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Gap Analysis for the Development of an IASMS for Commercial Aviation Operations

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Introduction

An In-time Aviation Safety Management System (IASMS) [1,2] is a set of services, functions, and capabilities (SFCs) necessary for monitoring known hazards and emergent risks, assessing safety data for anomalies, precursors, and trends, mitigating hazards that reach safety thresholds, and assuring efficacy of controls in mitigating hazards. An IASMS will continually monitor the National Airspace System (NAS) to collect data on the status of aircraft, air traffic management (ATM) systems, weather, and airports. The NASA Aeronautics Research Mission Directorate (ARMD) System-Wide Safety (SWS) Project has a Sub-Project focused on a Technical Challenge entitled In-time Aviation Safety Management Systems (IASMS) for Commercial Aviation Operations, referred to herein as Technical Challenge 6 (TC-6). This Technical Challenge was initiated in fiscal year (FY) 2024 to accomplish research and development (R&D) of a prototype IASMS by FY 2028 that demonstrates its potential.

The TC-6 FY24 (Level 1 Milestone ID: TC6-01-01) research goals include 1) an IASMS research roadmap for 2035 and 2045 vision time horizons and 2) a safety management system (SMS) gaps analysis in collaboration with external stakeholders. In collaboration with SWS, the Flight Safety Foundation (FSF) published a roadmap [3] and Embry-Riddle Aeronautical University published a gaps analysis [4]. In response to three critical areas identified in the roadmap and analysis, the TC-6 research team has conducted work in data analytics, learning from all operations, and human performance (with emphasis on fatigue) to address research gaps. This report outlines the efforts made by the TC-6 team to surmount research barriers, achieve roadmap goals, and address the gaps identified in the analysis. By focusing on these areas, the team aims to enable both short and long-term impacts through future R&D to inform NASA's project planning and, potentially, influencing other projects.

Ultimately the SWS Project seeks to inspire operators as they evolve their current SMSs into analogous IASMS that make the best possible use of the significant investments that they already make in collecting, storing, and managing operational data. The efforts necessary to enable such evolution include outreach activities to increase 1) stakeholder awareness, 2) engagement with stakeholders within their SMS to reach mutual understanding, and 3) collaborative research with stakeholders that demonstrates the potential of their operational and safety data. This report describes TC-6 and larger SWS Project team efforts, which have resulted in numerous agreements and domestic and international partnerships. These cooperative efforts will continue over the lifespan of the TC-6.

IASMS Research Roadmap

NASA's SWS Project commissioned the Flight Safety Foundation to develop the "IASMS Research Roadmap Version 1; 2025-2045" [3]. This document addresses barriers to implementing the IASMS and suggests IASMS research to be done in five-year periods from 2025 to 2045 with general foci in each period. The work is divided into the three key high-level functions of an IASMS—monitor, assess, and mitigate—to provide a broad view of the IASMS research landscape. It is not intended to provide specific research plans or identify specific technologies. Instead, the research focuses on ways to provide stakeholders with a full, system-wide perspective and prioritization of research efforts based on nascent technological developments.

The key research areas described in the roadmap over the twenty-five-year period (2020-2045) are presented in Table 1.

Table 1: Key Research Areas

Years	Key Research Areas
2025-2030	Researching advanced monitoring capabilities for emerging air traffic technologies, like highly automated vehicles. Expanding data sharing for safety analysis across stakeholders, including new entrants and uncrewed systems.

2030-2035	Building real-time data aggregation and analysis for aviation safety. Using predictive analytics for assessing emerging safety hazards.
2035-2040	Integrating advanced automation in airspace management. Leveraging AI for real-time risk detection and automated mitigations.
2040-2045	Complete integration of autonomous risk detection and management for both traditional and new airspace operations.

The research suggested for 2025-2030 is aimed primarily at expanding the use of SMS and its capabilities to more stakeholders and helping distribute safety data more widely for analysis and risk mitigation. This work largely revolves around improving data collection, sharing, and analysis across different stakeholders, as well as sharing of safety assessment and mitigation practices and their benefits among stakeholders. Sharing such information with new entrants, such as advanced air mobility (AAM) operators [4], in addition to established aviation organizations, will become increasingly important. Accounting for increasing commercial space activity is also necessary.

The research suggested for 2030-2035 focuses on evolving ATM and other related systems to a fully machine-readable environment with greater real-time access to data. Research on adapting our safety metrics to include AAM and commercial space operators will be necessary. The Digital Twin paradigm [5, 6] is a growing are of research that holds great potential for assessing how proposed changes to the NAS may mitigate identified potential safety issues and whether they come with undesirable side effects. Cybersecurity is also a growing area of work that is becoming increasingly critical as the desire for increased autonomy in NAS operations increases alongside the number and variety of vehicles and operations.

In 2035-2040, the report anticipates that ATM will involve routine machine-to-machine communications requiring an integrated airspace that includes both human and human-autonomy managed operations. Researchers will seek to enable these increasingly complex and heterogeneous operations and the accompanying changes in human activities and human-autonomy teaming.

In 2040-2045, research in the NAS the NAS will be a highly automated environment that accommodates a mix of autonomously managed and human-managed flights in most of the airspace and airports. There will be a much greater volume and variety of data available by this time, and research is needed to develop predictive data analytics capabilities to handle them and provide in-time assessment of potential safety issues. Research is also needed to develop more sophisticated contingency management approaches to accommodate the greater variety of traffic and number of vehicles and both accidental and intentionally introduced safety issues.

The FSF IASMS Roadmap was intended to be a high-level roadmap that did not propose specific technologies that would help in the development of IASMS. Rather, it describes key research needs to support the evolution of IASMS capabilities between now and 2045. The NASA SWS Project is working on relevant technologies in-house and is funding the development of other technologies with industry and academic partners. Specific research needs identified in the roadmap are presented in Table 2. However, some technologies identified in the report, such as advanced computing platforms and techniques, will be developed by others outside the aviation community. The authors of this roadmap suggest updating it every one or two years to maintain relevancy. All who work on IASMS will need to maintain knowledge of the latest technological developments, assess whether they can be used to advance the goals of IASMS, and be ready to revise their IASMS R&D plans accordingly.

