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Advancing Aviation Safety Through In-Time Safety Management, Resilience, and Learning from All Operations

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Reactive, accident-oriented safety management can no longer keep pace with the complexity and tempo of modern air operations. This position paper advocates advancing aviation safety by fusing three complementary developments. First, an In-Time Aviation Safety Management System (IASMS) brings predictive analytics and real-time data fusion to the flight deck, shifting risk control from retrospective analysis to live mitigation. Second, Resilience establishes the conceptual and practical foundation for crews, organizations, and technologies to adapt gracefully when novel challenges arise, preventing escalation. Third, a Learning from All Operations (LFAO) philosophy systematically mines routine flight data, voluntary reports, and observational audits to drive continuous improvement in training, procedures, and algorithms. Together, these elements recast pilots as active partners in safety creation rather than a residual source of error, combine machine intelligence with human expertise, and form a closed loop in which operations both inform and benefit from safety interventions. The paper offers implementation steps centered on data governance, human-machine interface design, cultural adaptations, regulatory actions, and resilience training to implement this architecture within commercial air transport.

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Introduction

Aviation safety has long been flying by the rearview mirror, fixated on what went wrong rather than empowering what goes right. Traditional safety management has been largely reactive, investigating accidents and human errors after the fact (Holbrook et al., 2019). The oft-cited statistic that roughly 70–80% of aviation accidents involve human error led to increased automation and stricter procedures, but this tells only half the story. Flight crews routinely prevent incidents in daily operations: studies show pilots must intervene in about 20% of flights to manage malfunctions or off-nominal situations (PARC/CAST Flight Deck Automation Working Group, 2013). In other words, human expertise regularly averts problems and contributes positively to safety.

Every incident-free flight partly owes its success to human capabilities, not just the absence of error. As Barshi (2024) notes, while human limitations play a role in most accidents, human skills and adaptability are factors in every safe flight. This recognition marks a paradigm shift – rather than treating humans as the weakest link, there is growing emphasis on their role as critical contributors to safety. Given how rare accidents have become, a purely reactive, accident-focused model yields diminishing returns for safety improvement. It also overlooks the wealth of safety data on successful flights every day. The industry needs to evolve its approach to flight deck safety by integrating real-time risk management, building system resilience, and continually learning from all operations – not only failures.

Purpose Statement

The purpose of this position paper is to assert that the next leap in aviation safety will come from uniting three concepts: In-Time Aviation Safety Management Systems (IASMS), resilience engineering, and a "Learning from All Operations" (LFAO) philosophy. This paper introduces a proactive, data-driven, and human-centered safety approach to reduce flight risks. A central theme is reframing the human role in safety: pilots should be seen as an essential partner in safety (not merely a source of error) whose actions often create safety rather than simply produce errors (Barshi, 2024). This paper reviews current research and developments in IASMS, mechanisms to enhance resilience at both individual and organizational levels, and methods to capture and learn from everyday flight data. This paper also addresses contrasting viewpoints – for example, the argument that more automation alone can solve human error or skepticism about "Safety-II" and resilience concepts – to ensure a balanced evaluation. Finally, it proposes an actionable plan for advancing flight deck safety by leveraging real-time systems, human resilience, and continuous learning, thus complementing and transcending the traditional accident-focused model. The main research question addressed in this paper is: How do IASMS, resilience engineering, and LFAO work together to improve safety during line operations?

Methodology

This manuscript is a position paper based on literature synthesis and conceptual integration. Sources were selected through targeted searches (2010–2025 with seminal earlier works) across peer-reviewed journals, National Aeronautics and Space Administration (NASA)/Federal Aviation Administration (FAA) technical reports, Flight Safety Foundation papers, relevant conference proceedings, and industry guidance referenced herein. Inclusion emphasized relevance to:

- In-Time Aviation Safety Management (IASMS),
- Safety-II, High-Reliability/Resilience Engineering, and
- Programs that learn from routine operations, such as Flight Operations Quality Assurance (FOQA), Line Operations Safety Assessment (LOSA), the Aviation Safety Reporting System (ASRS), the Aviation Safety Action Program (ASAP), and the Advanced Qualification Program (AQP).

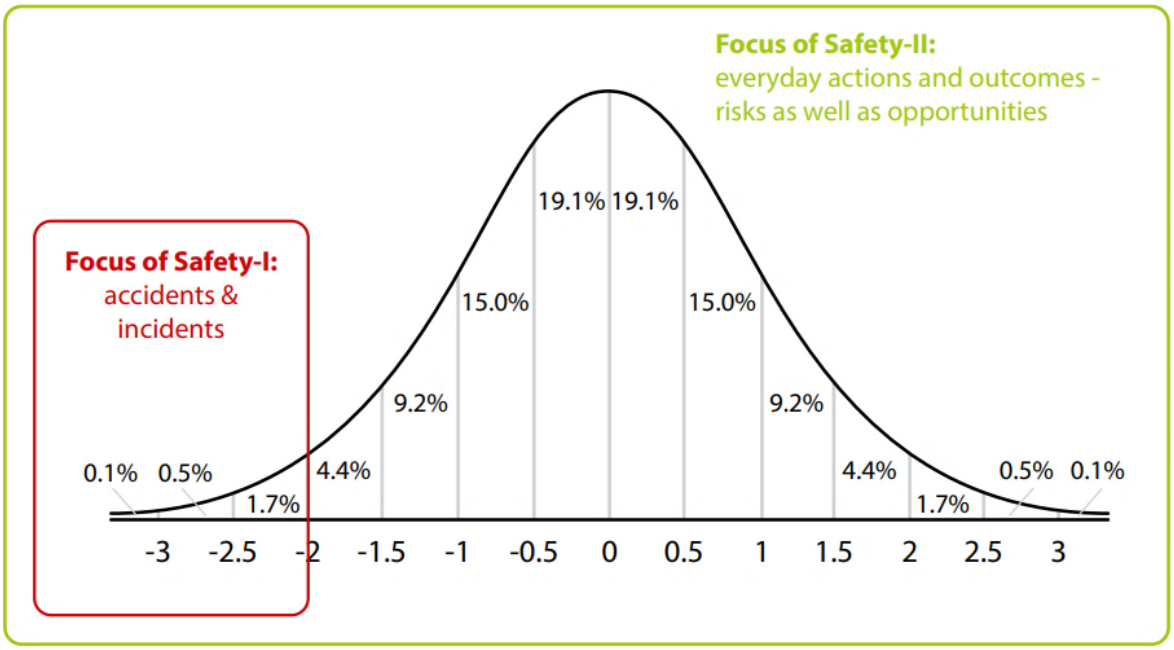
Priority was given to empirical studies, official frameworks, and technical concepts describing real-time risk monitoring, human performance, and organizational learning. The argument was constructed by mapping common mechanisms (anticipation, monitoring, response, and learning) onto IASMS functions and LFAO practices, then testing consistency against counter-arguments (automation-only claims, Normal Accident Theory concerns, and cost/resource constraints). This manuscript offers a structured synthesis of current knowledge intended to motivate a practical, staged path to implementation, without introducing new sampling, data collection, or statistical analysis.

From Reactive Safety to Proactive Learning: A Changing Safety Model

For decades, aviation safety was driven by "Safety-I," which sees safety as the absence of accidents (Hollnagel, 2018; Prinzel et al., 2022). This reactive approach achieved significant gains – for example, the fatal accident rate fell from around 5–6 per million flights in the 1970s to about 0.5 in recent years (Ortiz-Ospina, 2024) – but as accidents became exceedingly rare, focusing only on failures yielded diminishing returns. A complementary "Safety-II" perspective defines safety as the presence of successful operations and seeks to understand and foster the conditions that make things go right (Holbrook et al., 2019). Within this view, humans are viewed not as hazards but as a source of flexibility and resilience who help create safety. Every routine flight that ends without incident is an opportunity to learn how systems and people successfully adapt to challenges. Hollnagel famously remarked that we had been looking at safety "through the wrong end of the telescope" by examining only what goes wrong instead of also studying normal successes (Hollnagel, 2017; 2018; 2022). The emerging model encourages capturing everyday performance and near-misses so that frontline insights can improve the system. See Figure 1 for a side-by-side view of Safety-I and Safety-II. The Flight Safety Foundation's LFAO initiative calls for capturing routine performance, a practical embodiment of Safety-II thinking in aviation (Holbrook et al., 2019). This shift also aligns with Safety Differently (Dekker & Conklin, 2014), which centers everyday work and human expertise as sources of safety creation.

