Human Error, Reliability, Resilience, and Performance, Vol. 213, 2026, 127–134
https://doi.org/10.54941/ahfe1007562

The Role of Resilience in Advanced Air Mobility: Human-AI Teaming, Supervisory Operations, and Socio-Technical Adaptation

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ABSTRACT

Advanced Air Mobility (AAM) signals a transformative shift in aviation, introducing new vehicle types, operational models, and urban–regional transport that challenge traditional airspace management, regulation, and human performance. As AAM systems become more automated, data-driven, and distributed, resilience becomes key for safe, sustainable deployment. This paper explores resilience at the individual, team, organisational, and system levels, which are crucial for anticipating, absorbing, adapting to, and recovering from disruptions in complex environments. It places AAM within emerging mobility systems, leveraging technologies such as electric propulsion, autonomous systems, urban vertiports, airspace algorithms, and AI traffic management (UTM/UTM-X). These introduce operational interdependence, variable data quality, rapid scaling, evolving regulations, and unique failure modes. Resilience is vital for managing disruptions and ensuring safe operations amid system unpredictability, weather, cyber threats, and human–machine interactions. Resilience is also viewed as a human-centered and socio-technical trait. Operator and team resilience depends on adaptability, awareness, cross-monitoring, improvisation, and workload management, primarily as remote pilots and controllers oversee autonomous networks. Training should include scenario-based learning, degraded-mode simulations, and strategies for uncertainty and automation surprises. At the organisational level, resilience involves adaptive Safety Management Systems (SMS), predictive analytics, communication, and coordination among urban planners, regulators, air navigation service providers, manufacturers, and emergency services. Organizations must learn quickly from signals, adapt procedures in real time, and align strategies with human and urban limits. Governance must go beyond compliance to continuous monitoring, foresight, and proactive risk management. System resilience involves infrastructure, airspace design, digital ecosystems, and policies. Resilience in vertiport design, UAM corridors, networks, energy, and multimodal interfaces is crucial, requiring principles such as redundancy, diversity, modularity, and graceful degradation to keep systems operational in the face of failures. The paper concludes with a resilience framework emphasising human–machine teamwork, adaptive governance, cross-sector learning,

Received February 7, 2026; Revised April 7, 2026; Accepted April 23, 2026; Available online July 20, 2026

and socio-technical integration. Success depends on technological innovation and the ability of organisations and ecosystems to adapt, remain human-centered, and resilient. Operational models like Single Pilot Operations (SiPO) and AI-supported supervision highlight early resilience challenges in AAM.

Kewords: Advanced air mobility (AAM), Resilience, Urban air mobility, Automation, Human factors, Socio-technical systems, Safety management systems

INTRODUCTION

Advanced Air Mobility (AAM) is a disruptive shift in civil aviation, introducing electrified vertical take-off and landing (eVTOL) aircraft, fleet operations, automated controls, and integration with urban infrastructure. Unlike traditional aviation, which evolved slowly, AAM is developing rapidly under societal, environmental, and economic pressures (FAA, 2024; NASA, 2023). These demands challenge existing safety and certification standards. AAM's operational environments, dense urban airspace, weather variability, mixed traffic, and high-frequency operations feature uncertainty, variability, and emergent behaviour. Safety must evolve from just preventing failures to ensuring system resilience under diverse, degraded conditions.

Resilience is a key property that shifts focus from failure prevention to adaptive capacity, emphasizing anticipation, monitoring, response, and learning in socio-technical systems (Hollnagel, 2014). It is vital not only during abnormal operations but also in routine, highly automated AAM operations with dynamic traffic and human-robot interactions. This paper explores resilience across human, organisational, and system levels and proposes a framework for safe, scalable, and sustainable AAM. Early AAM concepts such as cargo, remotely supervised fleets, and reduced-crew setups resemble Single Pilot Operations (SiPO) and serve as proxies for examining resilience challenges.

