safely, existing SMSs must evolve to not only accommodate the expected surge in data volume and access needs but also to capitalize on opportunities presented by novel data analysis methods and modern approaches to system safety.

Addressing these forecasted airspace changes will require new skills, a reformed workforce, and innovative operational approaches, including major revisions to the FAA's flight certification process. As such, workforce management and safety cultures will need to adapt to these new technologies and challenges. Participants in the NAS must prepare by adopting new technologies and training its workforces to ensure the highest levels of safety and efficiency.

In addition to workforce and cultural shifts, NASA has identified the following key paradigm shifts that will transform today's aviation system:

- 1) Sustainable aviation actualized through breakthroughs in electrified engines and next generation propulsion technologies, new fuels, and improved operational efficiencies
- 2) Seamless skies and integrated and cooperative airspace
- 3) Ubiquitous operational resiliency enabled by distributed, in-time collaborative decision-making and uncertainty management with widely accessible information and tools
- 4) Operational interoperability and flexibility for increased access
- 5) Tailorable and scalable diverse operations
- 6) Adaptive and resilient continuous learning-based systems or systems that acquire and synthesize system-wide knowledge and capability to adapt and evolve to the pace of technological innovation
- 7) Accessibility and enhanced mobility for all users

V. In-Time Aviation Safety Management Systems

The current overarching Safety Management System (SMS) has significantly enhanced aviation safety by addressing accidents and incidents with reactive and proactive strategies. However, new operational concepts as described previously present unique safety challenges. The thesis of this paper is that safety management must evolve to include a predictive capability in the SMS, enabling it to adapt to these upcoming complex changes that will likely increase safety assurance demands in the future NAS.

The evolution of SMS may be achieved through the IASMS ConOps, which is not intended to replace SMS but rather is an advanced implementation of the ICAO SMS framework. This ConOps includes technological advancements, new safety assurance processes, and next generation in-time safety management systems. The objective is to evolve current SMSs, making them more responsive, extensible and, scalable, tailorable, integrated, and assured. These systems should be capable of quickly evaluating existing patterns and identifying new ones in diverse data sets through reactive, proactive, and predictive safety intelligence. They should also provide mitigations, ranging from advisories and alerts to autonomous actions. The IASMS is intended to help make this in-time safety capability possible.

As previously discussed, NASA's Strategic Implementation Plan for aeronautics Thrust 5, "In-Time System-Wide Safety Assurance," adds further clarity on NASA's research planning, which is complementary to FAA's Info-Centric NAS vision. Key elements for System-Wide Safety involve: (a) domain-specific in-time safety monitoring and alerting tools; (b) adaptive in-time safety threat management; and (c) integrated predictive technologies with domain-level application. Utilizing substantial big data resources, in-time safety mechanisms enable the proactive and predictive detection of indicators, precursors, and anomalies and provide timely notification to stakeholders through established protocols to mitigate hazards and threats in-time.

The IASMS ConOps meets the need described in NASA's Strategic Implementation Plan Thrust 5 by focusing on the goals of a proactive, predictive, adaptive, and resilient system for managing safety risks in-time [40]. This system integrates advanced hazard detection and evaluation capabilities, enabling reliable and dynamic multi-agent planning, evaluation, and execution of immediate risk mitigation in response to emerging hazards.

The transformation of SMS to IASMS involves the following system objectives that were preliminarily defined [46] and evolve as the concept is matured through the integration of research in the SWS project at NASA [3, 4, 7, 8, 15, 24, 28, 46, 47]:

- 1) In-time: IASMS will improve the responsiveness of SMS with faster detection, identification, and mitigation of known hazards and emergent risks.
- 2) Effective: IASMS will improve the mitigation efficacy of SMS for specific risks or classes of risks.
- 3) Tailorable: IASMS will tailor standards, flight rules, and services based on the operator mission, aircraft, and airspace. The IASMS will be open and extensible to address new risks or hazards as/if they are discovered.
- 4) Interoperable: IASMS will facilitate interoperability and data sharing between the FAA and different operators, service providers, original equipment manufacturers, and existing relevant information systems and services.
- 5) Scalable: IASMS will scale for differently sized operations—from fleet operations to single pilot and uncrewed aircraft.
- 6) Assured: IASMS will provide in-time SA and resiliency in abnormal situations and applies run-time assurance/verification techniques.
- 7) Teaming: IASMS will improve the design and operational use of the human within-the-loop, on-the-loop, or over-the-loop automated safety systems with transparent, trustworthy, and resilient human automation/autonomy/machine teaming (HAT).
- 8) Value: IASMS will support the safety business case for obtaining FAA certification and public acceptance.

R&D is one critical enabler for new and/or better ways to (a) monitor, assess, mitigate, and assure safety (e.g., evolved safety management systems using advanced data analytics), (b) perform verification and validation (V&V), (c) and provide methods to certify new autonomous systems in the future NAS. Both the FAA and NASA future NAS visions provide for these needs through in-time integrated safety management, tailored safety processes, interoperable safety systems, and safety assurance.