Figure 1

Safety-I versus Safety-II

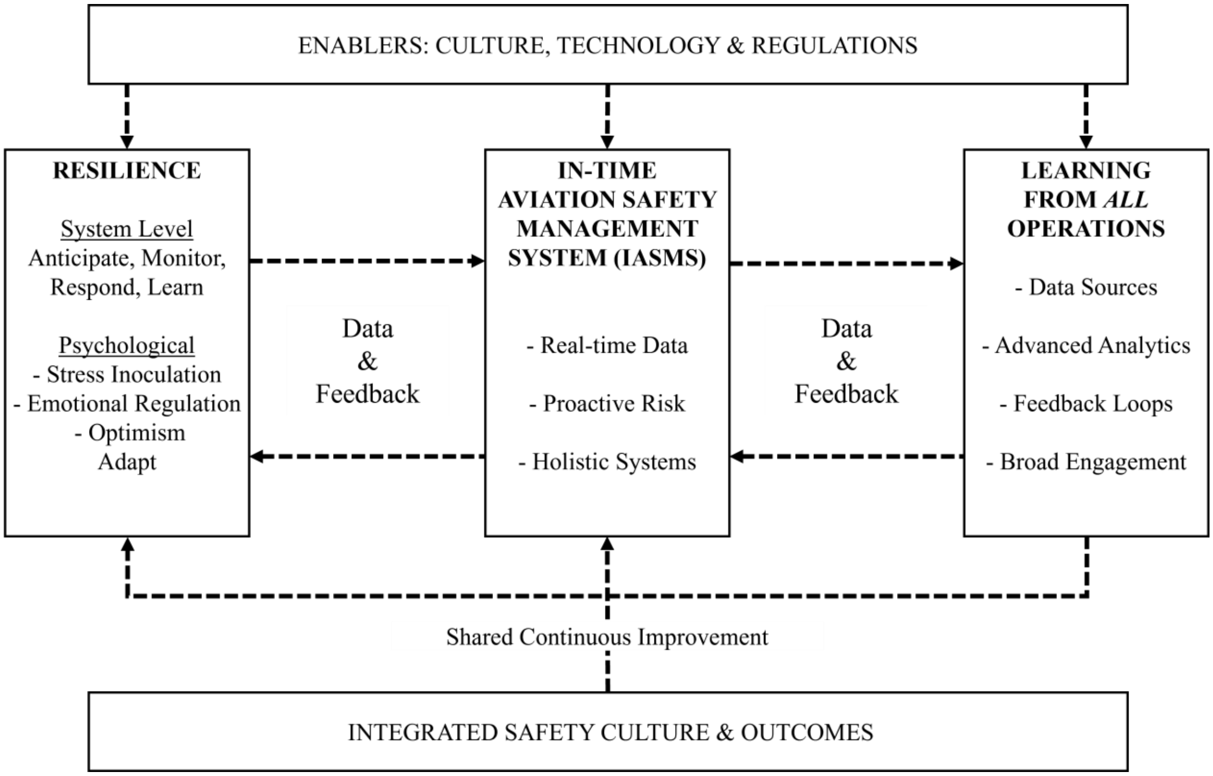


Note: Figure adapted from EUROCONTROL (2013) with permission for non-commercial purposes.

Modern aviation systems are highly complex and tightly coupled, meaning unexpected interactions can produce new hazards. Traditional hazard analysis – hindsight from accidents or foresight based on known failure modes – often fails to predict these emergent issues. High-Reliability Organization (HRO) theory and Resilience Engineering emphasize anticipation, monitoring, and rapid recovery as critical capabilities for safety management (Hollnagel et al., 2006). They assume surprises will occur and focus on preparing organizations to handle the unexpected (Hosseini et al., 2016; Kiernan et al., 2020). For example, a U.S. National Academies panel in 2018 urged the development of IASMS to enable real-time detection and mitigation of emerging risks in an evolving airspace (National Academies, 2018; Stolzer et al., 2023). This vision aligns with moving from a retrospective, reactive stance to a real-time, proactive approach. The following sections examine the three pillars of the new safety paradigm – In-Time Safety Systems, Resilience, and LFAO – and how together they reinforce a shift toward proactive safety management that builds on positive human contributions. A high-level view of these three elements and their connections appears in Figure 2.

Figure 2

Framework for Resilience, IASMS, And LFAO Working Together Under a Shared Safety Culture



In-Time Aviation Safety Management Systems

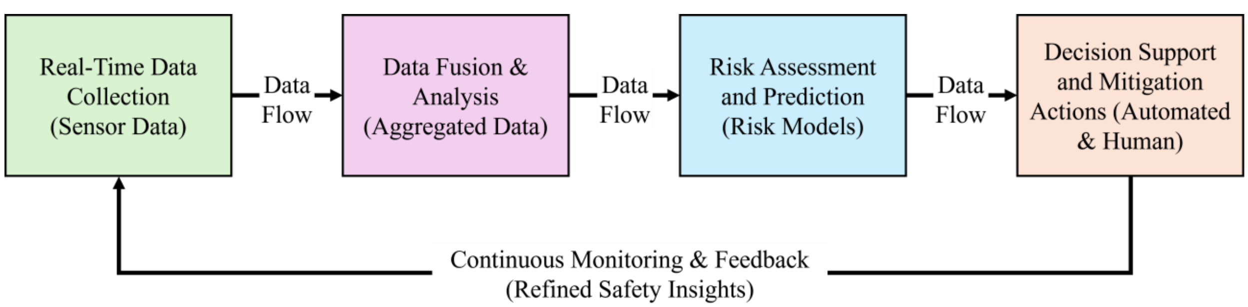
An In-Time Aviation Safety Management System (IASMS) is an integrated set of capabilities that identifies, assesses, and mitigates safety risks during ongoing operations rather than after the fact. It continuously aggregates data from multiple sources (e.g., flight data, aircraft health monitoring, weather, and air traffic systems) and uses predictive analytics to detect emerging hazards in real or near real-time (Ellis et al., 2021a; National Academies, 2018). The goal is to provide decision support or automated interventions *in time* to prevent an incident or accident, effectively shifting safety management closer to the operational timeline. This differs from traditional SMS, which relies on periodic audits, lagging indicators, and retrospective incident analysis (Ancel et al., 2022). Rather than waiting for an incident and then investigating, IASMS focuses on immediacy and proactivity: hazards are addressed as they arise, often before they materialize into adverse outcomes (Ellis et al., 2021a; Ellis et al., 2022b). For example, if predictive flight-data monitoring algorithms detect that an approach is trending towards becoming unstable, IASMS could alert the crew or airline operations center in real-time so that a go-around is initiated, preventing a hard landing or runway excursion. Implementing IASMS widely faces challenges: technological investment, industry coordination, and regulatory adaptation for proactive risk management (Ellis et al., 2022b; Stolzer et al., 2023). Early IASMS designs must also avoid crew task saturation and alert noise by using priority gating, phase-of-flight suppression, and mixed-initiative automation; later sections detail alert quality and workload management.

Several technological enablers underpin IASMS development. Advances in data connectivity allow aircraft to serve as “flying data hubs,” streaming flight parameters to the ground in near real-time. The proliferation of sensors and the digital twin concept provides a richer picture of the aircraft’s state and environment (Aydemir et al., 2020). Big data techniques and machine learning can detect anomalies and predict failures from large datasets. For example, researchers have used machine learning to identify subtle human-factor deviations in normal operations that could lead to incidents if uncorrected (Chen & Zhang, 2014; Nogueira et al., 2023). Such algorithms can reveal precursors, like shifts in pilot control behavior or aircraft performance, that might be missed by traditional rule-based analyses (Soori et al., 2023). However, these approaches face challenges involving validation and false alarms. Experience shows that aviation machine-learning applications must address transparency, large-volume data needs, and rigorous verification before they are trusted in safety-critical roles (Sridhar, 2019). Implementing IASMS involves carefully integrating automated tools with human expertise, a key research priority for future systems (Prinzel et al., 2022).

An IASMS typically involves a structured data-driven safety loop (see Figure 3). First, real-time data collection from onboard sensors, air traffic systems, and the environment feeds into data fusion and analysis algorithms. These algorithms aggregate inputs into a comprehensive risk picture and apply predictive models or machine learning to identify indicators of potential safety threats. Next, the system performs risk assessment and generates decision support for mitigation – for example, prioritizing an alert to a crew or dispatcher or suggesting a specific remedial action. Finally, there is a feedback loop: outcomes and new data are fed back to continually refine the risk models, improving predictive accuracy over time. This sense-and-respond architecture enables hazards to be discovered and mitigated “on the fly,” shifting safety management from a forensic, hindsight-driven activity to an active, foresight-driven one.

Figure 3

Real-Time Data-Driven Risk Assessment and Mitigation Framework For IASMS



NASA and other organizations have been prototyping IASMS concepts, particularly to address emerging domains like uncrewed aircraft systems (UAS) and advanced air mobility (AAM) (Ancel et al., 2022; Ellis et al. 2023). The National Academies (2018) roadmap envisions progressively adding real-time safety assurance capabilities to the National Airspace System over the next decades. Early implementations focus on real-time monitoring of known risks in limited operations, advancing toward adaptive real-time risk management in complex, multi-agent operations by the 2030s. One example is a system for small UAS that performs automated in-flight risk assessments and alerts the operator (or onboard autonomy) of impending safety threshold violations. Ancel et al. (2022) demonstrated an onboard risk management approach for UAS aligned with IASMS principles, using algorithms to continuously evaluate flight risk and trigger mitigating actions when needed. In the commercial air transport realm, Ellis et al. (2022a) describe a future IASMS concept for airlines that would ingest diverse data streams (flight parameters, crew reports, maintenance data, etc.) and provide a real-time risk picture to airline operations centers. Such a system could act as an "always-on safety radar," highlighting flights or situations that need immediate attention.

From an organizational perspective, adopting IASMS implies significant changes in policy and culture. Airlines and aviation authorities will need to enable real-time data sharing and decision-making processes. For example, the ability to quickly transfer data from aircraft to ground systems is essential, as is a mechanism to rapidly disseminate safety advisories system wide. There are early signs of this shift: American Airlines has experimented with near-real-time analysis of flight data to give pilots immediate feedback after landing (a "virtually instant" debrief) (Pasztor, 2017). This demonstrates an appetite for using operational data dynamically to enhance safety and training. Regulators have also encouraged such approaches. The FAA's FOQA program, for instance, was an early effort to collect and analyze routine flight data for proactive safety management (FAA, 2004). Likewise, LOSA involves observing normal flights to glean safety insights (FAA, 2023). An IASMS can be seen as a technologically advanced extension of FOQA/LOSA concepts, with automation and integration enabling a much faster turnaround from data to action.

To implement IASMS broadly, trust and data governance issues must be addressed. Operators may be concerned about data privacy or misuse of real-time monitoring information. It will be important to establish clear agreements that IASMS data is used for safety improvement not punishment, similar to the protections that exist for voluntary reporting programs like FOQA and ASAP (Air Charter Safety Foundation, 2024). With appropriate safeguards, an IASMS augments human vigilance rather than replacing it. Indeed, the greatest benefits occur when real-time technology is combined with resilient operators and a learning-oriented culture. IASMS provides the digital infrastructure for safety, but humans still need to exercise judgment, handle novel situations, and learn from the system's outputs. The following sections examine those human elements – resilience and continuous learning – which ensure that the information and alerts generated by an IASMS are effectively used to enhance safety.