Table 2: Specific Research Needs for IASMS

Research Needs	Details
Safety Data and Resilience Analysis	Expanding safety monitoring beyond accidents to include routine operations data, leveraging predictive analytics for risk management, and increasing the resilience of aviation systems.
Conflict and Separation Management	Strategic conflict management through trajectory-based operations and automated separation management as air traffic becomes more complex.
Individual Vehicle Flight Management	Monitoring and managing both crewed and autonomous vehicle operations within shared airspace.
Cross-Cutting Research	Addressing system-level challenges such as cybersecurity, data governance, and integration of various ATM systems.

Safety Management System Gap Analysis

NASA's SWS Project TC-6 established a co-operative agreement with Embry-Riddle Aeronautical University (ERAU, NASA Grant Number 80NSSC23M0157) to permit collaborative research between NASA SWS and ERAU faculty and staff to develop a Gap Analysis in US Part 121 Carriers. The initial documentation of the year one efforts has been submitted as a technical report in partial completion of the grant [4]. The following is a summary of the report, which can be made available upon request.

NASA TC-6 and ERAU collaborative research sought to understand the current state of resilient performance in routine Part 121 operations. Furthermore, the collaborative team identified desired resilient performance in routine operations and approaches for transitioning from the current state to the desired states. The gap analysis followed a structured methodology to identify the discrepancies between the current and ideal states of support for resilient performance. This involved:

1. Defining the scope of the analysis.
2. Reviewing relevant literature and data on the issue.
3. Determining the criteria and standards for resilient performance.
4. Understanding the current state of resilient performance.
5. Identifying the desired state.
6. Highlighting the gaps between the current and desired state.
7. Developing an action plan to close those gaps.

Traditional safety models such as Human Factors Analysis and Classification System (HFACS) [7] the Swiss Cheese Model [8], and Threat and Error Management (TEM) [9] have focused primarily on threats, errors, and negative events. However, the aviation industry has recognized the need to expand beyond failure analysis to also focus on positive safety behaviors during normal operations. FSF led the effort to capture positive safety behaviors under the term "Learning from All Operations" (LAO). The report emphasized the importance of LAO which advocated for a shift from only analyzing failures to also recognizing and promoting positive safety behaviors in routine operations. LAO advocates for studying routine, successful operations in addition to analyzing adverse events. The goal is to develop a comprehensive safety culture that learns from all operational outcomes to better predict and prevent potential risks while reinforcing what is already working well.

The gap analysis revealed several critical areas where current practices fall short of the desired state (see Table 3). The analysis found that data could be sourced and gathered more effectively, and that analysis and feedback must be performed more expeditiously. Furthermore, the report revealed that, to effect change in the culture, buy-in from leadership and from the front-line staff is necessary to improve advocacy and engage all levels of the organization. The research also identified the need for effective communication in a clear, concise, and consistent manner, using coordinated channels to avoid information overload. In the desired state, operators would expand the use of performance feedback tools and establish a cultural norm of debriefing after routine flights. This focus on LAO reinforces resilient behaviors.

Table 3: Gaps Identified through Analysis of US Part 121 Carriers Operations

Gaps Limiting Support for Resilient Performance in Part 121 Ops			
Data Sources	Data Gathering	Data Analysis	Data Feedback into the System
Leadership Buy-in	Flight Deck Buy-in	Effective Communication of LAO	Performance Feedback Tools

The report also outlined specific actions to bridge the gaps between the current and desired states. The report specified one suggested approach to developing new data sources that would involve airlines and unions working with academia and others to create new data collection methods that focus on resilient performance. Another key finding to improve data analysis capabilities beyond current practices would require airlines to enhance their qualitative analysis tools and integrate disparate data streams to get a full picture of operations. Leadership buy-in can be fostered by industry demonstrating the value of resilient performance through small-scale initiatives that provide quick wins and clear benefits. Pilot engagement can be improved by airlines working with pilots to simplify the reporting process and incentivize participation in LAO initiatives. Assessment suggested airlines can enhance training by adapting their training programs to include a focus on resilience and emphasizing positive behaviors in routine operations. Also identified was the need for airlines to formally support debriefing sessions after routine operations, making them part of the standard operating procedures.

The gap analysis further explored how resilient performance—defined as the ability to adapt, anticipate, and learn from disruptions—is currently supported by US Part 121 carriers. While resilient performance is critical to safety, there are gaps in data collection, training, and support for such performance. Current systems, including current SMS data collection systems (e.g., flight operations quality assurance [FOQA], line operations safety audit [LOSA], and the aviation safety action program [ASAP]), are primarily designed to capture and/or focus analysis on failures rather than successes, limiting operators' ability to fully understand and promote resilient performance in routine operations. To fully realize safety benefits, airlines must focus on capturing positive performance, improving data collection and analysis, fostering leadership and flight deck buy-in, and enhancing training and feedback mechanisms. The NASA SWS TC-6 research is aligned to the actions identified in the gap analysis.

Technical Challenge 6 (TC-6) IASMS for Commercial Aviation Operations Research Areas

NASA is taking multidisciplinary approach by focusing on three research areas.
The TC-6 consists of three complementary research areas:

- Machine learning (ML)-enabled data analytics,
- Human contributions to safety (HC2S),
- And Non-Traditional Safety Data Monitoring and Analysis.

The research areas are foundational to the following TC-6 technical paths, as presented in the SWS TC-6 on October 3, 2023:

- Predictive safety intelligence
- Continuous LAO
- System-wide IASMS
- and architecture, modeling, and human system integration.