A. Hazards and Sample Mitigations

FAA Order 8040.6A, Unmanned Aircraft Systems (UAS) Safety Risk Management (SRM) Policy [48] documents higher-level categorization of hazard types and mitigations. These hazard types and sample causes and mitigations are shown in Table 4.

IASMS complexity scales along multiple dimensions. A higher-level notional characterization of complexity involves four factors including aircraft flight management ranging from simple closed loop pilot operations to increasingly complex m:N managed flight, autonomous flight, and autonomous fleet management [28]. The environment factor corresponded to how well hazards were known and predictable, with complexity increasing due to factors like inclement weather, signal interference, rogue aircraft, temporary flight restrictions, and cyber threats. Airspace complexity ranged from simple, dedicated airspace to segregated airspace, such as for UTM and ATM, to fully mixed airspace. Contingency management would be least complex when managed by the human and become increasingly complex automated management with human fallback, autonomous human over-the-loop, and fully autonomous contingency management.

B. IASMS Roadmap

The Flight Safety Foundation (FSF) developed an IASMS roadmap identifying long-term research needs for higher-level evolution of IASMS capabilities through 2045 [49]. The roadmap translates various future operational concepts to identify research needs for IASMS evolution including capabilities, technologies, standards, and policies. Additional research is needed to develop design and operational safety assurance processes especially for automation that informs or makes operational decisions.

Table 4 Hazard types and samples causes and mitigations for UAS (adapted from [48]).

Type	Definition	Sample Causes	Sample Mitigations
Technical issues with UAS	Malfunction of any technical component of the UAS that causes a deviation from planned operations	<ul style="list-style-type: none"> - Monitor failure - Software failure - Lost link - GPS failure - Flyaway - Geofence failure - Battery/power failure 	<ul style="list-style-type: none"> - Competent applicant/operator - UAS manufactured by competent or proven entity - UAS developed to authority recognized design standards - UAS preflight checks - Validated operational procedures - Remote crew trained and current - Ground population density - Parachute or frangible aircraft
Deterioration of external systems supporting the UAS operation	Malfunction of any component that is not a part of the UAS but supports safe operations	<ul style="list-style-type: none"> - ADS-B signal degradation - GPS signal degradation - UTM failure - Package delivery system failure 	<ul style="list-style-type: none"> - Procedures are in place to handle deterioration of external systems - UAS is designed to manage deterioration of external systems - External services supporting UAS operation are adequate
Human error	A person's mistake causes a deviation from planned operations	<ul style="list-style-type: none"> - Pilot errors - Maintenance errors - Pre-flight planning errors - Flight into unplanned weather - Misloading of cargo or package 	<ul style="list-style-type: none"> - Operational procedures are defined, validated, and followed - Multi-crew coordination - Automated protection of flight envelope from human error - Safe recovery from human error - Human-machine interaction found appropriate to the mission - Crew resource management practices
Adverse operating conditions	Unintentionally operating into or within conditions that causes the UAS to deviate from planned operations	<ul style="list-style-type: none"> - Un-forecasted weather - Reduced visibility 	<ul style="list-style-type: none"> - Remote crew trained to identify environmental conditions and to avoid them - Environmental conditions for safe operations are defined, measurable, and followed
Unable to detect and avoid (DAA)	BVLOS operations and UAS design give the aircraft a limited ability to sense intruding aircraft and yield right of way	<ul style="list-style-type: none"> - Transponder failure - Communications failure - Traffic conflicts helicopter routes - Low altitude, GA operations - Crewed aircraft unable to see sUAS 	<ul style="list-style-type: none"> - Visual observers communicate with pilot - DAA system - Restricting operations within certain airspace boundaries or volumes - Proximity to structures - UTM

The following, as a higher-level summary of the roadmap, are highlights of its major sections and the key capabilities expected to be developed by 2045, along with their operational uses.

- 1) Safety data and resilience analysis – Autonomously identify and mitigate emerging safety risks at pace with the tempo and density of operations. IASMS autonomously monitors airspace, assesses, and identifies elevated risk states, and mitigates emerging risks through safety assurance action for both traditional operations and new entrants during airside and surface operations.
- 2) Strategic conflict management – Autonomously manage flexible airspace volumes and operations with strategic conflict and separation management. IASMS evaluates whether aircraft meet performance requirements within airspace boundaries, in environments that involve both human-managed and autonomously managed operations, such as space launches and reentries. IASMS forecasts safety levels considering traffic levels and complexity including adjustments for failure conditions.
- 3) Tactical separation management - Autonomously manage tactical separation for large transport and AAM operations. IASMS employs reliable, trusted automation for tactical separation management among most aircraft, including large passenger and cargo transport aircraft, with some autonomous systems operating with the human out-of-the-loop.
- 4) Individual aircraft flight management – Autonomously manage gate-to-gate aircraft operations. Aircraft certified for carrying people and/or cargo or performing advanced operations automatically adjust flight paths to avoid aircraft or hazards and complete flights with the pilot or operator on the ground intervening in certain error conditions.
- 5) Aviation weather – Weather information based on infrastructure, modeling, and data support safe aircraft operations. IASMS involves microclimate weather forecasting tailored for certain urban areas, and enhanced weather forecasts for Upper Class E airspace operations.