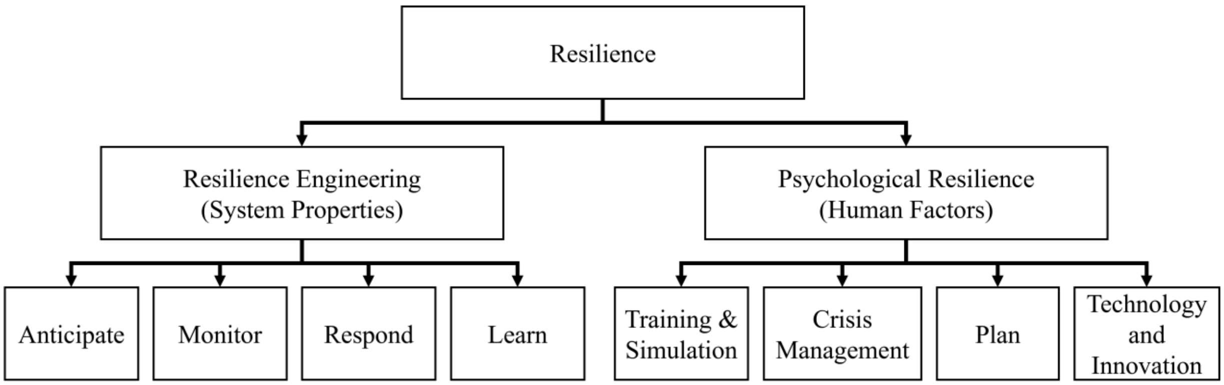
Resilience Engineering and Human Resilience in Aviation

In safety science, *resilience* refers to a socio-technical system's capacity to adapt to and recover from unexpected challenges while sustaining performance. In aviation, this maps to the ability of crews, organizations, and technologies to keep operations safe when conditions deviate from the norm. This modern understanding builds upon decades of foundational research, with the essential elements of resilience being continually revisited and refined (Woods, 2019). Resilience in this context has two interrelated dimensions: (1) *Resilience Engineering* at the system level – designing and managing technology, procedures, and organizations so they can withstand perturbations – and (2) *psychological resilience* at the individual level – equipping pilots, ATC, and others with the mental and behavioral skills to cope with stressors and surprises effectively. Both dimensions are critical to flight deck safety, and in practice, they work together: a resilient cockpit team (through training, experience, and mindset) operates within a resilient system (through a supportive safety culture, flexible procedures, and built-in redundancies). As Leveson (2020) and Carroll and Malmquist (2022) observe, operational flexibility and system design must reinforce each other to achieve resilient performance.

Resilience Engineering as a field arose from the recognition that traditional safety engineering – which focused on preventing component failures and human errors – was not sufficient in complex socio-technical systems (Hollnagel et al., 2006). Instead of only building barriers and redundancies, Resilience Engineering asks: *How can we enhance the system's capacity to adapt in real-time to the unexpected?* Researchers often cite four key capabilities of resilient systems: monitoring (knowing the system's state and environment), responding (reacting effectively to disturbances), learning (updating assumptions based on experience), and anticipating (foreseeing potential disruptions). The capacity to escape failures of foresight is a cornerstone of this approach (Woods, 2009). Woods (2006) introduced this framework, and subsequent work (e.g., Blok et al., 2018) has even attempted to formally model how a complex air transport system might anticipate and dampen emerging issues. In aviation, these principles translate into practices like dynamic re-planning by crews, flexibility in ATC, and extensive use of simulators to prepare for rare or unexpected events. For instance, aircraft are designed with redundant systems so that single failures can be managed – a classical engineering form of resilience (e.g. multiple hydraulic systems or fail-operational flight control modes) (Downer, 2011). But beyond hardware, procedural resilience is built through crew resource management (CRM) training, which instills teamwork and decision-making behaviors for high-pressure situations. A resilient aviation system also relies on a safety culture that encourages people to report problems and anomalies so the organization can learn and improve. Recent studies have proposed models to assess organizational resilience in aviation, linking factors such as management commitment, communication, and mindfulness to safety outcomes (Adjekum & Tous, 2020; Teske & Adjekum, 2022). For example, Teske and Adjekum (2022) found that key HRO principles (e.g., sensitivity to operations, reluctance to simplify, and preoccupation with failure) were positively associated with effective SMS implementation in aerospace organizations. This suggests that cultivating an HRO-style safety culture (sometimes called a *resilience safety culture*) can make an aviation organization more resilient and can complement its formal SMS. Figure 4 illustrates how resilience integrates system-level properties and psychological resilience, emphasizing these capabilities in aviation safety.

Figure 4

Framework for Resilience in Aviation: Resilience Engineering and Psychological Resilience



On the human side, psychological resilience involves an individual's capacity to handle high stress, recover from setbacks, and remain focused. Commercial pilots and controllers regularly face acute stressors (system failures, severe weather) and chronic ones (fatigue, high responsibility). Research shows that people with stronger resilience generally cope better with these challenges, make fewer errors, and experience lower burnout (Cahill et al., 2020; Schwarz et al., 2016). Similar patterns appear in other high-risk fields; for example, resilient firefighters show better health and performance (Blaney & Brunsden, 2015). Key resilience traits include adaptability, emotional regulation, and problem-solving under pressure (Dekker & Lundström, 2007; Perumal & Mariappan, 2023). Aviation increasingly fosters resilience through targeted selection, training, and practice. Military and space agencies include cognitive-behavioral techniques for managing extreme stress (McCall, 2019; McInerney et al., 2022; Whealin et al., 2013). In civilian aviation, CRM has evolved to address the "startle effect" and surprise management, teaching crews how to regain control after unexpected shocks like wind shear or dual-engine failure. Startle is an involuntary physiological and attentional response to a sudden stimulus that briefly degrades cognition and fine motor control (Lang et al., 1990). CRM literature now explicitly links resilience to performance (Martin, 2019). A simulator study by Landman et al. (2018) showed that exposing pilots to unpredictable scenarios improved their ability to handle novel emergencies, essentially "inoculating" them against surprise by building a reserve of adaptive capacity. Airlines now include more resilience-building exercises in recurrent training, and regulators, including the FAA (AC 120-111), mandate elements such as Upset Prevention and Recovery Training (UPRT), which covers both manual recovery techniques and psychological readiness.

Building resilience is not just the crew's responsibility; it also requires organizational support (Samu et al., 2025). A resilient safety culture empowers employees at all levels to act on potential issues and support one another. Such a culture emphasizes continuous learning, flexibility, and empowerment (Akselsson et al., 2009). Just Culture, reporting errors or hazards without fear of reprisal, is vital to ensure the system learns and people remain willing to adapt and speak up (Hollnagel, 2006). For instance, many airlines' ASAP allow voluntary, immunity-protected reporting of safety concerns or personal mistakes, feeding data back into system-wide improvements (Air Charter Safety Foundation, 2024). Further, organizations that invest in cross-training and role redundancy so that crew or dispatch duties, for instance, can be handed off when workload spikes, demonstrate how safety arises from a system's adaptive capacity. Achieving industry-wide resilience demands a unified effort from regulators, manufacturers, and airlines to integrate resilience engineering into standards, training, and design.

Safety culture has four key components: a reporting culture that protects and encourages disclosure of hazards and mistakes; a learning culture that turns reports and routine performance data into concrete changes; flexibility (mindfulness, deference to expertise) that allows roles and procedures to adapt under stress; and leadership commitment to safety that supports the process and resists normalization of deviance (Cooper, 2000; Teske & Adjekum, 2022). These elements align with HRO principles and predict SMS effectiveness in aviation settings.

The benefits of resilience are evident in both everyday work and extreme situations. In normal operations, resilient behaviors by crews can prevent an incident chain from progressing – for example, detecting a subtle instrument anomaly and troubleshooting it before it leads to a larger failure. In abnormal or emergency scenarios, resilience often spells the difference between a safe recovery and an accident. A frequently cited case is the 2010 Qantas Flight 32 engine failure: the crew faced dozens of cascading system failures, yet through teamwork, adaptable problem-solving, and effective use of available resources, they managed to land safely. Analyses attribute this outcome to both the crew's skill and psychological resilience *and* the aircraft's design redundancies that contained the damage (Dekker & Lundström, 2007). Resilience does not mean errors never occur; it means errors do not inevitably lead to catastrophe because they are caught and corrected. As Woods (2015) noted, a resilient system exhibits "graceful extensibility," meaning it can stretch its performance to handle surprises rather than collapse when something goes wrong.

In practical terms, advancing resilience in the flight deck involves:

- Selecting or assessing individuals for traits conducive to resilience (some ATC organizations, for example, use psychological tests for stress tolerance and adaptability in their hiring process) (Cosic et al., 2019);
- Training and experience that build adaptive skills – for instance, scenario-based training with novel and unexpected events (as discussed above) and CRM modules emphasizing decision-making under uncertainty;
- Providing tools and resources that support human adaptability (such as well-designed quick-reference handbooks for non-normal situations, or intelligent decision-support systems that help crews prioritize issues during high-workload situations); and
- Shaping a culture that values flexibility, open communication, and continual learning.

The last point ties directly into the next section: a culture of continuous learning from all operations ensures that both successes and failures inform improvements, thus continuously strengthening the system's resilience. In many ways, resilience and learning are two sides of the same coin – a system cannot be resilient if it does not learn, and what it learns should, in turn, enhance its resilience (Degerman & Wallo, 2024).