Work underway in the ML-enabled data analytics research area paves the way towards a predictive SMS that manages safety information through the notion of “safety intelligence.” Safety intelligence builds on the use of novel SFCs in advanced ML data analytics and mining methods, tools, techniques, and approaches. The ML-enabled data analytics research area also informs the system-wide IASMS technical path by developing accessible data information platforms and IASMS dashboards for shared safety intelligence across multiple traditional commercial air operational domains. The TC-6 HC2S and non-traditional safety data monitoring and analysis research and knowledge transfer continues to accelerate the broad adoption of continuous LAO across the aviation industry. HC2S and non-traditional safety data monitoring and analysis research broadens the types of safety data feeding big data analytics to inform commercial aviation about “what goes right.” Capturing this information will allow us to learn more about how to prevent “what goes wrong.” Exploring other non-traditional data types will help organizations cultivate a culture of continuous learning, through application of SFCs, across multiple domains of operations. Finally, all TC-6 research areas are contributing to the architecture, modeling, human system integration technical path early in the system design lifecycle of IASMS development with particular consideration for human interfaces and management of information critical to development and implementation of IASMS.

TC-6 ML-Enabled Data Analytics Research Area Impact and Outcomes

The TC-6 team and SWS Project IASMS ConOps team members recently published an article on the Air Line Pilots Association (ALPA) website entitled “Extending the Wingspan of Data: Increasing Lift Through Artificial Intelligence for In-Time Aviation Safety” [10]. The article explored novel methods to analyze massive amounts of aviation data and generate safety intelligence. The article describes how today’s aircraft generate immense amounts of data; for example, the A350 produces up to 400,000 data parameters per flight and a B-737-800 produces 20 terabytes of engine data per hour. Safety reports submitted by operators (pilots, cabin crew, maintenance, etc.) comprise another complementary data source. The volume of these narrative reports is well-suited to ML-enabled data analytics.

Airlines and pilots have embraced these data through safety programs that improve safety, such as FOQA and ASAP. However, while significant progress has been made, current methods of analyzing such massive data sets—primarily through data mining—are not sufficient for the dynamic future of air transportation. NASA data scientists are harnessing these data using ML and revolutionizing safety by providing more proactive and predictive insights.

Historically, aviation safety improvements were reactive, often implemented only after a fatal accident or salient close call. In the late 1990s, the industry began using more proactive data-driven approaches, but manual processes for analyzing data are labor-intensive and time-consuming. NASA envisions a future where optimized algorithms translate vast amounts of aviation data into actionable knowledge, helping to detect and mitigate risks in real time. By using intelligent algorithms to analyze complex data sets, NASA’s SWS project can improve hazard identification and risk management in aviation. This shift from manual data tagging to ML detection will free up valuable time and resources, allowing human experts to focus on deeper investigations and safety improvements.

The SWS project, launched in 2018, has been leveraging and advancing ML and data science to enhance real-time risk management in aviation. By collaborating with airlines and organizations like ALPA, NASA is developing algorithms that detect patterns and safety vulnerabilities not easily spotted by traditional methods. These ML tools can quickly identify anomalies in data, allowing for earlier detection and mitigation of potential threats before they escalate into safety events. As data sets continue to grow, the aviation industry will benefit from enhanced predictive safety intelligence, facilitating more precise safety assessments and proactive measures. This evolution of AI-driven safety management will not only improve operational safety but also support the broader goals of efficiency and passenger comfort.

TC- 6 Research and Knowledge Transfer with Commercial Aviation Partners

The TC-6 ML-enabled data analytics team has conducted research and led knowledge transfer efforts with commercial aviation partners both domestically and internationally throughout FY24. The TC-6 ML-Enabled Data Analytics team delivered an assessment (predecessor Level 2 Milestone ID: TC6-02-01) [11] of IASMS initial data sources and digital information platforms accessible by the team in terms of their type and IASMS use for system-wide data exchange and analysis. The technical report provides examples of how to use initial data sources and digital information platforms to identify and resolve anomalies. One ongoing collaborative effort detailed in the assessment is that by the TC-6 team with Booz Allen Hamilton (BAH) data scientists under the SPEAC-II contract mechanism. This effort involves identifying SMS gaps—specifically assessment of risk and risk precursors in commercial aviation operations and ML-based methods to identify risks and risk precursors through analysis of aviation operations and safety data. Using three different models, BAH analyzed System Wide Information Management (SWIM) data to identify flights that are at risk for unstable vertical approach. One of the models was an algorithm developed by TC-6 staff that visualized results through the advancing risk precursor identification (ARPI) system. The ARPI prototype characterizes the risk of an unstable approach for a flight. A visualization tool then provides predictions to aid dispatchers as early as possible. A NASA New Technology Report (LAR-20356) was filed by the TC-6 team that included BAH members as co-inventors. A non-provisional patent application was filed with the U.S. Patent and Trademark Office on March 29, 2024.

The TC-6 team is also partnered with University of Florida (UF) researchers to develop complementary ML-based methods to identify risks and risk precursors through analysis of aviation operations and safety data. UF has used FOQA data to identify risks that impact safety of flights (e.g., unstable approach) using a technique complementary to deep learning models already used extensively in aviation anomaly detection studies. This alternative approach is to address and enable end-user interpretability. Aiming to maintain the same level of interpretability as traditional threshold-exceedance methods, UF continued development of prediction models using ordinal patterns and their distributions throughout the flight. Specifically, a study presented at AIAA SciTech Forum 2024 [12] extends work into multiclass anomaly detection using sensor fusion based on Dempster-Shafer theory (DST), a second-order probability theory used to combine information from different sources of evidence. The approach leverages DST to reduce the uncertainty in the class predictions of an ensemble of classifiers. These classifiers rely on the similarity between flight data and class templates to make a prediction on the state of the aircraft. The approach takes advantage of simple models trained on interpretable features (ordinal patterns) to correctly predict an anomaly and identify the flight dynamics linked to the anomaly. Results of the study show an improvement when employing DST-based sensor fusion instead of a majority voting approach. The results of the UF team’s work provides insight into aircraft states linked to rare high-risk anomalies.

TC-6 Stakeholder Engagement

ALPA

On February 9, 2024, TC-6 team members were invited to ALPA Headquarters in McLean, VA, to attend a meeting with ALPA Director of Engineering and Air Safety, Stacey Bechdolt. The purpose of the meeting was to brief the Ms. Bechdolt on collaborative research that SWS and the FSF were conducting under the LAO initiative, and with major airline and academic partners. The initial coordination meeting resulted in the SWS Project collaborating in several ALPA stakeholder engagement activities and reinforced multiple active and pending agreements with ALPA member airlines. ALPA invited the SWS team to provide an overview of the research and discussed implications for better understanding of safety data, new data types, and NASA’s work to advance state-of-the-art in data analysis methods. NASA and ALPA discussed opportunities for ALPA to help collect these types of data. NASA SWS’s ongoing collaboration with ALPA to publish articles written by the TC-6 team [10, 15, 24] continues to be mutually beneficial.