The IASMS roadmap identified a sixth area focused on detailed cross-cutting topics with broad applications or implications for system design. These include cybersecurity, acceptable levels of risk for new operations, HAT, and (V&V) and assurance of autonomous aviation systems. FSF’s industry-vetted IASMS roadmap exists to facilitate industry-wide R&D coordination to meet operational and design safety needs of a transformed NAS.

C. Monitor-Assess-Mitigate-Assure

Safety risks can stem from monitoring operational data for any known hazard and emergent risk, assessing that data for patterns in precursors, anomalies, and trends, mitigating a hazard when a risk threshold is reached, and assuring the efficacy of controls. Safety risks can manifest as concerns already known to designers and operators and can be detected and mitigated by safety assurance systems (known knowns). On the other hand, emergent risks may be unknown to designers and operators, but the system detects an abnormality in data (unknown known). However, safety assurance systems can apply AI to better detect, understand, adapt to, and manage such abnormalities. There may also be risks that designers or operators recognize that are beyond the scope of detection and mitigation by safety assurance systems (known unknowns). Lastly, designers, operators, or safety assurance systems may not recognize unforeseen risks (unknown unknowns) and require further discovery [46]. To identify safety risks arising from patterns in precursors, anomalies, and trends in new data types and increased data volume, SFCs will enable proactive/predictive safety management with its new data analytical methods and innovative approaches to system safety thinking. Based on the National Academies recommendation for development of an IASMS ConOps, high level functions of monitor, assess, and mitigate, form the framework for in-time safety management and the function of assure was added to address operational SA [8, 50].

These functions include domain-specific safety monitoring and alerting tools, integrated proactive/predictive technologies with domain-level applications, and safety risk management. Safety assurance systems are required to enable predictive safety management with new data analytical methods and innovative approaches to system safety thinking that identify safety risks arising from patterns in new data types and increased data volume.

The monitoring function observes and characterizes the system state by collecting, fusing, and assessing data from a variety of sensors. Monitoring is conceptualized as a set of information services and an underlying architecture

that allows for acquisition, integration, and quality assurance of heterogeneous safety-relevant data that may come from a diverse set of sources (including aircraft) [8, 51].

The assessing function enabled by sophisticated data analytics and proactive/predictive modeling identifies and characterizes known hazards risk states in the time frame of interest to an IASMS. That is, the assessing function examines large volumes of stored flight and ground operations data with anomaly detection methods to identify and assess hazards compared to risk thresholds and the overall safety margin based on the current operational context, transitioning of event sequences, and longer-term trends, followed by updating IASMS risk assessment algorithms [8, 51].

The mitigation function has been operationally defined as “a set of methods, tools, and procedures that provide for multi-agent or automated planning and execution of timely responses to hazardous events or event sequences when/if safety margins are observed or are predicted to deteriorate below acceptable levels” and must be accomplished in-time [8, 51].

The assure function involves monitoring system data to identify known and potential new hazards, ineffective or inadequate safety risk controls, and cases of operational nonconformance with risk controls [46]. When controls are found inadequate, the controls would be modified and/or additional controls developed through SRM. IASMS aims to collect, analyze, and assess data and information that is in-time relative to the nature of safety risk, and assure efficacy of hazard controls.

D. Services, Functions, Capabilities (SFCs)

SFCs make up the underlying foundation of monitor, assess, mitigate, and assure functions. A *service* uses safety-relevant data or information to prevent or contain a hazard before it can cause harm [51, 52, 53]. The emergence of hazards during the design or operational phases highlights the need for a service to manage them. Services can be provided by the aircraft, a UAM/UTM/ATM system, or other agents in the architecture. The data or information used in a service will be generated at a remote site and available for operational use. This presumes the data or information needed or useful to the operation is available from a service provider or remote server such as via “request-reply,” “publish-subscribe,” and/or “broadcast.”

A *function* is the action(s) required of automation or autonomy, increasingly automated or autonomous systems, and pilots or other human operators [51, 52, 53]. Functions integrate streams of data and information to determine the necessary steps and timing to prevent or contain risks and apply proactive/predictive analytics for emergent indicators, precursors, anomalies, and trends from system-wide performance data. Functions translate a set of inputs to a desired set of outputs such as for producing safety-relevant metrics and reside in ground stations and onboard systems.