Learning from All Operations (LFAO)

Traditional aviation safety practice has relied on event-driven learning: the industry learns from accidents (and serious incidents) by investigating causes and implementing changes. While invaluable, this reactive learning approach has limitations in a high-reliability domain like commercial aviation, where accidents are extremely infrequent (Holbrook et al., 2019). The concept of Learning from All Operations (LFAO) is a more expansive approach that seeks to extract safety lessons continuously from the full spectrum of operations – normal, atypical, and everything in between (Flight Safety Foundation, 2021). The premise is simple: *every* flight is a rich source of data about what went right (or almost went wrong), and by analyzing these data, one can identify trends, precursors, and best practices that would remain invisible if one only studied accidents (Holbrook et al., 2019). This aligns with the Safety-II philosophy of also learning from success. LFAO operationalizes that idea by establishing processes and systems to gather and learn from routine performance, not just anomalies. Implementing LFAO requires a cultural shift to Just Culture, promoting open communication without blame or fear of reprisal.

The aviation industry has been applying these methods for some time through programs like FOQA, LOSA, and ASRS. FOQA continuously monitors digital flight data (from onboard recorders) for deviations or exceedances, allowing airlines to detect unsafe patterns and address them before an incident occurs. For instance, if FOQA data show a rise in unstable approaches at a specific airport, the airline can respond with extra pilot training or revised procedures (Pasztor, 2017). Essentially, FOQA learns from routine flights by flagging parameters that deviate from normal ranges. The FAA acknowledged FOQA’s benefits in a 2004 Advisory Circular, advising airlines to adopt these voluntary programs and noting that early intervention can significantly improve safety (Federal Aviation Administration [FAA], 2004). Line Operations Safety Audit (LOSA) is another tool: trained observers ride in the cockpit jump seat on regular flights to catalog the threats crews face and how they manage them. The LOSA framework specifically focuses on effective threat and error management, not just failures (Klinect et al., 2003). It recognizes that each flight encounters challenges, such as weather, ATC delays, or minor malfunctions and that crew responses can determine whether these issues end safely or lead to an incident. By observing a broad sample of flights without interfering, LOSA captures resilient practices and hidden safety vulnerabilities. Studies like Klinect et al. (2003) show LOSA’s value in identifying both strengths and areas of concern in everyday operations, such as how often crews spot errors and which countermeasures work best.

The ASRS, a national, de-identified reporting system created through a 1976 FAA–NASA memorandum of understanding following the 1974 TWA 514 accident, is a good source to learn from everyday routine operations (NASA, 2001). ASRS gathers voluntary, confidential reports from pilots, controllers, and others on safety issues or anomalies they observe. It holds a wealth of qualitative data on errors, hazards, and successful recoveries in the national airspace. Reporters often describe not only what went wrong but also how it was managed, effectively sharing lessons learned. Over the years, ASRS analysts have identified many systemic issues (e.g., confusing procedures, airport signage problems, automation quirks) by finding patterns in these reports, resulting in fixes without waiting for an accident. One limitation is that ASRS depends on self-reports, so it captures only what individuals notice and decide to share. Even so, it remains a strong example of learning from daily operations. A study by Vempati et al. (2023)

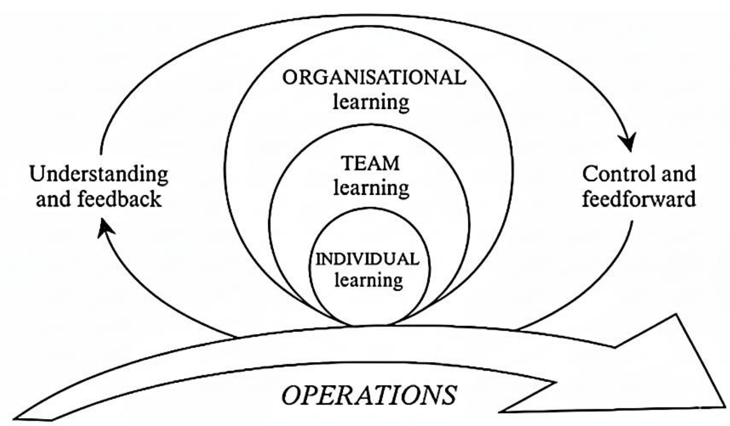
applied text mining to ASRS narrative reports to categorize human factors issues, showing how modern analytics can make the most of free-form data. Many airlines have similar internal ASAP initiatives, encouraging employees to report issues under non-punitive policies. These programs are valuable for uncovering latent problems and "near misses" in which only luck or quick action prevented an accident (Air Charter Safety Foundation, 2024).

Despite these initiatives, LFAO advocates for an even more comprehensive and systematic approach. In 2021, the Flight Safety Foundation published a white paper, "Learning from All Operations: Expanding the Field of Vision to Improve Aviation Safety," essentially a call to adopt LFAO industry-wide (Flight Safety Foundation, 2021). It argues that in an era of ever-safer aviation, waiting for accidents to guide safety strategy is no longer tenable; instead, organizations should leverage all available operational data to drive safety improvements proactively. In 2022, the FSF followed up with a series of "Learning from All Operations" concept notes on operational resilience mechanisms, recognizing that routine operations harbor valuable information about how resilience is achieved or could be strengthened.

LFAO takes place at multiple interdependent levels – individual, team, and organizational learning – as illustrated in Figure 5. At the individual level, learning occurs through a pilot's or controller's personal experience, reflection, and debriefing. Technology can aid this (for example, flight replay software that allows pilots to review their performance shortly after landing, visualizing any deviations or maneuvers). At the team level, learning is facilitated by shared experiences and discussions – crew debriefs or hangar talks where insights into handling complex or unexpected situations are exchanged, improving collective know-how. At the organizational level, lessons from individuals and teams are consolidated to update training programs, standard operating procedures, and safety policies so that improvements discovered on the front lines become embedded in the system. This structured learning process creates both feedback loops (learning from experience) and feedforward loops (anticipating future issues), ensuring that lessons from routine operations continuously refine aviation safety at all levels.

Figure 5

Safety Learning at Three Levels



Note: Adapted from Flight Safety Foundation (2023) with permission for non-commercial purposes.

Concretely, LFAO means integrating diverse data sources: flight data (FOQA), safety reports (ASRS/ASAP), maintenance records, air traffic data, weather information, and even positive feedback mechanisms (like "what went well" reports). By analyzing these collectively, one can identify both emerging risks and exemplars of excellence. For example, Burnell et al. (2022) describe how operators can "create safety in an uncertain world" by studying normal operations to understand how crews successfully navigate uncertainty. They highlight operational practices that are not in manuals but nevertheless contribute to safety – the so-called "untold stories" of success. Some airlines have even established formal Learning Teams; for instance, the American Airlines *Learning and Improvement Team* (LIT), launched in 2020, brings frontline employees together to discuss not just incidents but also instances of exceptionally effective performance to glean practices that could be shared more widely (American Airlines, 2020). In its first phase, American's LIT focused on "what goes well and why," documenting successful strategies crews used in challenging situations (American Airlines, 2021). Such knowledge can then be folded back into training programs or SOP revisions. This approach shifts the safety narrative to also include praise and propagation of positive behaviors, not solely the correction of negatives.

Implementing LFAO on a large scale is greatly aided by technology. Modern data platforms and AI techniques can handle the big data generated by thousands of flights (Aydemir et al., 2020). For instance, Natural Language Processing (NLP) can sift through vast numbers of safety reports to find common themes (NASA has demonstrated this by applying machine learning to ASRS reports – Barshi et al., 2023). Data fusion can link disparate streams – for example, correlating a spike in unstable approach parameters from FOQA with an uptick in ASRS pilot reports about a particular runway's optical illusion. As noted earlier, an IASMS provides an ideal infrastructure for LFAO: it is essentially the data "plumbing" and analytics engine that can facilitate continuous learning. Ellis et al. (2023) highlight that IASMS and LFAO are complementary – an IASMS enables LFAO by integrating safety management with everyday operational data. In fact, one envisioned function of an IASMS is to act as a real-time learning system, where each operational data point updates risk models and informs the next flight or shift in near real time (Nogueira et al., 2023).

Table 1 catalogs the main LFAO data sources; FOQA (parametric), LOSA (observational), ASRS/ASAP (narrative), AQP/IEP (training/assurance), and local debrief tools, plus typical uses and constraints. Two practical takeaways: parametric exceedances need context to avoid false signals, and narrative sources require trust and non-punitive protections to sustain reporting.

Table 1

Key LFAO Data Sources and Their Applications in Aviation Safety Management

Data Source	What is Collected	Use in Safety Management	Challenges and Limitations
Flight Operational Quality Assurance (FOQA)	Digital flight parameters (FDR/QAR data) on normal ops, e.g. airspeed, altitude, attitude, config, event flags	Early risk detection via exceedance trending, pinpoint training/procedural gaps, proactive hazard fixes, refined SOP	High cost for data systems and analysis, pilot trust concerns, potential data overload, context missing if only numeric exceedances are used
Line Operations Safety Audit (LOSA)	In-flight observations by trained auditors capturing real-time crew actions, threat/error management, CRM usage	Identifies everyday ops successes and vulnerabilities, reveals how threats and errors are managed or mismanaged, shapes targeted safety improvements	Labor-intensive, sample limited to a few flights, potential Hawthorne effect, requires strong crew buy-in and non-punitive culture
Aviation Safety Action Program (ASAP)	Voluntary safety event narratives from employees (pilots, mechanics, dispatch) under ERC oversight, describing near misses or errors	Feeds SMS with insider operational insights, captures context behind incidents, fosters fix-before-accident approach, synergy with FOQA for root causes	Participation hinges on non-punitive trust, narrative is subjective, analyzing large unstructured text is resource-heavy, some events may remain under-reported
Aviation Safety Reporting System (ASRS)	National-level, de-identified, first-person incident reports from all aviation personnel, describing anomalies or close calls	Spotlights emergent hazards system-wide, prompts bulletins/alerts, fosters cross-industry lessons to close safety gaps without waiting for accidents	Entirely voluntary, might miss hidden or routine issues, can be incomplete or biased, no direct follow-up with reporters, a "big data" text-mining challenge
Advanced Qualification Program (AQP)	Extensive crew performance data from simulator checks, LOFT, plus operational data to shape training design, repeated skill evaluations over time	Enables data-driven, scenario-based training customized to actual line risks, continuous feedback loop ensures training evolves with new hazards	Implementation complexity, heavy data demands, requires instructor calibration, risk of "training to the metrics," smaller ops find it expensive to maintain
Internal Evaluation Program (IEP)	Self-audit metrics across flight, dispatch, maintenance, ground ops, assessing compliance with regs and SOP, yields findings and recommended actions	Provides ongoing organizational "health check," detects compliance drift or hidden hazards, supports early correction prior to incidents, merges into SMS for assurance	Possibly shallow if not strongly supported, risk of internal bias or ignoring negative findings, requires rigorous close loop fix enforcement
"Shop Talk" (e.g. American Airlines LIT)	Informal, facilitated discussions with flight crews capturing day-to-day successes, near misses, workarounds, or best practices, focusing on how operations really happen	Surfaces resilience strategies, small "wins," unseen friction points, fosters an environment where line employees shape safety improvements, complements numeric data with context of "why it worked"	Demand on time for personal interviews, building trust so crews share openly, data is anecdotal, must be carefully codified to yield systemic improvements, scale is limited
Flight Data Replay Tools (CEFA etc.)	Post-flight high-fidelity flight animations derived from recorded flight parameters, enabling immediate 3D visual replays of the crew's operation	Facilitates personal pilot debrief, helps them see subtle errors or successes, fosters a self-correcting culture in normal ops, synergy with FOQA if used to contextualize exceedances, strengthens continuous learning	Potential misuse or perceived punitive effect if not carefully implemented, demands robust software/EFB infrastructure, some flight parameters might be lacking detail, no direct organizational aggregator unless pilots voluntarily share insights