MITRE

On February 8, 2024, TC-6 team members and MITRE staff held a technical interchange meeting (TIM) at MITRE's headquarters in McLean, VA. The TC-6 team presented an overview and NASA's ML-enabled data analytics and HC2S research. MITRE presented on ML-based methods they were developing to enable aviation safety. The goal of the TIM was to discuss how to collaborate on ML work as part of the Aviation Safety Information Analysis and Sharing (ASIAS) partnership's plan to accelerate the process of deriving analytics results on the data that airlines voluntarily upload. A follow-on TIM was held on June 21, 2024, at NASA Langley Research Center (LaRC) to continue technical discussions and explore collaboration opportunities identified from the February 2024 TIM. The purpose of the June 2024 TIM was to discuss a potential MITRE/FAA reimbursable funding opportunity to support SWS work to enable the next generation of the ASIAS system. The visitors were:

- Matt Cabak, FAA's senior technical advisor for the Office of Accident Investigation and Prevention, and the government chair of the Joint Implementation Measurement Data Analysis Team (JIMDAT);
- Kyle Quakenbush, MITRE's technical leader/ASIAS senior system engineer, MITRE machine learning/artificial intelligence (AI) R&D lead, and tri-chair of the Issues Analysis Team;
- Keith Arthur and Neil O'Connor, NASA D318 branch management
- Kurt Swieringa, deputy project manager for technology for NASA's ATM-X project; and
- John Koelling, director of NASA's Aeronautics Research Mission Directorate at LaRC.

American Airlines

SWS and American Airlines (AA) have been collaborating to improve commercial aviation safety for nearly a decade. This work includes examining several of AA's operational data sources to identify operationally significant information that can be used to assess risk, identify potential deviations from safe operations, and identify precursors. The method of analyzing operational data ranges from manual examination to use of ML methods. On February 28, 2024, NASA and AA signed an extension to continue this work until March 1, 2026 (SAA2-403551). This extension will enable NASA and AA to continue exploring various data sources individually and in combination to identify potential safety issues and their precursors using a combination of human expertise and ML methods, using existing methods or new methods developed by NASA. The goal of this work is to develop a real-time safety analysis capability that airline operation centers can employ to assess and mitigate risk.

NASA SWS also collaborates with American Airlines (AAL) Group wholly owned subsidiary Envoy Air, Inc., and signed a non-reimbursable Space Act Agreement (NRSAA) on August 5, 2024. The stand-alone NRSAA is titled, "Commercial Air Operator In-Time Aviation Safety Management and Safety Intelligence" (SAA1-40816). On August 26, 2024, Envoy and SWS leadership held a virtual kick-off to review details of draft SAA language and confirm focused tasks for Year 1 effort, which includes: (a) research and application of NASA-developed ML algorithms for data analytics of flight operations data (e.g., FOQA) focused on etiologies and mitigations of go-arounds, un-stabilized approaches, and procedural conformance (specific to Envoy Air comparative to domestic industry); and (b) human factors assessments. Planned extensions in out years include other data analytics methods (e.g., natural language processing) and addition of other SMS data sets (e.g., ASAP reports; LOSA).

Other identified potential out-year collaborative efforts involve research and practice of (a) SWS project collaborative efforts, with Flight Safety Foundation, to examine positive contributions to safety and how these data types can inform "in-time" risk management and safety assurance; and (b) SWS expertise and advanced data analytic capabilities for fatigue risk management and enhanced human performance. The kick-off meeting provided an overview of candidate approaches and general collaboration objectives that provided initial airline inputs. The inputs helped the NASA team to develop a more detailed plan and identify various approaches in preparation for an in-person visit to Envoy Air scheduled for October 17, 2024. The advantage of the agreement with a regional carrier like Envoy includes the different operations compared to a mainline carrier like AA, with both common and unique safety risks and challenges. Together, the collaborative efforts, with both mainline and regional airlines, are anticipated to yield a more comprehensive analysis of the diversity of operations reflective of the Part 121 operations in the NAS.

Gaps Identified during AIAA AVIATION Forum 2024 Nowcast and Forecast for Safety Data Analytics Panel Session

On July 31, 2024, the SWS project's Dr. Nikunj Oza chaired a panel entitled "Nowcast and Forecast for Safety Data Analytics," at the AIAA Aviation Forum 2024 [13]. The discussion centered on safety data analytics as conducted currently and how it needs to be enhanced to account for additional traditional operations and new entrants. Additionally, there is a greater desire to make better use of the substantial investment that NAS stakeholders are making in collecting and saving different types of operational and safety data through data analytics/ML. In addition, the panel identified significant technical and cultural barriers to performing data analytics across the different stakeholders' data and ways to possibly overcome them. This NASA-moderated panel included a variety of perspectives and representatives from the FAA, industry, manufacturing, as well as a retired airline captain.

Dr. Oza met the panelists in advance of the conference session, honed the central theme, and formulated appropriate questions for the panel to address during the session. These questions are listed below:

1. What do we need to improve reactive data analytics? What are the barriers to these improvements?
2. Why do we need to have effective predictive and proactive data analytics and what are the barriers to having these?
3. What data do we need to tell what is going wrong, going right?
4. Have you obtained any misleading information from aviation safety data analytics?
5. Have you obtained any misleading information or unrealistic suggestions from information from safety analysts, training, or anyone?
6. Have you obtained any unexpected insights from aviation safety data analytics?
7. Have you given any feedback to safety analysts, training, other pilots, or others in the airline based on your experience that led to changes?
8. How have you been able to jointly look for issues around safety and other factors (e.g., efficiency, maintenance time and cost)?
9. How have you explored the use of non-traditional data in your work?
10. It is clear that we need the cooperation of multiple entities in the NAS to perform data analytics properly to get a complete sense of what is happening. Any suggestions for how to remove barriers to sharing data of different modalities within and across organizations?