A *capability* is the ability to perform or achieve certain actions or outcomes having safety-relevant benefit [51, 52, 53]. A capability uses technology including sensors and models to detect, validate, generate, and distribute information and data across network architectures. A capability may involve a service(s), function(s), underlying system, and human involvement, with procedures, training, and an interface for any required human involvement.

Many SFCs are in some form already used in conventional operations with today’s aircraft while more advanced versions and new SFCs are anticipated in future IASMS designs. These SFCs can operate pre-flight, in-flight, and post-flight phases depending on what purposes they serve in addressing hazards. Pre-flight SFCs would automatically assess flight plans to identify necessary changes such as for forecast adverse weather, notify the pilot/operator about these changes, and inform go/no-go decisions. In-flight SFCs assess hazards and either initiate mitigations automatically or inform the pilot/operator of recommended changes in-time. Primary functions include real-time risk assessment, constraint monitoring, and contingency selection and triggering. Post-flight SFCs fuse data off-line across selected flights and apply analytical modeling to identify known and emerging anomalies and trends and updates to pre-flight and in-flight SFCs to improve their effectiveness. SMEs review and interpret results of post-flight analyses to identify safety concerns such as changes in operational procedures.

As applied to UAS, one suite of SFCs consisted of 10 services, 11 functions, and 12 assessment capabilities (does not include monitoring capabilities) [51]. Other researchers have developed and tested additional SFCs, some of which may be proprietary.

E. IASMS Architecture for FAA’s Modernization Efforts

The IASMS is the network of integrated safety management services that produce and use data from aircraft, airspace management, operational procedures, operational and data standards, and environmental information from various sources [54]. The key services will manage, distribute, and apply data from central agents and external services. An example was developed to illustrate the software architecture, information requirements, and SFC safety software necessary to assess and predict flight safety risks during highly autonomous urban flight operations [51]. The SFCs used in this IASMS architecture can be shown to address the sample hazard mitigations identified by the FAA for UAS operations in Table 4 [54].

VI. Safety Intelligence

As the NAS grows in complexity, current and future aviation safety issues require synthesizing different current types of safety, typically framed as reactive, proactive, and predictive safety thinking. This evolution relies on the development of innovative techniques and tools for identifying intricate and sometimes weak patterns and detecting emerging risks in a manner reflected by in-time safety management [55].

Today, SMS data collection, extraction, and interpretation is a very laborious, time-consuming process that, in the highly dynamic and quickly changing environment of commercial aviation, is inefficient and unwieldy. Forecasts, leveraging big data, project system-wide safety risks to become less manageable in the not-too-distant future. Current limitations may come into sharper focus as future SMSs (e.g., for new entrants) are implemented and the IASMS ConOps addresses those potential challenges. The opportunity to take advantage of the wealth of these data is apparent, but if not addressed now, effectively using these big datasets for data-driven safety decision-making will become increasingly challenging. The potential for mass data fragmentation could unintentionally lead, for example, to new safety events going undetected, safety blind spots triggering unexpected safety critical events (accidents/incidents), or the failure to recognize weak signals as hazards or threats.

In response to these new risks, the international aviation community has called for harmonizing and the standardizing safety information management through the concept of “safety intelligence.” This concept advocates the use of novel advanced ML-based data analytics and mining methods, tools, techniques, and approaches [e.g., 55, 56]. In part, the IASMS is intended to help meet this need and enable in-time integrated proactive/predictive safety management for aviation operators and regulators. ML will be instrumental in implementing SFCs and enabling proactive/predictive safety management. Autonomous data analytics may include future methods to automatically mitigate and assure against risks identified by both humans and machines working together as part of a hybrid intelligence symbiotic partnership. In this symbiotic relationship, each side contributes and each of these contributions may adapt and evolve over time as proactive/predictive safety intelligence SFCs develop and mature. How this hybrid intelligence partnership between humans and machines actualizes remains a relatively nascent topic requiring significantly more R&D investment; research may provide a means to achieve in-time, integrated safety management through more advanced methods of generating complementary reactive, proactive, and particularly in-time integrated predictive safety management resulting in data-driven-informed safety intelligence.

A. Reactive and Proactive Safety

The airline SMS was originally developed as a purely reactive measure to address safety events that had already occurred and typically draws lessons from a relatively small set of accidents and incidents. These narrow datasets hamper the system’s ability to apply these lessons broadly to daily operations. Since the adoption of Annex 19, however, the aviation safety community is increasingly adopting proactive safety management strategies that seek to anticipate and mitigate risks before they manifest [55].

The proactive SMS differs from its reactive counterparts in its ability to identify and address potential risks before they lead to incidents. The primary goal of a proactive SMS is to identify early warning signs, anomalies, and potential causative factors using data markers, analyzing system behavior, utilizing passive sensors, and applying human performance models. By leveraging leading indicators, the proactive SMS can enhance safety by evaluating

underlying risk factors and precursors to build a system for predicting and preventing future risks. This approach is designed to prevent unsafe conditions and operations.