Note: Acronym definitions for terms used in this table are provided in Appendix A.

LFAO is not without challenges. A major challenge is data management and quality. Routine operations produce an ocean of data, and making sense of it requires robust analytical capabilities as well as discernment to separate signal from noise. The U.S. National Academies (2018) noted that aligning and fusing heterogeneous data sources is difficult, as is developing algorithms to reliably identify safety-relevant patterns. Not every exceedance or anomaly truly indicates a safety risk – context matters (for example, a steep approach angle might be intentional for a short runway). This means human expertise remains vital to interpret analysis outputs and to decide which findings are truly actionable. Another challenge is organizational culture and resource allocation. Committing to LFAO means investing time and money into analyzing data that, on the surface, did not cause an obvious incident. Organizations might be tempted to prioritize other areas with clearer immediate ROI. There is also a risk of information overload for frontline crews if feedback is not managed well – pilots cannot be inundated with dozens of minor findings after every flight without diminishing returns. Effective LFAO requires focusing on the most important insights and presenting them in a way that supports improvement without overwhelming staff. However, these efforts need regulatory and organizational support.

Resistance to change may arise when implementing LFAO, as with any new safety program. Employees might worry that expanded monitoring equates to “Big Brother” surveillance of their work. *Trust* and *Just Culture* are crucial components of what scholar Amy Edmondson (2018) calls psychological safety — a shared belief that one will not be punished or humiliated for speaking up with ideas, questions, concerns, or mistakes. Without psychological safety, data from normal operations will not be shared freely for learning, and the LFAO data stream will dry up as personnel avoid reporting (Samu et al., 2025). The United States Government Accountability Office (GAO, 1997) observed that early FOQA efforts succeeded only after clear agreements ensured the data would not be used for individual discipline. The same principle extends to any LFAO initiative. Transparent communication about LFAO’s goals and safeguards – for example, stating that if a trend of unstable approaches is identified, the response will be additional training or procedure changes, *not* reprimands for individual pilots – can help alleviate concerns. Some skeptics of Safety-II initially worried that focusing on successes might breed complacency, but proponents clarify that it is *not* about ignoring problems – it is about capturing all data, good and bad, to get a complete picture of safety. Building an LFAO culture requires change management: people may resist new practices, especially if they see them as extra work or a threat to established routines. Management must be convinced of the long-term benefits and champion the effort. Showing “quick wins” from early LFAO efforts – for instance, how analyzing routine data *prevented* a potential incident or saved costs by improving efficiency – can build buy-in and momentum. These efforts must be supported by targeted investments in infrastructure and workforce.

Despite these hurdles, the opportunities presented by LFAO are enormous. By learning from day-to-day operations, aviation can address risks at an earlier stage – for example, discovering a subtle procedural issue that crews consistently work around (and fixing it) before it contributes to an incident (Burnell et al., 2022; Prinzel et al., 2024). Importantly, safety data often reveal operational inefficiencies where improvements benefit both safety *and* productivity, demonstrating how these frameworks collectively advance operational excellence. Integrating IASMS, LFAO, and Resilience does not merely mitigate risks; it raises a more adaptive, efficient, and optimized aviation ecosystem. Furthermore, LFAO feeds directly into resilience: understanding how and why operations succeed under varying conditions helps in training others to be more adaptable and in refining system designs to support those successful behaviors. The continuous feedback loop essentially turns the operation itself into a learning environment. As Hollnagel (2018) put it, *even when nothing bad happens, there is still something to be learned about why it went right*.

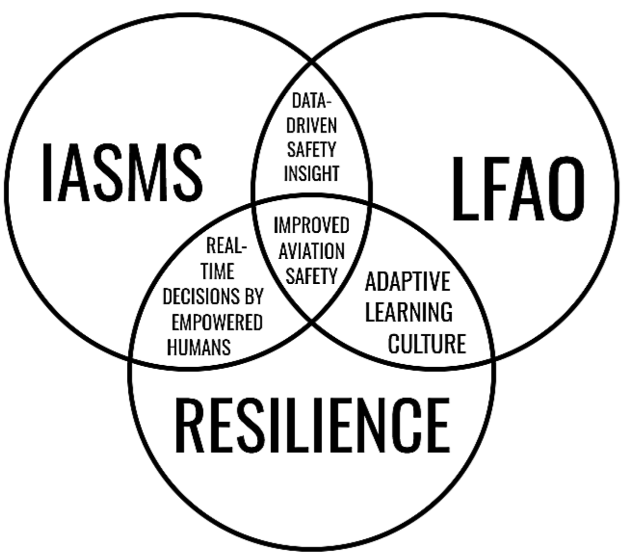
LFAO extends the scope of safety management to *every* flight, *every* day. It uses technology and human expertise to transform the vast amount of routine operational data into practical safety knowledge. Combined with an IASMS framework to gather and analyze data in real-time, and a resilience ethos that values human adaptability, LFAO is a key pillar of the evolved safety strategy. It ensures that the aviation system is not just waiting to react to rare failures but is actively learning and improving from the constant flow of experiences in normal service.

Integration of In-Time Systems, Resilience, and Continuous Learning

Addressing the research question, this section shows how IASMS (real-time monitoring), resilience (adaptive capacity), and LFAO (continuous learning) operate as a single safety loop during line operations. Individually, IASMS, resilience, and LFAO each offer significant safety benefits. Together, as illustrated by overlapping circles in Figure 6, they form a mutually reinforcing triad that defines a new, holistic approach to flight deck safety. An IASMS provides the digital and procedural infrastructure for real-time monitoring and response – essentially the "nervous system" of the safety organism (Ellis et al., 2021a; 2022b). Resilience provides the muscles and reflexes – the ability of human and organizational elements to respond effectively to the signals the IASMS detects. LFAO serves as the memory and brain – continuously updating the system's knowledge and improving both the IASMS's algorithms and the humans' strategies over time (Holbrook et al., 2019). Each component also reinforces the others: insights from everyday operations (via continuous learning) can feed into IASMS models so that automated recommendations reflect successful human strategies and resilience principles can guide the design of IASMS interventions, so the system supports human adaptability rather than undermining it. When these components operate in harmony, safety management becomes a dynamic, adaptive process grounded equally in technology and human expertise. Beyond safety gains, this integration drives overall operational benefits: streamlined workflows, reduced delays from proactive risk mitigation, and data-informed process optimizations that enhance both reliability and resource efficiency.

Figure 6

IASMS, Resilience, and LFAO Reinforcement Triad to Improved Aviation Safety



To illustrate how this integrated approach differs from a traditional one, consider a hypothetical scenario: A new avionics software update inadvertently causes occasional *spurious warnings* in the cockpit that startle or confuse pilots. Under a conventional Safety-I setup, if these false alerts do not directly lead to an incident, they might go unnoticed by safety managers for a long time (perhaps only a few pilot complaints or a maintenance log entry would trickle in). Under an integrated IASMS–Resilience–LFAO approach, several things would happen in short order. The IASMS, continuously monitoring flight data, might detect an uptick in unusual autopilot disconnects or button presses associated with the spurious warnings and flag this as an anomalous pattern (Nogueira et al., 2023). Pilots, feeling safe to report even non-critical issues thanks to a just culture, would submit ASAP reports about confusing or distracting alerts. The LFAO process would correlate these inputs (data and human reports) and quickly identify that the new software version is prompting unexpected crew responses. Because the organization values frontline feedback, an expedited safety assessment or user evaluation would be initiated. In the meantime, resilience in practice is shown by crews adapting – for example, they might develop a quick workaround or an extra verbal cross-check to verify whether an alert is real or false. Those resilient behaviors (if effective) would be captured via LOSA observations or debriefs and shared as interim guidance to other crews (i.e., learning from what operations are already doing to cope). Ultimately, engineering fixes the software bug – but in the interim, the integrated system *already mitigated* the safety risk through human adaptation informed by data (and ensured the workaround was disseminated). This example demonstrates the synergy: IASMS catches the early signs, human resilience manages the issue safely in real-time, and continuous LFAO disseminates the solution across the fleet.