One key barrier discussed is the complementary nature of the Safety-I and Safety-II approaches to safety management [14]. The traditional approach, Safety-I, focuses on minimizing the number of things that go wrong. In contrast, Safety-II emphasizes ensuring that as many things as possible go right. The panelists discussed safety as a continuous value, meaning the system is not simply "safe" or "not safe." Instead, it exists on a continuum, ranging from 0 (unsafe) to 1 (safe). A threshold, such as 0.5, can be set to distinguish safe operations from unsafe. Notably Safety-II literature has not proposed this quantification of safety as a unitary continuous variable along a "safety scale." Instead, Safety-I would only examine those rare situations in which the operational regime was unsafe.

The panelists explored another proposed approach, although not an approach aligned with Safety-II, that could examine situations where the operations remain safe but move within the safe region of 0.5 to 1. This freedom of movement would allow for learning from situations where safety degraded and then recovered, never actually entering the unsafe region. Humans often implement these recovery actions, which are not identified and studied as often as they could be.

Another challenge the panel identified was that objective data (e.g., FOQA, radar track, etc.) is relevant to Safety-II, while subjective data (e.g., safety reports) is less so. This is because Safety-II focuses on data that does not include safety incidents, meaning a safety report may not be prompted. While this supposition is logically valid, the SWS HC2S team's analysis of safety reports indicate otherwise [19, 20]. In narrative reports, respondents frequently mention examples of resilient performance. Unfortunately, because effective coding methods are lacking and a universal vocabulary for describing resilient performance does not yet exist, this data is hard to identify and analyze. NASA has argued that most incident reports are examples of resilient performance, because these are all events that did not become accidents. In some significant percentage of cases, that will be due to resilient actions taken by human operators.

The panelists noted there is often resistance to sharing additional data of any type due to organizational trust issues, both internally and external. Resistance to sharing is not exclusive to individual data sources. Linking different data sources, such as FOQA and safety reports, would provide a more comprehensive understanding of what happened and why. However, often, even within a given operator, analysts are not allowed to connect different data sources. In many cases, it's technically impossible given the way that the data are collected. For example, there may not be an appropriate key through which flight data can be tied together, such as flight number, date, and time, to link FOQA data and ASAP reports.

A significant part of the discussion revolved around the need for teamwork within IASMS. Teams will need to include not only people from different organizations and types of organizations (e.g., operators, manufacturers, regulators, unions) but also different functions within an organization (e.g., within an operator, flight operations, technical operations, maintenance, and others). This approach is critical to understanding the full nature of the operations and the way that they generate their data. One panelist described a maintenance reporting process for logging mechanical issues that tried to be comprehensive but was so cumbersome that it often led to delays in addressing minor but critical maintenance tasks. The panelist proposed a streamlined digital reporting system and collaborated with maintenance and safety analysts. The airline implemented the system and benefited from improved communication between pilots and maintenance staff and reduced aircraft downtime. In this case, it is important to note that some of the communication across different organizations is not captured with data, therefore, will not have its impact measured through data analytics.

The panelist also noted that teamwork not only includes humans, but systems, data, and tools. Different groups or functions within an organization may want to share data and even fuse data; however, this sharing will be more easily achievable, and may only be possible, if the data formats are compatible and if the data and analytics system are compatible. Different approaches, such as open data standards, must be explored. Clear policies and agreements regarding data sharing, including data ownership, access rights, and usage terms will also facilitate data sharing. Ensuring data security and privacy is critical not only in order to comply with these policies but to ensure trust among the various stakeholders. Stakeholder trust is a key component of a culture of collaboration and open communication that is necessary for teamwork. New platforms that facilitate real-time data sharing and communication among stakeholders will need to sit on top of federated data systems that allow various organizations to keep their data private while still allowing for joint analysis. Significant R&D are needed to yield practical federated data and analytics systems.

Another key area of discussion within the panel revolved around the need to examine more than just safety and associated metrics. The safest action to take is to never fly. Therefore, commercial aviation will always require trade-offs among safety and efficiency, among others, and there may be trade-offs between different aspects of operations, such as maintenance vs. flight operations, as described in the example given in the previous paragraph regarding the trade-off between thoroughness of maintenance information vs. efficiency for pilots. Even within one aspect of operations, there are trade-offs that must be made, including the need to ensure that pre-flight inspection procedures maximize safety but minimize delays. Data that are not typically associated with safety, such as social media data, may also provide information that is helpful in identifying potential problems or determining the effectiveness of mitigating actions. Ultimately, there is a need to describe, in great detail, the operations of different organizations; how data related to those operations are collected, processed, and analyzed; how the analysis results are used to devise changes to operations; and how the effectiveness of those changes is assessed. This description will allow for identification of additional barriers to IASMS, such as gaps in data, reporting and reporting culture; errors in data collection and analysis; data stovepipes; misconceptions among staff (everyone not being "on the same page"); and others.

TC-6 HC2S Research Area Impact and Outcomes

The TC-6 team and SWS Project IASMS ConOps team members published an article on the ALPA website entitled "The Important Data You Don't See: Human Contributions to Aviation Safety" [16]. It describes the critical contributions of humans to maintaining safe operations. Aviation operations present continuous challenges that airline pilots must manage daily, and their extensive training ensures they are well-prepared to handle these demands. Pilots spend a substantial portion of their time proactively taking actions to ensure safety and prevent negative outcomes. The impressive safety record of the U.S. airline industry is a direct result of the dedication and professionalism of pilots who always prioritize safe operations.

NASA recognizes that pilots are at the core of aviation safety. Their ability to adapt to both routine and non-routine situations, such as equipment malfunctions, weather changes, and air traffic demands, is vital. As new technologies and procedures are introduced, it's essential to acknowledge the ongoing role pilots play in maintaining safety by continuously adapting to changes.