Proactive approaches involve analyzing a much wider array of safety operational data, including historical records and latent information from past accidents, incidents, and other safety-related events. Prominent examples of data-driven proactive SMS initiatives are LOSA, ASAP, and FOQA [18].

ICAO Safety Management System document 9589 and SARPs contained in Annex 19 already provide provisions for the use of: a) proactive safety activities to collect safety information and safety data; b) proactive methods for hazard identification; c) predictive safety indicators focused on processes and activities to improve and maintain safety; and d) predictive analysis based upon current operations [12, 15]. The capability to fully identify safety indicators, including use of new data types, and perform predictive analyses, are not yet realized. However, NASA and others in the data science research community are making significant progress in developing new data processing and ML-enabled data analytics methods, along with related supporting SFCs.

B. In-Time Predictive Safety Management

The goal of predictive safety is to quickly identify data patterns that could predict adverse events before the next safety incident occurs. ICAO Safety Management System document 9589 and SARPs contained in Annex 19 already provide provisions for the use of predictive safety indicators focused on processes and activities to improve and maintain safety [12, 15]. The capability to fully identify safety indicators, including use of new data types, and perform predictive analyses, are not yet realized. However, NASA and others in the data science research community are making significant progress in developing new data processing and ML-enabled data analytics methods, along with related supporting SFCs. These breakthroughs are instantiations of in-time predictive safety management [55, 56].

This forward-looking approach leverages data analytics to enhance actionable safety intelligence and risk visualization beyond the conventional forensic and reactive safety measures. Predictive safety management provides timely identification of potential risks within a specific context and anticipates the requisite risk-mitigation measures. Concurrently, proactive safety management focuses on the identification of root causes that may lead to hazardous occurrences and deviations in operational practices from nominal patterns or procedural requirements. In contrast, reactive safety management scrutinizes the specific causal and contributory factors behind an incident or accident, encompassing both design and operational phases. Subsequently, reactive safety management formulates measures to diminish the likelihood of those factors culminating in subsequent incidents or accidents [46].

Modern SMSs seamlessly integrate reactive and proactive safety management, leveraging actionable data to yield data-informed approaches that systematically assess safety events and conditions in real-time. However, contemporary SMSs face significant challenges due to the massive increase in data volume and the escalating complexity and uncertainty of the factors influencing contemporary safety paradigms. Predictive analytics within the future IASMS leverage sophisticated ML methods and techniques for data-driven anomaly detection. Amalgamating data-driven anomaly detection with expert insights from domain specialists about the operational significance of identified off-nominal conditions is expected to prove effective in discerning operationally significant anomalies during operations and developing comprehensive explanations for them. Furthermore, precursor identification methods facilitated by domain experts (e.g., through active learning) can identify antecedents to known undesirable safety events and predict and mitigate events before they present. The predictive capability does not yet exist as practiced with today's SMSs but will be an essential component of IASMS. These ML-enabled data analytical capabilities are a cornerstone for advancing safety intelligence and serve as a crucial enabler for in-time integrated safety management that IASMS will make possible.

Predictive safety management focuses on recognizing potential risks in their native contexts and determining necessary risk-mitigation measures. The growing demand for digital data in predictive analytics and ML is not just about enabling new operations; it is likely to become a necessary requirement for all NAS operators in the future.

Traditional operators (e.g., Part 121, 135) and OEMs who have SMSs or similar safety systems must be included (e.g., ISO SMS [57]) to transform the future aviation system safely.

A premise of IASMS, and future NAS visions, is that every operator will need to tailor a safety strategy to effectively leverage the expected increase in data volume, employing an architecture specifically crafted to enhance accessibility and facilitate data aggregation and fusion. These strategies should exploit opportunities arising from inventive data analytical methods and novel perspectives on system safety. Regulators like the FAA and European Union Aviation Safety Agency (EASA) and safety organizations (e.g., ICAO) have a similar need. For example, the FAA has incorporated the three distinct ways of safety thinking into policy guidance—that is, reactive, proactive, and predictive [58]. ICAO, in the currently pending Amendment 3 to Annex 19, emphasizes development of safety intelligence to maintain and continuously improve the effectiveness of safety programs [59]. Guidance is expected that will provide strategy for development of safety intelligence [60].

C. Safety Intelligence and IASMS

The NASA SWS project’s leading-edge efforts include developing unique SFCs [61], innovative V&V methods [62], tailored ML/AI-based data analytic methods [57], digital data platforms made available system-wide, newly forming model-based system engineering (MBSE) safety management system architecture requirements, and novel means to certify future autonomous systems.

The IASMS offers a unified approach for operators to create a safety intelligence vision and “learn from all operations” [63]. This approach aligns with the fundamental components of the ICAO SMS and presents new opportunities to enrich the pool of data available to various data repositories. These data can be used to enhance risk management and safety assurance processes by providing valuable insights and lessons learned on how to mitigate risks in similar circumstances. In the IASMS ConOps, safety information and data sharing are more widely promoted among all involved parties, spanning from the FAA and Aviation Safety Information Analysis and Sharing (ASIAS) to ICAO, IATA, and other stakeholders.