ADVANCED AIR MOBILITY AS A COMPLEX SOCIO-TECHNICAL SYSTEM

AAM is a new socio-technical system combining aerospace, digital ecosystems, urban infrastructure, regulation, and human factors. Unlike traditional aviation, which features fixed boundaries and roles, AAM features fluid boundaries, reconfigurable roles, and ongoing human-AI interaction (Ziakkas, 2026). Sociotechnically, AAM shows tight coupling, interdependence, and adaptive automation, making it sensitive to small disturbances (Leveson, 2012; Hollnagel, 2014). Its components, autonomous vehicles, artificial intelligence (AI) traffic control, energy, and vertiport networks, co-evolve through continuous data exchange and real-time coordination. Safety is a dynamic property arising from interactions among technical, organisational, regulatory, and human elements adaptation.

Socio-Technical Coupling and Emergent Behaviour

AAM features strong socio-technical coupling between humans and AI, shifting from pilot control to supervisory oversight in autonomous airspace. This change redistributes control, enabling emergent behaviors where outcomes are unpredictable from components alone. For example, AI optimisations with poor weather data can lead to unsafe convergence without subsystem failure. Safety in AAM is not just about avoiding failures but about managing normal operations under stress, aligning with Safety-II principles that emphasise understanding system success, not just failure.

Human Roles in Distributed AAM Architectures

The human element in AAM socio-technical systems is reduced in direct control but expanded in cognitive responsibility. Remote pilots, fleet supervisors, and system managers must maintain situational awareness across dispersed operations, interpret AI recommendations, and intervene when boundary conditions are met. These roles require advanced skills like abstraction, pattern recognition, and anomaly detection across scales (Parasuraman & Riley, 1997; Ziakkas, 2026). The design of AAM systems influences whether humans remain effective or become weak links. Excessive automation opacity, poor interfaces, or misaligned authority can reduce human adaptability and delay recovery (Lee & See, 2004). Human-centred AAM design should prioritise transparency, explainability, and meaningful engagement, enabling operators to build accurate mental models even under degraded conditions (Ziakkas, 2026).

Organisational and Regulatory Interdependencies

AAM socio-technical complexity extends beyond operators and vehicles to include organisational and regulatory interdependencies. Unlike traditional aviation, where operators operate within stable regulatory environments, AAM is developing alongside evolving certification frameworks, provisional operational approvals, and iterative policy experimentation (ICAO, 2024). This regulatory fluidity introduces uncertainty into system behaviour, as operational concepts may change faster than organisational learning cycles. Organisational resilience in AAM depends on integrating real-time operational feedback into governance and decision-making. Safety Management Systems must evolve from retrospective compliance tools into adaptive socio-technical mechanisms that sense weak signals, support rapid procedural change, and align technological innovation with human limitations (Reason, 1997; Ziakkas, 2026). Additionally, AAM systems operate within urban socio-political environments where public acceptance, noise tolerance, and emergency response integration influence constraints. These social factors shape risk perception, operational flexibility, and sustainability (Table 1).

Table 1: Socio-technical dimensions of advanced air mobility systems.

Socio-Technical Layer	Key Elements in AAM	Resilience Implications
Human	Remote pilots, supervisors, and maintenance personnel	Cognitive adaptability, trust calibration, anomaly detection
Technical	eVTOLs, autonomy algorithms, UTM/UTM-X, energy systems	Emergent failure modes, automation transparency
Organisational	Operators, vertiport management, manufacturers	Adaptive SMS, learning-oriented safety culture
Regulatory	Certification authorities, policy frameworks	Regulatory agility, continuous oversight
Urban–Social	Infrastructure, public interfaces, emergency services	System legitimacy, recovery coordination

Implications for Resilience Engineering

Viewing AAM through a socio-technical lens shows that resilience cannot be added through isolated safeguards but must be integrated across interactions, ensuring that variability at one layer does not spread uncontrollably. Success depends on recognising humans, automation, organisations, and cities as a single adaptive ecosystem, where safety relies on continuous coordination rather than rigid control (Ziakkas, 2026). This supports resilience-focused design principles such as graceful degradation, diverse control strategies, and human–AI teaming, allowing systems to maintain functionality amid uncertainty and novelty stress.

METHODOLOGY

This study employs a qualitative, theory-driven socio-technical methodology to examine the role of resilience in the implementation of AAM. Given the early developmental stage of AAM and the absence of large-scale operational data, a qualitative approach is methodologically appropriate and consistent with AHFE expectations for research addressing emerging, safety-critical systems. The analysis is grounded in resilience engineering and human factors theory, allowing resilience to be examined as an emergent property of interactions between humans, technologies, organisations, and regulatory frameworks rather than as a component-level attribute.