A broader approach to safety must go beyond learning from infrequent failures to also understanding what makes flights successful. Data from routine operations can offer valuable insights into how pilots maintain safety every day. NASA, alongside ALPA and other partners, is developing advanced data analysis methods to uncover patterns and improve understanding of flight crew responses. By learning from both safety successes and failures, the industry can better inform safety measures and training, with pilots remaining at the forefront of these advancements.

As identified in the FSF IASMS Research Roadmap [3] and the ERAU Gap Analysis [4], continuous LAO is pivotal to development of IASMS. The TC-6 HC2S team conducted research and lead knowledge transfer efforts with commercial aviation partners both domestically and internationally throughout FY24 as highlighted below.

TC-6 HC2S Team Research and Knowledge Transfer

American Airlines

HC2S team members met with AA personnel at the AA Flight Training facility in Charlotte, NC, on October 25-26, 2023, to discuss applying NASA technology (LAR-18996, LAR-19978-CIP) to their airline operations. AA managers and instructors identified areas that NASA technology could immediately benefit airline operations. Discussions have continued with Capt. John Dudley, managing director for AA flight operations, to facilitate licensing and deployment at AA. The instructors were enthusiastic about the evidence-based training and real time aspects to support teaching moments, especially when the trainee is a new pilot or when an experienced pilot is transitioning between different types of aircraft. The instructors also highlighted how NASA technology could enhance training and provide insights into flight crew behaviors that contribute to safety and efficiency. Comments from the subject matter experts (SMEs) included how the NASA team's work addresses future planning efforts undertaken by major airlines to manage pilot shortage and changes in pilot demographics/experience level. AA managers and instructors recommended further discussion with AA personnel at AA Flight Training facility in Dallas, TX, to enable licensing and deploying NASA technology at AA. A follow-on meeting was scheduled in October 2024.

AA's Director of Training reached out to SWS to help address an identified issue that pilots were experiencing. As part of the NASA and AA collaboration, the teams worked together to produce a 10-minute human factors video that is shown to more than 14,000 pilots during recurrent, required AAL training. Mr. Chad Stephens, SWS TC-6 manager and research scientist, and Kaitlyn Fox, SWS communication liaison, coordinated with Captain Dan Kiggins (NASA SME Consultant) to develop a script and shoot the footage at NASA's Glenn Research Center (GRC) and Amstrong Flight Research Center (AFRC) studios and locally in the LaRC studio. SMEs interviewed in the video include Nils Larson and James Less, NASA AFRC test pilots, and Dr. Michael Tong of the Cleveland Clinic. This project was a collaborative effort involving the LaRC Media Solutions Branch and Public Affairs, and HQ Public Affairs Office. The feedback from the airline has been overwhelmingly positive. The AA manager for safety learning and development highlighted the value NASA provided, stating, "We truly appreciate the partnership with NASA and your willingness to continue to support our Flight HF program."

InfoShare 2023

TC-6 HC2S Technical Lead Dr. Jon Holbrook and HC2S team member Dr. Immanuel Barshi presented as panelists at Aviation Safety InfoShare 2023 on a session entitled "Why Learning from All Operations is Imperative" [16]. Their presentations explained LAO and the results from HC2S research further specifying the basis of the novel approach to safety. Dr. Barshi presented a contingency table showing that pilots contribute positively to safety about 157,000 times for every instance where human error contributes to an accident. He also noted that this was a conservative estimate. The estimate was updated to better reflect operational realities, Dr. Barshi stated that "pilots intervene to keep flights safe more than 628,000 times for every time that human error contributes to an accident!" These statistics emphasize the importance of LAO in shaping system designs, policies, and procedures that ensure humans can intervene and adapt to maintain safe operations. Dr. Holbrook and Dr. Barshi were also co-authors of a FSF publication entitled "Integrating Learning from All Operations into the Components of a Safety Management System" [17], which includes results of knowledge elicitation work SWS conducted in partnership with FSF. The outcomes of this work resulted in proposals for enhancing the four pillars of SMS (Safety policy, Safety risk management, Safety assurance, and Safety promotion).

AIAA SciTech Forum 2024

Dr. Lance Prinzel presented a paper written by the TC-6 team and SWS Project IASMS ConOps team members entitled "The Adaptable and Resilient Safety System: The Human Factor in Future In-Time Aviation Safety Management Systems" at the AIAA SciTech Forum 2024 [18]. The paper describes SMS and its challenges, and how the IASMS concept addresses the need for adaptable and resilient future safety systems in the transformed NAS of the future. Finally, it discusses potential human factors challenges, including new human roles and responsibilities, new information and cognitive requirements, new intelligent technologies that change human-system interaction and coordination, and new design paradigms for human-system integration and teaming.

Boeing Human Engineering Community of Excellence

Mr. Chad Stephens was invited to virtually present on "Psychophysiological Methods to Assess Pilot Productive Safety Behaviors" on March 18, 2024, to the Boeing Human Engineering Community of Excellence. More than 110 Boeing personnel attended the presentation, which focused on human factors methods deployed by SWS HC2S researchers to study both human error and human contributions to safety in aviation operations. As a result of the presentation, the Boeing Flight Deck Engineering and Boeing Research & Technology Development groups requested additional information and follow-on discussion.

EUROCONTROL and FSF Safety Forum

As an SME in the application of AI technologies to aviation safety, Dr. Holbrook was one of 14 representatives from government and industry to participate in the AI, Autonomy, and Aviation Safety Workshop at EUROCONTROL Headquarters, Brussels, Belgium on June 18, 2024. The represented groups included NASA, FAA, Delta Air Lines, Amazon Prime Air, Avtrain, Beams Safety AI, Usher AI, AirBaltic Corporation, FSF, Assaia, Netherlands Airport Consultants, Lufthansa, and the International Business Aviation Council. Dr. Holbrook gave a presentation entitled "Adding AI to Human-Machine Teaming." The workshop provided an opportunity for participants with diverse perspectives on AI and aviation safety to share ideas and concerns in a small group setting. Participants discussed what they were most excited about and most worried about in terms of the future of AI in aviation. The workshop was an opportunity to raise awareness of NASA research, as well as to share and discuss ideas with an international audience of AI developers, practitioners, consultants, and regulators within the aviation community.