Safety intelligence, especially proactive predictive safety intelligence, is a pivotal component of the IASMS. In the developing AAM ecosystem, challenges and opportunities underlie the complex role of safety intelligence and safety performance management and continuous safety improvement. Using safety data and information to evaluate what is and what is not working in a system is an essential management practice. AAM domain considerations include identifying the main steps in continuously improving systems and processes, how collection and sharing of safety intelligence contribute to proactive safety improvement, and how AAM stakeholders can use safety performance management to improve safety.

The purview of predictive safety intelligence is broad and primarily includes identifying and prioritizing applications and improvements for predictive analytics and prototype data decision dashboards. Such capabilities further empower human safety intelligence and continuous learning from all operations, thereby enhancing human and machine diagnostic sensitivity across the spectrum of SMS applications. This approach bridges IASMS with safety policy and safety promotion, fostering more effective advancement of organizational continuous learning strategies aimed at proactive and predictive safety intelligence. New emergent operators and those that may be required to have SMS in the future (e.g., UAM operators [20]) can utilize tailorable and scalable SFCs and architectures that enable better interoperability across all actors and stakeholders. Research on practical implementable ML methods, tools, and techniques requires continued investment. NASA is actively collaborating with partner organizations to build on the existing body of both NASA and non-NASA ML work and develop in-time predictive safety management [64].

VII. Challenges and Opportunities

Over the past decade, there has been profound growth in the development of aviation technologies leveraging AI, including more sophisticated sensors, high-performance acceleration hardware, and innovative computational architectures. Substantial investments from both industry and government in autonomous systems—such as UAS—have further propelled the development of advanced autonomy and highly automated systems. The anticipated autonomy capabilities offer up much opportunity to reimagine how aircraft will fly tomorrow and what new missions

and operations will become possible. Technological advancements will yield opportunity in critical areas including perception, localization, mapping, planning, and control. However, reaching these goals will require breakthroughs in enabling technologies. Some advancements, such as ensuring safety involving V&V systems, will prove most challenging [62].

The shift towards a data-driven learning paradigm and the transition from human-operated to autonomous systems present significant challenges. These include human factors, system interpretability, formalization, specification, V&V, and certification. Traditional methodologies previously used in aviation that focused on system behavior were found insufficient and have been replaced by data-centric performance-based approaches. Proactive and predictive in-time approaches will ensure both design and operational safety. A significant challenge is keeping up with the rapid pace of innovation, as the envisioned transformation must align with progress already achieved. This impacts every aspect of current technological pathways for future airspace modernization, all while ensuring design success and safety.

Consequently, there is an urgent need to examine how autonomous systems can solve some of these challenges, address R&D gaps, and create solutions that support the safety-critical functions, all while still keeping humans in-the-loop. Although new technologies bring opportunities for achieving design goals, they also introduce potential risks to the NAS. Thus, while there is considerable potential in technology-focused R&D, investments must be balanced to address the shifting roles of humans and the safety challenges posed by the future's highly complex, interconnected airspace ecosystem.

A. Human Factors

The IASMS emphasizes in-time collaborative decision-making and execution, utilizing human factors to help inform design and ensure optimal performance. Human factors considerations for a multi-agent adaptive and resilient safety system include continued human-centered design principles, paradigms for HAT, identifying human contributions to safety, “learning from all operations,” and translating insights and learnings to build predictive safety intelligence. A NASA SWS paper presented at SciTech 2024 provided an assessment of key human factors R&D gaps focused on design and operational challenges such as new human roles and responsibilities, new information and cognitive requirements, intelligent technologies that change human-system interaction and coordination, and new design paradigms for human-system integration and teaming [46]. Additional research topics identified in the paper included how new types of interactions might reveal knowledge gaps in the design of IASMS, how safety dashboards could be tailored to accommodate information requirements of decision makers, how time critical information should be pushed to the display even if it disrupts whatever was being displayed at that time, and how training and education should be scaled relative to the level of understanding needed of the underlying analytical models. NASA further explores human factors and safety in human-autonomy interaction through the lens of V&V requirements and methods to certify and assure these systems in future [62].

B. Verification & Validation

V&V and certification remain key challenges to the fielding and usage of increasingly autonomous systems in safety-critical contexts within the future NAS. These issues involve several barriers such as: (a) most existing methods are insufficient for assuring advanced autonomous systems; (b) current certification criteria, processes, and methods do not address critical aspects factors, such as the potential for non-deterministic behavior; and (c) safety standards and requirements must include all safety considerations, including those not directly tied to operations, such as the safety of people on the ground beneath the flight path. Promising solutions include runtime assurance and verification techniques, formal methods and analysis, and advanced simulation, testing, and evaluation. Still, it is difficult to properly measure their potential or assurance efficacy [50, 62].