Implementing this integration may require evolving an organization's safety structure. Traditionally, flight safety departments analyze incidents, training departments train for known scenarios, and operational control centers focus on flight-following and daily efficiency. In a fully integrated model, these silos blur. We may see safety intelligence centers where data analysts (from safety) sit side by side with operations controllers, jointly using IASMS tools to inform decisions in real time (Stephens, 2023). Training departments would receive continuous feedback from LFAO outputs – if data show that pilots handle one scenario well but struggle with another, training programs can be adjusted within months rather than waiting for years or an accident to reveal the gap. In effect, continuous learning permeates into continuous training and procedure development. American Airlines' approach with its LIT foreshadows this, as insights from frontline discussions were fed into new safety strategies and training in subsequent phases (American Airlines, 2020; 2021).

Integration also needs to extend beyond a single airline because the aviation system is highly interdependent. A resilient, in-time safety approach will likely involve real-time data sharing across stakeholders – airlines, ATC, manufacturers, and regulators. For example, if an airline's IASMS detects a novel hazard (say, a rapidly forming microburst on an approach path or a confusing navigation anomaly), it could alert air traffic control and other nearby aircraft, essentially performing a real-time safety broadcast to the wider system. This suggests the need for system-wide IASMS interoperability and data standards. NASA's vision of a "Sky for All" future airspace (with drones, air taxis, and other new vehicles) anticipates extensive data exchange and collaboration to manage safety in a complex environment, and IASMS is a cornerstone of that vision (Yu et al., 2022). Achieving it will require integrating technology, human resilience, and learning at a broad scale – not just within one company but across the aviation ecosystem.

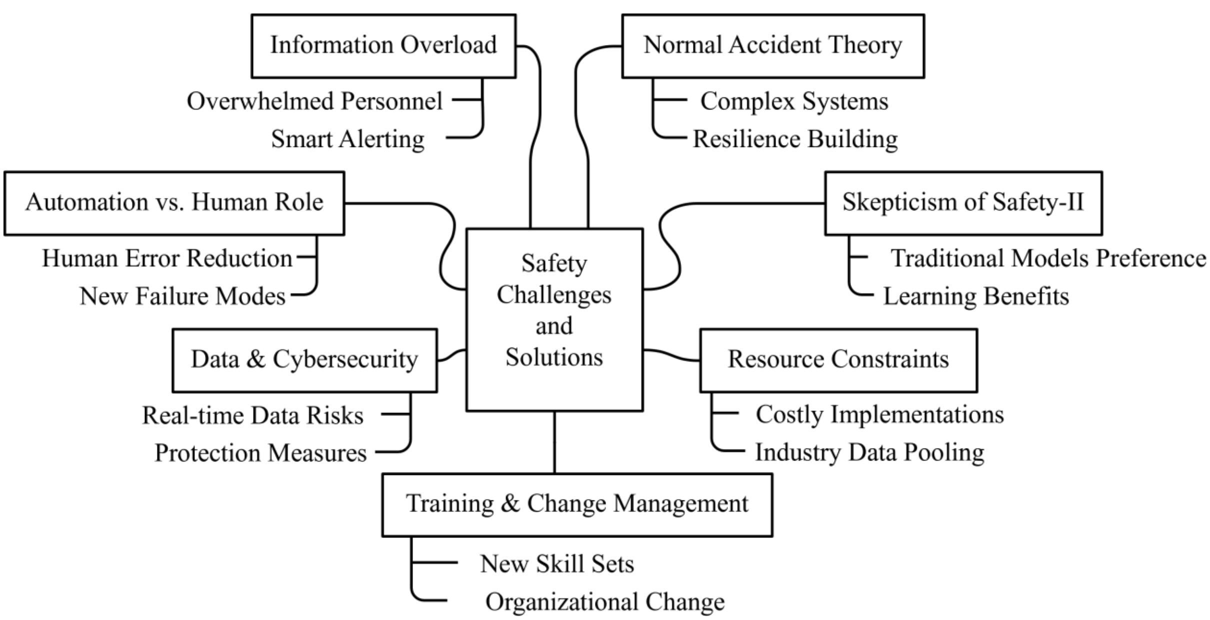
Integration means that IASMS (the technological nervous system), human/organizational resilience (the adaptive capacity), and LFAO (the continual learning process) are designed to function as one safety ecosystem. Data from operations feed the safety system; the safety system supports the humans; the humans adapt and innovate; and those innovations are captured as data and turned into new safety knowledge. This creates a reinforcing loop: the more we learn from operations, the more we can enhance both automation and training; the better our automation and training, the more resilient our operations become; and the more resilient and well-monitored the operations, the more data we gather and the fewer incidents we experience – allowing us to learn even subtler lessons. Over time, this should yield a safety performance that asymptotically approaches perfection (even if absolute perfection is unreachable, the gap becomes vanishingly small) while simultaneously advancing operational efficiency, adaptability, and systemic excellence. It is an ambitious vision, essentially aiming for an accident-free aviation system by harnessing the full capabilities of both humans and machines, a future where 'safer' unequivocally means 'better.'

Contrasting Perspectives and Challenges

While the integrated approach of in-time systems, resilience, and LFAO is compelling, it is important to critically examine potential counterarguments, limitations, and implementation challenges (Figure 7). Not everyone in the aviation community is fully convinced of these new concepts, and legitimate concerns have been raised that must be addressed to ensure successful adoption.

Figure 7

Safety Challenges and Solutions in Aviation



Automation vs. Human Role

An automation-centric view argues that the solution to human error lies in removing or minimizing the human role through advanced automation or autonomous aircraft. Advocates see investments in human resilience or human performance learning as temporary measures, suggesting that highly automated or pilotless aircraft could eventually eliminate human variability. This perspective posits that automation alone can achieve higher reliability by standardizing responses to known risks and eliminating the unpredictability of human decision-making. Recent industry positions resisting single-pilot airliners cite workload, abnormal-event management, and the value of team resilience, consistent with treating humans and automation as a coupled team (States News Service, 2025; Varley, 2025). Rather than removing humans, this paper supports redefining their role: automation should manage routine tasks and known risks, while humans focus on high-level decision-making and adaptive responses to novel situations (Prinzel et al., 2023; Weick & Sutcliffe, 2007). The integrated approach treats humans and automation as a resilient team. Notably, growing autonomy in domains like Advanced Air Mobility has only reinforced the need for IASMS; NASA researchers emphasize that as autonomy increases, real-time safety assurance must also expand to manage new risk types (Ellis et al., 2022b).

Information Overload and HMI

A key concern from the human-factors perspective is information overload: could IASMS flood pilots and dispatchers with too many alerts and too much data? Poorly tuned systems may overwhelm crews with nuisance warnings or ambiguous guidance, risking distraction and degraded performance. The situation mirrors modern cars, whose excessive alerts prompt users to tune them out. To prevent this, human-factors engineering must be applied rigorously: alerts should be meaningful, properly prioritized, and minimally intrusive. Tiered or "smart" alerting systems can help — for example, suppressing lower-priority warnings during high-workload phases, much like the Traffic Collision Avoidance System (TCAS) and Enhanced Ground Proximity Warning System (EGPWS) defer non-urgent messages in critical flight segments. Research on adaptive interfaces supports this approach (Prinzel et al., 2024; Prinzel et al., 2023). The system should act like a well-trained copilot, offering the *right information at the right time*. This requires iterative design, testing, pilot, and operator involvement in development through simulations and trial programs, reinforcing the role of learning and feedback in building usable, trusted systems.

"Normal Accident" Theory and Complexity

Charles Perrow's Normal Accident Theory (NAT) argues that, in complex, tightly coupled systems like aviation, accidents are inevitable ("normal") due to unforeseen interactions. From this perspective, even with IASMS, resilience, and LFAO, incidents will still occur, and added complexity from new safety systems may introduce novel failure modes. A recent review by Muecklich et al. (2023) of NAT vs. HRO vs. Resilience Engineering noted that while NAT highlights irreducible risk, HRO and resilience frameworks provide ways to manage complexity. The integrated approach in this paper directly addresses NAT's concerns: recognizing that surprises will happen, it focuses on enhancing the system's capacity to cope (via resilience), detect early signals (via IASMS), and adapt continuously (via LFAO). It is true that IASMS adds complexity and could itself fail—through bugs, data errors, or misclassification. To manage this, IASMS must be designed with fail-safe logic so that failures do not worsen outcomes, and its implementation should be incremental and carefully tested (for example, running it in advisory mode alongside normal ops before entirely relying on it) to ensure it does not inadvertently reduce safety.

Skepticism of Safety-II/Learning Approach

Some critics question whether the Safety-II philosophy and its emphasis on learning from success yield actionable safety improvements (Carson-Stevens et al., 2018; Lawton, 2018). Detractors argue it may distract from failure prevention or lack a clear methodology. This is especially common among those grounded in the Safety-I paradigm, where risk is managed by eliminating known causes of failure. Safety-II implementation has faced barriers in fields like healthcare due to vague guidance on collecting and applying data from everyday successes. However, such critiques hold less weight in aviation, where established practices like LOSA, ASAP, and FOQA already institutionalize learning from normal operations. For example, LOSA has led to procedure changes and training adjustments by uncovering crew strategies for managing threats and errors during regular flights (Klinect et al., 2003). Building a Safety-II culture requires organizational change. People and institutions can resist new practices, especially if they see them as extra work or threatening established routines. Management must be convinced of the long-term return on investment of practices like LFAO that may not show an immediate dramatic gain (since the gains are often *incidents that never happened* and thus "invisible"). Strong safety leadership and clear communication of the long-term benefits are key. Demonstrating some quick, concrete wins from early LFAO initiatives – for example, showing how analysis of routine data prevented a potential incident or saved money by optimizing operations – can help overcome skepticism and build momentum.