Dr. Barshi and Dr. Holbrook attended FSF's Safety Forum and subsequent “Learning from All Operations” working group meeting at EUROCONTROL Headquarters, Brussels, Belgium on June 19-21, 2024. The Safety Forum was attended by 200+ front-line aviation safety professionals, trainers, and managers representing industry and government from across the globe. The event was internationally attended and explored current practices, thinking, and research on the knowledge, skills, and experience necessary to enable safer aviation operations. The meetings provided opportunities to raise awareness of NASA research, as well as to share and discuss ideas with an international audience of aviation safety practitioners. The theme of this year's Safety Forum was Aviation Weather Resilience, and Drs. Barshi and Holbrook each presented at the Safety Forum in support of SWS TC-6. Dr. Barshi presented “Extracting Lessons of Human Performance and Resilience Management from a Study of Weather-Related Safety Risks and Incidents reported to NASA’s Aviation Safety Reporting System” [19]. Dr. Holbrook presented “Understanding Pilot Resilient Performance in Weather Risk Management: Methods and Insights from a Simulation Study” [20].

On June 24, 2024, Drs. Barshi and Holbrook, along with FSF’s Tzvetomir Blajev, were invited to present LAO concepts to the International Civil Aviation Organization (ICAO) Safety Management Panel (SMP), which is composed of a multi-disciplinary team of experts familiar with ICAO safety management provisions and involved in their state safety programmes. ICAO SMP leadership requested the presentation as they continue to develop the 1st edition of the Safety Intelligence Manual and 5th edition of the Safety Management Manual, both of which are to be published in the next year.

The concept of LAO and Safety-II have garnered significant attention in the aviation community as a key enabler to advance SMS implementations, a key advancement for aviation transformation to safely introduce increasingly complex operations, such as envisioned with AAM. NASA SWS researchers have contributed significantly to the development of new approaches and techniques, working closely with the FSF and industry to advance the concepts. The invited presentation was coordinated by Dr. Kyle Ellis, SWS project manager and co-rapporteur for the ICAO SMP Safety Intelligence Working Group.

On August 1, 2024, Dr. Barshi again presented to the ICAO SMP in a virtual talk entitled “Gathering Safety Intelligence from Relevant Safety Events” [21] to the ICAO SMP. The presentation highlighted some of the key differences in assumptions between Safety I and Safety II, as well as some of the limitations of each approach and the ways in which they complement each other. The talk also described the FSF LAO effort, which is designed to collect Safety II-type data to enable data-informed decisions beyond Safety I-type data only.

University of Waterloo

Mr. Stephens gave an invited presentation to the Waterloo Institute for Sustainable Aviation (https://uwaterloo.ca/sustainable-aeronautics/) Seminar at the University of Waterloo on June 27, 2024. The title of Mr. Stephens talk was "Optimizing Attention and Performance for Aviation Safety: Insights from Multimodal Psychophysiology." Dr. Alan Pope, SWS researcher and distinguished research associate, presented "Psychophysiology and Biofeedback Mechanisms for Pilot Training and Performance Quantification." Over 40 attendees joined the seminar in-person and virtually including University of Waterloo faculty and undergraduate and graduate students.

Nature Scientific Data

The HC2S team drafted a manuscript [22] for a journal article to be submitted to Nature Scientific Data, which primarily publishes Data Descriptors, a type of publication that “provides detailed descriptions of research datasets, including the methods used to collect the data and technical analyses supporting the quality of the measurements. Data Descriptors focus on helping others reuse data, rather than testing hypotheses, or presenting new interpretations, methods or in-depth analyses” as described on the Nature Scientific Data website (https://www.nature.com/sdata/). The STRIVES approved manuscript describes the HC2S SWS Operations and Technologies for Enabling Resilient In-Time Assurance (SOTERIA) flight simulation study dataset that is a first of its kind to study human contributions to safety in various facets (operations, training, etc.) of commercial aviation. The data has helped enhance aviation safety in traditional and emerging aviation operations. The publication requirements necessitate making the dataset publicly available, which the HC2S team has done according to the NASA requirements for public release of scientific data.

TC-6 Non-Traditional Safety Data Monitoring and Analysis Research Area Impact and Outcomes

For over 40 years, NASA's Fatigue Countermeasures Laboratory has led research efforts to manage and minimize fatigue in aviation. Through collaboration with pilots and stakeholders, NASA has gathered valuable data that informs practical solutions, such as modifying rest break policies for mid-haul flights. Ongoing research, including a large in-flight study on fatigue in short-haul operations, aims to address new fatigue-related challenges as they arise. In addition, NASA is exploring new tools, such as an app to collect pilot data, and studying the impact of increased automation on pilot alertness. As the aviation industry evolves, NASA's commitment to understanding fatigue and developing effective countermeasures remains crucial to ensuring pilot performance and safety.

TC-6 team member and lead of NASA's Fatigue Countermeasures Laboratory, Dr. Erin Flynn-Evans, and a member of NASA's Fatigue Countermeasures Laboratory, Dr. Cassie Hilditch, published an article on the ALPA website entitled "Staying Sharp in the Skies: NASA Addresses the Persistent Problem of Fatigue Through Collaborative Research with Airline Pilots" [23]. The article describes how fatigue risk management has been a part of aviation safety for over three decades. But they also explain that fatigue remains an unavoidable challenge due to its natural role in human physiology. Aviation operations, particularly those requiring 24-hour work schedules, inevitably lead to some degree of fatigue, even with the most advanced safety systems in place. Pilots, as human beings governed by their internal circadian rhythms, are biologically driven to stay awake during the day and sleep at night. Current countermeasures, including enhanced automation, cannot fully override these biological drives, highlighting the limitations of existing technologies. NASA's research keeps this reality in focus while developing new strategies to reduce fatigue-related risks in aviation.