A team from NASA, FSF, industry (Boeing, Collins Aerospace, and General Electric), and academia (University of Michigan, University of Texas, and Massachusetts Institute of Technology) collaborated to publish the comprehensive “Autonomy Verification and Validation Roadmap and Vision 2025” to inform future investments and standardization efforts in autonomy, aerospace systems, and assurance of AI systems and accelerate progress in the safety of autonomous aviation [62]. The roadmap defines a comprehensive list of verification challenges and needs

for autonomous aerospace systems, an R&D path to meet those needs, the services they can enable, and the certification gaps they can fill. The roadmap provides guidance and potential directions for future V&V technology investment, planning, and development and integrates expertise and experience, national and international research strategies, industry needs, and certification requirements. The scope of the roadmap encompassed representative use cases and autonomous functions in modern autonomous systems that could operate in the envisioned future NAS. The following research questions were promulgated based on assessment of anticipated changes and the enabling technology required to make the vision a reality:

- 1) What new technologies are needed to enable increasingly autonomous air services?
- 2) What limitations do current V&V capabilities have with respect to these new technologies? For example, are current testing techniques sufficient for deploying ML-enabled systems?
- 3) What are the gaps with current certification standards (such as DO-178C) in failing to address assurance needs for these new technologies or considering V&V results with these technologies?
- 4) What role can new certification approaches, such as safety cases, play in the certification of increasingly autonomous systems?
- 5) What paradigm shifts in the existing regulations are necessary to implement new certification approaches?
- 6) How will the assurance of cyber-physical-human systems need to change to accommodate shifting roles and responsibilities between humans and automation? What new technologies will be required to assure anticipated systems architectures? How will we account for the implicit contributions to safety that are provided by humans in today's systems?

A variety of assurance challenges remain unresolved for new aircraft and systems under development. These challenges pose significant barriers to innovation and achieving envisioned transformations to the NAS and its operators and operations. Many of the envisioned capabilities will depend upon AI technologies to support autonomous operations and enable advanced aircraft functions, yet neither autonomous operations or AI-based systems are addressed within current assurance frameworks. Over time, however, demand will increase for new verification technologies and associated certification guidance, such as run-time assurance methods.

These challenges have been categorized into the following R&D areas: (a) autonomy software; (b) contingency management systems; (c) safety in human-autonomy interaction; (d) verification factors and trade-offs; (e) UTM for autonomous aircraft; (f) MBSE for AI; (g) run-time assurance; (h) AI certification; (i) ML V&V; and (j) general autonomy software certification. Identified research priorities have been grouped by short-, mid-, and long-term time horizons [62]:

Short-term Research Priorities (1 – 5 Years)

- Open case studies to develop and demonstrate how ML-based systems or components can satisfy emerging certification guidance to remove uncertainty, establish expectations, and improve communication among stakeholders (applicants and regulators). This is analogous to an effort undertaken for formal methods assurance tools and certification guidance following publication of DO-333 [65].
- Test generation and coverage metrics for ML-based systems (neural networks in particular) should provide a replacement for the structural coverage and model coverage metrics used in traditional software systems. A test completeness metric that is effective for fault-finding and provides confidence in the absence of unintended behaviors could then be considered for incorporation in ML certification standards.
- Run-time assurance (RTA) can limit or prevent unintended behaviors in some systems and address scalability limits for systems beyond the capabilities of current analysis tools. Develop case studies that integrate RTA into real system designs demonstrate how to satisfy the specific objectives of current and new certification guidance.

Mid-term Research Priorities (6 – 10 years)

- Researchers develop new methods and tools to demonstrate that training and verification datasets are complete and representative with respect to the operational design domain (ODD) of ML-based systems.
- To build large, complex systems, RTA architectures must contain many different monitor and mitigation subsystems to identify and control risk. New methods ensure that interactions among monitor and mitigation controls are not in conflict. These methods must be integrated with current standards and certification practices for design and safety analysis.
- New methods, languages, and tools are needed for specifying requirements for vision-based systems. This research could include scenario-based methods for ODD specification, validation, and coverage. These methods, languages, and tools will support completeness/representativeness objectives for datasets, verification of functional correctness, and absence of unintended function.
- Research is needed to dramatically improve the scalability of formal analysis tools (for property verification, robustness, and reachability). These tools may include combinations of exact and approximate analysis methods.

Long-term (10 - 25 years) Research Priorities (10 – 25 years)

- Trustworthy vision systems based on ML may require a completely new approach. Neuro-symbolic AI integrates neural and symbolic mechanisms to address complementary strengths and weaknesses of each. This research results in a robust system capable of reasoning, learning, and cognitive modeling. Neuro-symbolic or “hybrid AI” research may eventually lead to vision systems whose behavior flows from symbolic methods.
- Learning during online operations must safely integrate into an ML-based sensing or control system. Dynamic or incremental assurance methods that produce (and assess) assurance evidence during system operation work toward this goal.