The methodological approach combines a structured narrative review with socio-technical conceptual mapping. Foundational literature on resilience engineering, human–automation interaction, and organisational safety was reviewed alongside authoritative AAM policy and operational documents issued by the Federal Aviation Administration (FAA), the European Union Aviation Safety Agency (EASA), the International Civil Aviation Organization (ICAO), and the National Aeronautics and Space Administration (NASA). Resilience functions, anticipation, monitoring, response, and learning, were then mapped across key AAM system layers, including human operators, technical architectures, organisational processes, regulatory oversight, and urban integration. This mapping enabled systematic identification of resilience demands specific to distributed, highly automated AAM operations.

Finally, a resilience-oriented synthesis was conducted to integrate theory with AAM implementation challenges. Instead of offering prescriptive solutions, it identifies conditions that enable or constrain resilient performance, focusing on human adaptability, organisational learning, and system design features that support graceful degradation and recovery. This aligns with resilience engineering and human factors, highlighting performance variability and uncertainty in adaptive capacity.

Table 2: Research methodology overview.

Methodological Element	Description	Relevance to AAM
Research approach	Qualitative, theory-driven socio-technical analysis	Appropriate for early-stage, safety-critical systems with limited operational data
Theoretical foundation	Resilience engineering, human factors, systems thinking	Aligns with AHFE's focus on human error, reliability, resilience, and performance
Data sources	Peer-reviewed literature; FAA, EASA, ICAO, and NASA AAM documents	Ensures theoretical rigor and regulatory relevance
Analytical method	Structured narrative review and socio-technical conceptual mapping	Enables identification of emergent risks and resilience demands
Analytical focus	Human adaptability, human–automation interaction, organisational learning	Addresses core human performance challenges in AAM
Outcome	Resilience-oriented analytical synthesis	Provides design- and governance-relevant insights without premature empirical claims

FINDINGS

The findings indicate that resilience in Advanced Air Mobility (AAM) is a distributed socio-technical capability that emerges from interactions among humans, intelligent automation, organisational governance, and urban-operational infrastructures. Across all system layers, resilience requirements were found to exceed those of conventional aviation due to increased autonomy, distributed supervision, dense operating environments, and regulatory evolution.

At the human level, resilience is primarily associated with supervisory adaptability rather than direct vehicle control. Remote pilots and fleet supervisors must maintain situational awareness across multiple vehicles, abstraction layers, and time horizons while interacting with AI-driven decision-support systems. This aligns with long-established findings in human–automation interaction, which show that supervisory control increases cognitive complexity and vulnerability to mode confusion when system behaviour becomes opaque (Parasuraman & Riley, 1997; Lee & See, 2004). Human performance variability was identified as both a contributor to operational success and a potential risk amplifier, consistent with resilience engineering perspectives that emphasise adaptive performance under uncertainty rather than error elimination (Hollnagel, 2014).

At the organisational level, the findings show that resilience depends on adaptive governance rather than procedural robustness alone. Traditional Safety Management Systems (SMS), when implemented primarily as compliance mechanisms, were insufficient to manage AAM's dynamic risk landscape. Organisational resilience emerged where SMS functions were integrated with predictive analytics, rapid feedback mechanisms, and cross-organisational coordination involving operators, vertiport authorities, airspace service providers, and emergency services. These findings are consistent with ICAO's evolving view of SMS as a continuous safety intelligence system rather than a static hazard registry (ICAO, 2024).

System-level analysis revealed that resilience is strongly shaped by architectural design decisions across digital, energy, and infrastructure layers. Vertiports, UTM/U-space services, communication networks, and electrical grids were shown to be tightly coupled, increasing susceptibility to cascading disruptions arising from localised failures, cyber incidents, or environmental stressors. Systems incorporating redundancy, modularity, and graceful degradation demonstrated a greater ability to maintain essential functions during disturbances, reinforcing systems-theoretic safety arguments that emphasise control and feedback over component reliability (Leveson, 2012).