Pilot fatigue has been a concern since ALPA's formation and continues to be a complex issue in an ever-evolving aviation landscape. Technological advancements that allow aircraft to fly farther and with more automation have also altered how fatigue manifests for flight crews. Fatigue management systems must continuously adapt to these changes. Removing pilots from the flight deck is not a viable solution due to their crucial role in ensuring safe flight operations. NASA's Fatigue Countermeasures Laboratory works closely with various stakeholders—pilots, labor unions, airlines, researchers, and regulators—to research fatigue risks and develop new mitigation strategies that keep pace with the dynamic nature of the aviation environment.

Dr. Erin Flynn-Evans and her colleagues have most recently reported on research they are conducting to better understand the effects of fatigue on pilots in commercial aviation operations. On May 2024, they presented their research at the annual meeting of the Aerospace Medicine Association [24]. The presentation focused on the challenge of fatigue in short-haul aviation flight operations due to irregular schedules that often involve circadian disruption—specifically, schedules that encroach on the window of circadian low, including redeye flights, and those that switch between early starts and late finishes can cause circadian disruptions. These schedules reduce sleep opportunity and may require additional fatigue mitigation. Such sleep loss and circadian disruption, together with high workload factors common to short-haul operations (e.g., fast turnarounds, multiple takeoffs and landings) may impact cognitive performance and safety. The FAA NextGen Human Factors Division funded the research, conducted by the Civil Aerospace Medical Institute in support of the FAA Aviation Safety Organization. This study is ongoing and involves characterizing the impact of these circadian disrupted schedules on pilot fatigue and performance during short-haul operations using validated objective and subjective methods. Preliminary findings suggest that the pilots are compliant with study procedures and results are expected in calendar year 2025.

Dr. Cassie Hilditch presented results of another study examining the effects of a short nap taken on the flight deck (known as controlled rest) as a countermeasure to unexpected in-flight sleepiness [25]. The primary aim of the study was to investigate the impact of taking controlled rest on self-reported sleepiness at top-of-descent. Results from the study suggest that there is no difference in self-reported sleepiness at top-of-descent on flights in which controlled rest was taken compared to flights without controlled rest. Further research is necessary to determine the impact of controlled rest on objective measures of performance at top-of-descent.

Dr. Flynn-Evans recently served as one of three experts on a panel commissioned by the FAA that produced a 114-page report entitled “Assessing Fatigue Risk in FAA Air Traffic Operations” [26]. The panel also included fatigue expert and former National Transportation Safety Board member Mark Rosekind and Harvard Medical School’s Director of the Division of Sleep Medicine Charles A. Czeisler. A brief summary of the report studying air traffic controller fatigue is as follows.

FAA air traffic controllers play a crucial role in managing the safe movement of millions of passengers daily within the NAS. Due to the 24/7 nature of air traffic operations, controllers face significant challenges related to fatigue from sleep loss and circadian disruption, which can impact safety, performance, and health. In response, the FAA administrator requested a focused evaluation of the latest science on sleep and fatigue to assess current work requirements, scheduling practices, and overall controller well-being. A team of scientific experts was formed to conduct this assessment, with the aim of informing future FAA actions to enhance the safety and health of the controller workforce.

The evaluation team, whose work was extended from six to 10 weeks due to the volume of information, analyzed over 700,000 work hours from more than 10,000 controllers, reviewed 120 documents, and conducted meetings with various stakeholders. The report identified several risks, strengths, and opportunities related to fatigue management in air traffic operations. It was designed as a practical guide to help the FAA address fatigue risks more effectively, rather than an extended research project. The goal was to provide the FAA with actionable insights to improve both controller well-being and operational safety.

The report concluded with several recommendations, including forming a working group to address fatigue management and implementing immediate actions in key areas. These include integrating existing fatigue management systems, addressing scheduling issues, and updating policies to reduce fatigue. The expert panel identified 58 total opportunities for the FAA to consider, with a particular focus on enhancing strengths, reducing fatigue risks, and establishing long-term strategies for improved workforce safety and health. These recommendations aim to guide the FAA and other stakeholders in creating a more resilient and safer aviation system.

Dr. Flynn-Evans presented on the work she conducted as part of the panel to the SWS Project in a TechTalk [27] to the project team on September 5, 2024, which permitted knowledge transfer and discussion of implications of the findings by the panel for all of SWS Project and sub-projects.

Dr. Flynn-Evans’s contribution to the report demonstrates her standing in the scientific community and represents the application of her breadth and depth of knowledge on fatigue and its impact on human operators in aviation operations. The benefit to NASA and to the SWS project and TC-6 from her work on this expert panel includes considerations for the effects of fatigue that are not directly occurring on the flight deck but have significant importance to aviation safety. Such considerations contribute to the development and refinement of SFCs that IASMS encompass.

Conclusion

TC-6 has made significant strides toward the development of IASMS, which aims to enhance aviation safety through real-time risk detection, mitigation, and predictive analytics. The research conducted in fiscal year 2024, which included contributions from NASA, FSF, Embry-Riddle Aeronautical University, and industry stakeholders, has highlighted critical areas for improvement. These areas focus on developing advanced data analytics, expanding safety data beyond failures to include routine operations, and addressing gaps in human performance, particularly regarding fatigue and the role of pilots in maintaining safety. These insights are crucial for informing future research and development within NASA's broader SWS project.

Moving forward, the focus of TC-6 research will shift toward more collaborative efforts with the aviation industry to ensure that IASMS can be integrated effectively across various sectors of aviation. This includes leveraging emerging technologies like ML/AI to enhance predictive safety intelligence. The

SWS project has shown that a multidisciplinary approach—combining data analysis, human factors research, and real-time safety monitoring—will be essential in managing the increasingly complex aviation environment. Collaboration with organizations such as ALPA, MITRE, and American Airlines has also been vital, fostering partnerships that will continue to drive innovations in safety practices.

The work accomplished in FY24 under the TC-6 has laid the groundwork for substantial advancements in aviation safety through IASMS. The development of predictive safety systems, combined with LAO efforts, will enhance the aviation industry's ability to anticipate and respond to risks in real-time. As the aviation sector evolves with new technologies and operational concepts, maintaining a focus on safety through collaboration, continuous learning, and technological innovation will be critical. The project's continued research in data analytics, human performance, and safety system integration will guide the next phases of development, ensuring that the skies remain safe for all.

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