Future assurance process solutions and elements identified by NASA involve the challenges of developing and assuring autonomous systems. The necessary assurance process elements include, but are not limited to, the following [66]:

- 1) Applying an assurance-centered development process that documents the justification for having sufficient confidence in the essential systems attributes, using an assurance case that drives the system’s development process.
- 2) Characterizing and defining the operational design domain.
- 3) Applying formal methods for requirements development to encourage adequate specification of these requirements, enable requirements validation and analysis, and enable the creation of test cases.
- 4) Applying resilience modeling, simulation, and analysis techniques to enable the iterative analysis of operational safety over a wide range of operating environments.
- 5) Applying adaptive stress testing techniques to verify and validate the system over a wide range of operating environments.
- 6) Applying statistical frameworks for black-box and white-box analysis of autonomy-enabling components.
- 7) Using abstractions to obtain formal safety guarantees about autonomy-enabling components.

The FAA safety assurance roadmap for artificial intelligence addresses these and additional considerations for the application of artificial neural network (ANN) models [67]. For example, when differentiating between safety assurance methods for static AI implementations (such as ML algorithms developed and verified through offline training) and dynamic AI implementations (which continuously learn and adapt in real-world environments), the latter requires a safety assurance strategy that specifically addresses the learning process itself. That is, learning systems can pose a safety concern when learning from anomalous, ungeneralizable, incomplete, or inaccurate information and adapting in a manner that degrades performance.

The solution set addresses the challenges of conceptual architecture development, safety assessment, requirements development, and those involving V&V, assurance, and certification, specific to shifting responsibility from human to automation [61]. The scope and complexity of the problem are immense within the broader design and operational safety assurance context. Some of the areas identified in these roadmaps are being explored by NASA,

and planning for future research and development will be aligned to the steps described in them [55]. These considerations may arguably be the key limiting factors on what technology is even possible and how it may be used in a future air transportation system.

VIII. Conclusion

The future NAS will be characterized by transformative changes in how aircraft operate, what missions they perform, and how people and goods travel in the NAS. The FAA’s approach integrates operational improvements for current users and accommodates the growth of new operators and their missions within the NAS. It establishes a framework that allows the NAS to adopt new technologies and evolve with the changing ecosystem. Data sharing is essential for interoperability in the NAS, enabling an efficient, equitable, and fair system while ensuring system-wide safety. An integrated information environment processes and shares data to facilitate collaboration, distributed decision-making, and interoperability among traffic management services and NAS users. Progress in cybersecurity protects information integrity, and increased network diversity ensures consistent and continuous service for all operations. An IASMS is paramount; without IASMS, it is possible, if not probable, that increased operational volume, complexity, and introduction of new technologies will unintentionally introduce unforeseen demands and new risks. The IASMS addresses this imperative through in-time risk management and safety assurance capabilities involving an extensible, scalable, and tailored integrated safety technologies that monitor, assess, and mitigate operational risk with assured controls. Such future safety systems must quickly evaluate existing patterns and discovering new ones within diverse data sets. They should employ reactive, proactive, and predictive safety intelligence to provide mitigations that range from advisories and alerts to autonomous actions.

IASMS, as an integral part of revolutionary changes forecasted for the future NAS, is an advanced implementation of the ICAO SMS framework that addresses risk in-time to prevent accidents and incidents, enabling a new safety paradigm in the NAS when viewed through the FAA’s airspace modernization lens. To achieve NAS modernization, safety must transform proportionally and scale with new operations and technologies. IASMS will evolve beyond today’s SMS to provide more predictive safety intelligence and the requisite system-level SFCs to address identified safety hazards and emergent concerns that could pose real or potential critical risks in the future NAS. IASMS is not a singular design for a one-size-fits-all monolithic system-of-systems. Key challenges necessitating SMS evolution with IASMS include:

- 1) Interoperability and other challenges of new and emergent operations integrated with legacy operations,
- 2) Complex multi-variate collaborative autonomous aircraft and traffic management systems,
- 3) Aviation safety implications of forecasted advancements and the increased introduction and use of ML and AI more broadly.

One potential outcome of technological advances is the emergence of new roles and responsibilities for humans and machines. This may lead to multi-agent adaptive joint-cognitive systems, as well as new challenges and unknown complexities for humans and machines including emergence of new and changed roles and responsibilities. These systems pose new burdens and unknown complexities for humans and HAT [46].

NASA’s IASMS ConOps identifies potential new human-system dynamics in future airspace, aircraft, and safety data/management systems and helps human operators understand the risks such changes may introduce. Research will further explore the safety implications of shared responsibilities between humans and automation for monitoring, assessment, mitigation, and assurance against hazards and risks in future integrated SMSs of high consequence and complex NAS operations. The IASMS research roadmap identified gaps and future directions [49].

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