Resource and Cost Constraints

A practical challenge in implementing advanced safety systems like IASMS with sophisticated analytics, conducting LOSA observations, and analyzing extensive ASRS/ASAP datasets is the substantial resources and cost required (Ellis et al., 2021b). IASMS and advanced analytics require skilled personnel, advanced data infrastructure, computational architectures, data processing capabilities for large, disparate datasets, and sustained funding for technology, staffing, and operations (Stolzer et al., 2023). These demands can strain smaller operators, who often have limited financial resources and face challenges scaling SMS complexity to their size (National Academies, 2018). The high cost-to-benefit ratio can impede implementation, especially for operators unable to invest in new systems. Industry-wide data-sharing initiatives and centralized tools like ASIAS aggregate data across carriers, enabling the identification of systemic problems and emerging risks that individual carriers might miss while reducing the burden on smaller operators (Ellis et al., 2022b; Prinzel et al., 2023). Third-party providers also offer SMS services to assist smaller operators (Ellis et al., 2022b). Engaging pilots, controllers, maintenance staff, and leadership is necessary to ensure frontline feedback drives safety strategies (Danner & Geske, 2022). Voluntary, non-punitive reporting through platforms like ASRS remains critical for capturing frontline reports and identifying gaps between operations and procedures, supported by strong non-punitive policies (Chialastri & Pozzi, 2008). Regulators can further promote adoption by offering incentives, facilitating shared services, and harmonizing measures among stakeholders (Danner & Geske, 2022; Ellis et al., 2023b). Given today's low accident rates, some question whether further investment delivers diminishing returns, making the cost-benefit argument difficult (PARC-CAST, 2013). However, as air traffic grows, even a stable accident rate results in more events, and a single major accident can impose immense human and financial costs (FAA, 2004). Preventing one catastrophe justifies the investment based on low-probability, high-consequence risk logic (Chialastri & Pozzi, 2008). These efforts can also yield tangible economic benefits, such as increased reliability, reduced fuel consumption, decreased maintenance costs, and increased operational efficiency by minimizing delays and equipment damage (Ellis et al., 2022b; Muecklich et al., 2023).

Training and Change Management

A key implementation challenge is cultivating the necessary skills and mindset among personnel. Pilots, dispatchers, and safety managers will need training to interpret and apply outputs from advanced analytics and decision-support tools. Tomorrow's airline pilot may need to work as comfortably with AI-generated safety recommendations as with traditional checklists, an area not typically addressed in current pilot training. Safety analysts may also require cross-training in data science to manage large-scale data flows effectively. This reflects a fundamental transformation of the safety professional's role, shifting from a compliance focus to one that actively engineers resilience into practice (Provan et al., 2020). Resistance from veteran staff accustomed to established practices is likely. Overcoming this resistance is essential for building system resilience (Laidoune et al., 2022). Organizational change management strategies, such as early stakeholder involvement, sufficient training, and strong leadership support, will be critical (Jacobs et al., 2013). Regulatory frameworks must also adapt. Current rules assume fixed reporting and procedural models that may not accommodate real-time safety management. Agencies like the FAA and EASA will need to provide guidance on operationalizing IASMS outputs and evaluating LFAO processes, as they did when implementing SMS requirements. Legal and liability questions will also emerge: for example, if an IASMS predicts a risk that is ignored and an accident follows, how is accountability determined? These issues must be resolved as the technology matures. Encouragingly, regulators are actively evolving the framework to support such advancements. While ICAO's 2016 Annex 19 update emphasized proactive safety management, Amendment 2 of 2025 signals a continued push towards more integrated and effective SMS implementation (FAA, 2025). By extending safety management principles to new sectors like remotely piloted aircraft and enhancing the links between state and service provider systems, this change underscores the regulatory trajectory towards the exact type of proactive, data-driven oversight that an IASMS would provide.

Data and Cybersecurity Challenges

There are also technical and logistical challenges to integration. For IASMS, one challenge is ensuring data interoperability and cybersecurity. Real-time data sharing between aircraft, airlines, and possibly ATC means a lot of data in motion. Protecting this data from cyber threats is critical – a compromised safety monitoring system could itself become a hazard (Mäurer & Bilzhause, 2018). Robust encryption, access controls, and fail-safe modes if data become unreliable will be needed. Likewise, standard data formats and protocols must be developed so that different systems (across manufacturers or between aircraft and ground) can communicate seamlessly. Government and industry standards bodies will need to collaborate on this front (perhaps extend existing standards like ARINC or develop new ones specifically for real-time safety data exchange).

In weighing these counterpoints, while the integrated approach is not a cure-all and must be implemented carefully, its potential benefits far outweigh the drawbacks, provided the challenges are managed. Aviation history shows repeated success in balancing technology with human factors and overcoming initial skepticism, examples include early resistance to crew resource management and fly-by-wire systems, both now standard. This paper's position is that by acknowledging criticisms and addressing them through sound design, policy, training, and cultural adaptation, the aviation community can move confidently toward a proactive safety system. The following section synthesizes this discussion and outlines practical steps forward.

Limitations and Future Work

Current limitations include the IASMS–Resilience–LFAO model's reliance on established data infrastructure and governance, which some operators have yet to implement. The validation of machine-learning-based monitors can be complex and subject to false alerts. Reporting and acceptance of real-time feedback may be affected by organizational culture, while regulatory frameworks continue to adjust for in-time use of safety data. Cybersecurity and interoperability issues also impact real-time data exchange. Smaller operators may encounter resource constraints that impede adoption.

Future work priorities include: (1) human-machine interface research that reduces alert fatigue and supports prioritization under high workload; (2) quantitative measures for "time from hazard detection to mitigation" to track system performance; (3) data-ethics models for real-time safety use, including guardrails against punitive misuse; (4) methods to integrate ATC safety cues with airline IASMS tools; (5) replication studies that show incident-rate or precursor-rate changes from LFAO programs; and (6) scalable pathways for small operators (shared services, pooled analytics).

Conclusion and Recommendations for Advancing Flight Deck Safety

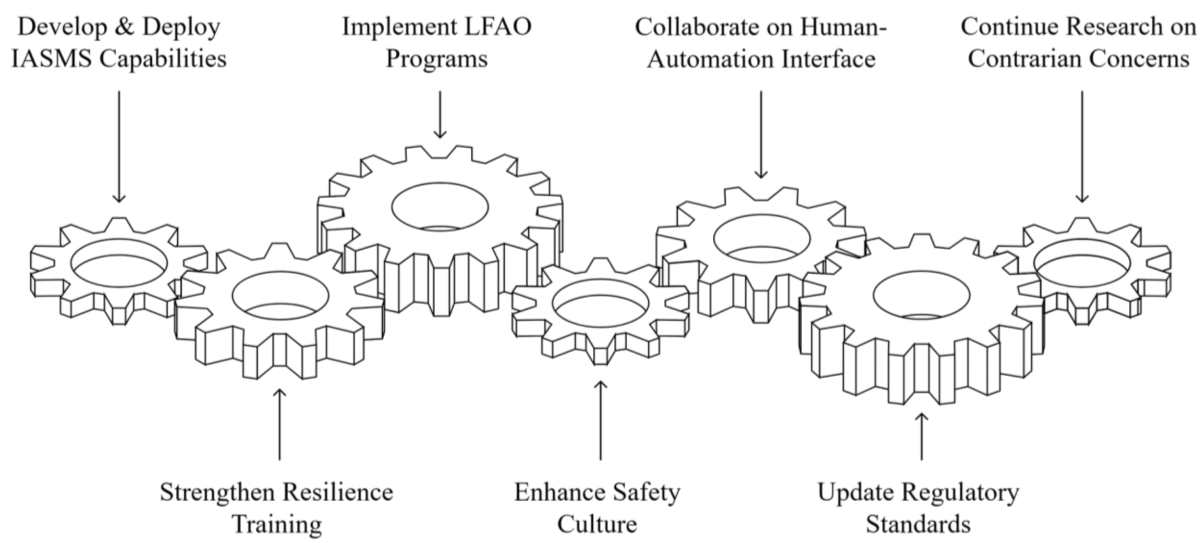
The analysis presented in this paper supports a clear position: the future of flight deck safety lies in a proactive, integrated safety management paradigm that fuses advanced real-time safety systems (IASMS), the cultivation of resilience at all levels, and continuous learning from the full breadth of operations. This integrated approach represents an evolution from the traditional accident-centric view of safety to one that harnesses both technology and human adaptability to prevent accidents and incidents *before* they occur. Rather than viewing pilots and other humans as problems to be managed, it treats them as essential partners in safety – agents whose actions often create safety and whose insights are invaluable (Barshi, 2024; Holbrook et al., 2019). In-Time Safety Management Systems provide unprecedented capability to detect and mitigate risks in flight; resilience principles ensure that both the system and the personnel can effectively handle those risks and surprises; and LFAO closes the loop by using everyday data to drive improvements in both technology and human performance. Together, these elements form a reinforcing cycle of safety improvement that can help aviation reach new levels of safety performance, even as the industry grows, and new complexities arise. This position is evidence-based: research and trials have demonstrated the feasibility and benefits of each component – from NASA's IASMS prototypes (Ellis et al., 2023), to tangible safety gains from FOQA/LOSA programs (FAA, 2023; Klinect et al., 2003), to case studies of resilient responses averting disaster (Dekker & Lundström, 2007). By embracing this integrated philosophy, the aviation industry can move closer to the aspirational goal of zero accidents, while also enhancing efficiency and adaptability. Considering these findings, a multi-faceted action plan is proposed below to implement this vision. Together, the integration mapping (Figures 2–6), the line-ops scenario, and the operational metrics address the research question.