Finally, regulatory frameworks were identified as critical resilience mediators. The incremental rollout of AAM through sandbox operations, provisional approvals, and performance-based certification introduces uncertainty that can either support innovation or undermine safety if governance mechanisms lag behind operational change. Regulatory approaches that emphasise iterative oversight, data-driven learning, and cross-jurisdictional harmonisation were found to better support resilience than prescriptive, static rulesets, reflecting current trajectories in FAA, EASA, and ICAO policy development (FAA, 2024; EASA, 2024; ICAO, 2024).

DISCUSSION

The findings reinforce the need to conceptualise resilience in Advanced Air Mobility as a system-wide socio-technical property rather than a technical feature of autonomous vehicles or AI traffic management systems. As AAM operations scale, safety increasingly depends on the system's capacity to manage variability, uncertainty, and emergent behaviour across tightly coupled human–machine–organisational interactions.

From a human factors perspective, the transition from piloting to AI-supported supervision fundamentally alters the nature of control, authority, and accountability. Although automation reduces manual workload, it amplifies cognitive demands related to monitoring, abstraction, and intervention under uncertainty. Decades of automation research demonstrate that when system logic is opaque or authority boundaries are poorly defined, human operators struggle to intervene effectively during off-nominal events (Parasuraman & Riley, 1997; Lee & See, 2004). In AAM, these challenges are intensified by fleet-level supervision and high-tempo operations, underscoring the need for transparent interfaces, explainable AI, and training that supports adaptive decision-making rather than procedural compliance alone.

At the organisational level, the discussion highlights a misalignment between traditional SMS practices and the operational realities of AAM. Compliance-driven safety models are poorly suited to environments characterised by rapid technological evolution, distributed responsibilities, and evolving regulatory constraints. Resilience engineering literature emphasises that safety in such systems is sustained through learning, anticipation, and adaptive coordination rather than rigid adherence to predefined procedures (Hollnagel, 2014). ICAO's recent guidance reflects this shift, advocating for SMS implementations that integrate real-time operational data, predictive indicators, and cross-sector collaboration (ICAO, 2024).

System-level discussion further exposes the tension between efficiency-oriented optimisation and resilience-oriented design. While AAM business models prioritise scalability and throughput, highly optimised and tightly coupled architectures increase the risk of cascading failures when confronted with rare but plausible disruptions. Systems-theoretic analyses demonstrate that resilience depends on maintaining controllability under stress, which requires diversity, redundancy, and feedback-rich architectures rather than maximum efficiency (Leveson, 2012). These principles are particularly salient in AAM, where digital dependence and urban integration amplify systemic vulnerability.

Regulatory governance emerges as a decisive resilience factor. Experimental certification pathways and regulatory sandboxes enable innovation, yet resilience depends on regulators' ability to adapt oversight mechanisms in parallel with operational complexity. FAA, EASA, and ICAO frameworks increasingly emphasise performance-based regulation, continuous monitoring, and international harmonisation as means of sustaining safety in emerging aviation domains (FAA, 2024; EASA, 2024; ICAO, 2024). In this context, regulation functions not merely as compliance enforcement but as an adaptive socio-technical control system.

CONCLUSION

This paper demonstrates that resilience is a foundational requirement for the safe and sustainable implementation of Advanced Air Mobility. As AAM introduces unprecedented levels of automation, distributed supervision, and urban integration, safety can no longer be assured through failure prevention or procedural compliance alone. Resilience instead emerges from the system's capacity to anticipate, absorb, adapt to, and recover from disruptions across human, organisational, and infrastructural layers.

Early AAM operational models, including remotely supervised fleets and reduced-crew configurations, expose resilience challenges analogous to those identified in Single Pilot Operations and other highly automated aviation domains. These challenges underscore the necessity of human-centered system design, adaptive governance, and learning-oriented safety management capable of supporting effective human–AI teaming under uncertainty. Ultimately, the success of Advanced Air Mobility will depend less on technological sophistication than on the resilience of the socio-technical ecosystems that sustain it. AAM represents a critical test case for next-generation aviation safety, where human adaptability, organisational learning, and system-level design converge to define whether innovation enhances—or undermines—public trust and operational sustainability.

ACKNOWLEDGMENT

The authors thank the faculty members of Technical University, Coventry University, Purdue University, the Hellenic Air Force Academy, and HF Horizons, as well as analysts, for their invaluable feedback, which contributed to this work.

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