Action Plan

To advance flight deck safety in line with this position, a multi-faceted and phased action plan is necessary. Realizing this vision will also require a concerted industry-wide effort, including regulatory evolution and organizational culture change to embrace proactive safety management. The following recommendations (Figure 8) outline steps for industry stakeholders – airlines, regulators, manufacturers, and researchers – to implement the vision:

Figure 8

Multi-Faceted Aviation Safety Action Plan (Summary of Recommended Steps)



Develop and Deploy IASMS Capabilities Gradually

Collaborate on developing in-time safety management capabilities through pilot programs and incremental rollouts. For instance, airlines can introduce IASMS tools in a *shadow* (advisory-only) mode in their operations control centers to validate hazard-detection algorithms without affecting real flights. Regulators (e.g. FAA) should provide guidance and oversight into these trials, ensuring data accuracy and addressing any compliance issues. Early implementations might focus on specific risk areas with well-characterized data – for example, real-time monitoring of approach-and-landing stability or of engine health parameters. Research by NASA and others (e.g. Ellis et al., 2022a; 2023 on commercial IASMS concepts) can guide system requirements. Over time, as confidence in the system grows, integrate IASMS alerts into decision-making processes: for example, allow airline ops controllers to recommend flight profile changes or proactive maintenance actions based on IASMS predictions (with appropriate training and protocols). Eventually, formalize IASMS as part of standard SMS processes, with regulatory acceptance, such that credit is given for hazards mitigated in real-time. A key part of this rollout is establishing data-sharing standards and cybersecurity measures. Industry committees (RTCA, EUROCAE, etc.) should develop common standards for IASMS data formats and protection, learning from existing ones (such as those for ACARS or for ASAP data).

Strengthen Resilience Training and Assessment

To make full use of in-time safety data and prepare for unexpected situations, the industry should formalize resilience training for flight crews and safety-critical personnel. Pilot curricula should include novel, unpredictable scenarios (building on UPRT and CRM) to strengthen adaptive decision-making (Green, 2023; Landman et al., 2018). Ground school should incorporate real-world examples of resilience, not just technical instruction. Beyond the simulator, workshops and debriefs (e.g., post-LOSA) can help crews reflect on and refine adaptive strategies. Regulators should embed resilience in competency frameworks (IATA, 2025). Though measuring resilience is complex, practical indicators include self-assessments (Pediconi et al., 2020), observed performance in surprise drills, and incident outcome trends (Taran, 2019). Cross-sector expertise—such as cognitive training from military domains—can strengthen program design (McCall, 2019; McGraw, 2023; McInerney et al., 2022). Organizations should formally recognize resilient performance. Normalizing resilience as a shared responsibility fosters a culture of adaptability and proactive safety.

Implement Comprehensive LFAO Programs

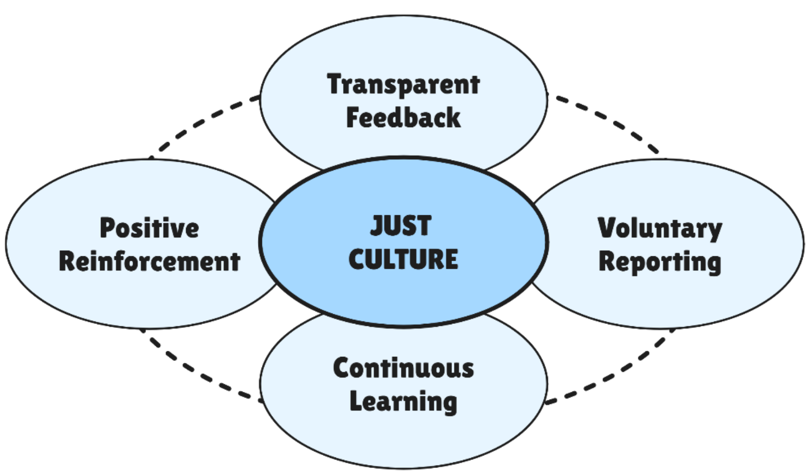
Airlines should support learning from all operations at both the individual and organizational level (Samu et al., 2025). To support LFAO at the individual level, airlines should enhance opportunities for continuous learning such as debrief tools and techniques. A telling indicator of change will be when debriefings after normal flights become as routine for noting successes as they are for dissecting problems. Industry conferences and publications should also regularly feature “what goes right” case studies, not just incident or accident analyses, reinforcing positive learning. Disseminating these findings ensures that the industry provides structural support for front-line workers to learn from all operations. At an organizational level, the industry should establish structures for sharing non-competitive safety knowledge. The FAA’s Aviation Safety Information Analysis and Sharing program (ASIAS) serves as a strong example, aggregating FOQA and ASRS data across airlines to identify systemic issues (for instance, industry-wide unstable approach trends) while preserving anonymity. Expanding ASIAS and similar initiatives globally, backed by broader participation and near-real-time data sharing of selected metrics, will amplify LFAO gains across the sector. Regulators should encourage or mandate airline involvement in these data-sharing networks as part of SMS requirements, with suitable protections in place to maintain trust. Further, airlines must include frontline employees in driving organizational resilience for example, replicating programs like American Airlines LIT, which hold periodic “shop talk” sessions with pilots, flight attendants, and dispatchers to surface new ideas on improving safety and efficiency (American Airlines, 2020; 2021). These qualitative contributions supplement quantitative data, often revealing human, organizational, or design-related concerns that raw numbers alone might miss, for example, an awkward checklist that crews consistently find workarounds for. By adopting and acting on such feedback, airlines can make ongoing incremental refinements that, together, yield a safer system.

Enhance Safety Culture and Just Culture Policies

A positive, informed safety culture supports resilience and learning. Airline management must reinforce Just Culture principles and ensure that front line workers know that new data streams will not be used punitively but to drive improvement. Strong, effective leadership is key to resilience (Yu et al., 2022), so leaders must champion these cultural changes. Regulators can assist by providing legal protections for voluntary safety information sharing (as the FAA and NASA do with ASRS immunity in the U.S.). To acknowledge human contributions, organizations should collect information on positive human performance and return that information into training design to support and encourage an effective safety culture. Another cultural factor is mindfulness, in line with High Reliability Theory (Weick & Sutcliffe, 2007). Training and workshops on HRO principles, sensitivity to operations, deference to expertise, preoccupation with failure, can embed vigilance and open communication about possible safety concerns. For example, a ramp worker who notices an unusual pattern of ice accumulation might feel empowered to alert flight operations because the culture values speaking up, even outside one’s direct responsibilities. Because safety culture strongly affects performance (Cooper, 2000), organizations should regularly assess it (through surveys or audits; Freiwald et al., 2013) while implementing these Just Culture and learning-oriented policies. Figure 9 shows the safety culture ecosystem helping these practices.

Figure 9

Enhanced Safety Culture Ecosystem



Collaborate on Human–Automation Interface Improvements

As IASMS and other advanced tools enter operations, industry and academia must collaborate, so these technologies aid rather than hinder the humans in the loop. Research and development should continue in areas such as adaptive alerting, intuitive data visualization, and crew decision-support systems. End users (pilots, dispatchers, ATC) should be involved early in design through human-in-the-loop simulations.

Update Regulatory and Industry Standards

Regulators should integrate the principles discussed here into their safety oversight frameworks. New Advisory Circulars or guidance could be published on implementing LFAO or strengthening resilience, ensuring consistent adoption. Over time, elements such as IASMS may become expected components of an airline's SMS. ICAO could fold in-time risk management and continuous monitoring into its safety management SARPs, which would then influence member-state regulations. Industry audit standards (e.g., IATA Operational Safety Audit) can add sections on how operators collect and employ operational data for learning, as well as how they foster resilience within their organizations. It is also recommended to form a cross-stakeholder task force to define metrics for success in this new paradigm. Traditional safety metrics (accident and serious incident rates) won't fully capture the effects of proactive safety management. New metrics might include things like "time from hazard detection to mitigation" (to gauge IASMS effectiveness) or "number of actionable safety improvements derived from routine operational data per year" (to gauge LFAO productivity). These measures give operators a straightforward way to see how the combined approach is working in day-to-day line operations. It can also supplement the usual lagging indicators and provide a more proactive measure of safety health. By updating regulations and standards to formally recognize and reward proactive safety efforts, regulators can accelerate the shift.

Continuing Research on Contrarian Concerns

To continually improve the approach, the areas of contention identified earlier should remain research priorities. For example, address potential information overload by studying and refining alerting strategies; address algorithmic bias by testing IASMS algorithms on diverse scenarios and datasets. Independent audits or peer reviews of advanced safety systems should be periodically conducted to ensure they do not inadvertently introduce new risks.

Summary and Future Outlook

The action plans provided here are a sincere attempt to operationalize the concepts discussed and progressively achieve an even safer flight deck environment. The safety benefits will manifest as fewer incidents, better prediction and mitigation of emerging risks, and a robust safety culture that permeates all levels of operation. Importantly, this action plan is not a one-off project but an ongoing journey – the systems will continue to evolve, new data sources (like novel avionics or passenger-sourced data) will come online, and the cycle of learning and improvement will continue indefinitely. The synergistic combination of real-time monitoring, human adaptability, and continuous learning transforms safety management into a catalyst for systemic improvement, where 'safer' inherently means 'better.' Evolving flight deck safety through in-time systems, resilience, and LFAO is not only feasible but *essential*. It leverages the best of modern technology and human expertise to proactively manage emerging risks. The positive contributions of humans, enhanced by intelligent systems and nurtured by an organizational thirst for learning, will be the cornerstone of aviation safety in the 21st century.

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Appendix A

Acronyms and Abbreviations Used in This Paper

Acronym	Full Term
AAM	Advanced Air Mobility
AQP	Advanced Qualification Program
ASAP	Aviation Safety Action Program
ASIAS	Aviation Safety Information Analysis and Sharing
ASRS	Aviation Safety Reporting System
ATC	Air Traffic Control
CEFA	Cockpit Emulator for Flight Analysis
CRM	Crew Resource Management
EGPWS	Enhanced Ground Proximity Warning System
ERC	Event Review Committee
FAA	Federal Aviation Administration
FOQA	Flight Operational Quality Assurance
FSF	Flight Safety Foundation
GAO	Government Accountability Office
HMI	Human–Machine Interface
HRO	High Reliability Organization
IASMS	In-Time Aviation Safety Management System
ICAO	International Civil Aviation Organization
LFAO	Learning From All Operations
LIT	Learning and Improvement Team
LOFT	Line Oriented Flight Training
LOSA	Line Operations Safety Assessment
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NLP	Natural Language Processing
SMS	Safety Management System
SOP	Standard Operating Procedure
TCAS	Traffic Collision Avoidance System
UPRT	Upset Prevention and Recovery Training