

ADVANCED AIR MOBILITY: THE CURRENT STATE OF DEVELOPMENT AND THE CHALLENGES

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Abstract

This comprehensive review articulates the multidimensional landscape of Advanced Air Mobility (AAM) and synthesizes critical insights from global scientific consortia, regulatory authorities, and pioneering national deployment initiatives. The analysis is anchored in the Scientific Assessment for Urban Air Mobility (UAM), a landmark consensus document formulated by the 27-member International Forum for Aviation Research (IFAR) at the strategic behest of the International Civil Aviation Organization (ICAO). Building on this empirical foundation, the study critically evaluates the current state of the AAM domain through the lens of global harmonization. The study examines ongoing AAM initiatives, elucidating the strategic shift toward a holistic, interoperable vision that reconciles legacy aviation provisions with the unique operational profiles of highly automated new entrants. The study concludes by synthesizing these divergent regional trajectories into a cohesive global perspective. By establishing this comprehensive baseline, the research serves as a critical navigational resource for the global scientific community, national aviation regulators, and industry practitioners. It equips these key stakeholders with an actionable understanding of current developmental milestones and emerging trends shaping the new airspace ecosystem. For regulatory bodies, the analysis underscores the urgent need for harmonized rulemaking to prevent market fragmentation and accelerate cross-border operations. Simultaneously, it provides AAM practitioners and academic researchers with a targeted diagnosis of the most critical operational bottlenecks that must be collaboratively resolved to unlock commercial viability. It also serves as a basis for a strategic roadmap for sustained international research collaboration to bridge the protracted valley that currently separates high technological readiness levels from true, scalable operational maturity.

Keywords: Advanced Air Mobility (AAM), Urban Air Mobility (UAM), Unmanned Aircraft System (UAS), UAS Traffic Management (UTM), Vertical Take-Off and Landing (VTOL)

1. General Introduction

The global aviation landscape is entering a new era, marked by the emergence of Advanced Air Mobility (AAM) as a distinct third pillar of civil aviation alongside legacy commercial and general aviation. While commercial aviation remains optimized for high-altitude, fixed-route operations between established airport hubs, and general aviation accommodates localized state or public services, and private or low-tempo corporate profiles, AAM establishes an entirely novel operational branch. This branch introduces highly automated systems that rely on a range of digital services, spatial, and multi-layered operations, predominantly in lower-altitude airspaces [1], [2]. The envisioned operations areas are urban, suburban, rural, regional, and cross-border [1], [3]. Rather than being confined to legacy fleet taxonomies, the AAM domain is defined as a comprehensive global framework encompassing novel aircraft platforms that operate outside traditional Air Traffic Management (ATM) boundaries [3], [4], [5]. The integration of these new aircraft into highly complex, multimodal transport networks necessitates the harmonization of global regulatory frameworks, the fundamental redesign of traditional airspace architectures, the revision of certification baselines, the occurrence of technical breakthroughs, and the achievement of social acceptance and economic viability [2], [3], [4], [5].

The active operational layer of the AAM domain is defined by a highly heterogeneous fleet of novel aircraft platforms whose designs diverge fundamentally from legacy fixed-wing and rotorcraft taxonomies [4], [6]. Among those are Unmanned Aircraft Systems (UAS), also known as drones or Remotely Piloted Aircraft Systems (RPAS), as well as Vertical Take-Off and Landing (VTOL), Short Take-Off and Landing (STOL), and Conventional Take-Off and Landing (CTOL) capable aircraft [3], [4]. UAS is typically formed by the Unmanned Aircraft (UA) itself, a technical means to control it remotely, the communication between the two, and any other elements specified in the UAS design [7]. UAS may include UA ranging from tiny to as heavy as conventional long-range aircraft. The typical operations of smaller UAS are in Very Low Level (VLL) altitudes and within visual line of sight (VLOS), and of the bigger UAS at higher altitudes and Beyond Visual Line of Sight (BVLOS). VTOL-capable aircraft may range in size from small to mid-sized and engage in operations similar to those of helicopters [3], [4]. STOL-capable aircraft may be used in challenging terrain and at airfields and airports with short runways, while CTOL-capable aircraft can be used in typical airport environments [3], [4]. These aircraft may be powered by electric, hydrogen, or hybrid power, and some may operate without a pilot on board [3], [4]. Along with other aircraft forms that are yet to shape future AAM operations, they may be referred to as AAM aircraft, and most such operations are envisioned at lower altitudes [3], [4].

The taxonomy of AAM has matured progressively alongside rapid advancements in AAM aircraft capabilities and operational concepts. Because most UAS operations were envisioned in uncontrolled Class G airspace and no infrastructure to support the safety of UAS operations was available, there was a need for such a system. Thus, the UAS Traffic Management System was introduced by the US National Aeronautics and Space Administration (NASA) [8]. It was proposed as a federated, digital ecosystem capable of safely managing high-density aircraft operations at lower altitudes by replacing legacy, voice-based communication loops with machine-to-machine application interfaces. The concept of Urban Air Mobility (UAM) emerged as a distinct evolutionary branch of civil aviation, describing automated transport networks in metropolitan airspace. NASA formally adopted, defined, and structured the UAM framework to organize its upcoming national market studies and aircraft integration goals [9] and to develop airspace integration concepts and technical roadmaps detailing UAM flight trajectories [10]. Early technical roadmaps and empirical flight simulations demonstrated that restricting this aerospace revolution to metropolitan environments artificially constrained its economic viability and global utility. Recognizing these operational boundaries, NASA executed a pivotal structural shift by officially expanding the scope of its research from UAM to AAM, redefining distance boundaries, updating the airspace taxonomy, and expanding real-world test scenarios [11].

In response to the rapid technological evolution of new airspace entrants, ICAO, as the highest international aviation body responsible for developing global aviation Standards and Recommended Practices (SARPs), acknowledged the need for global harmonization of the AAM domain and, in 2022, established the AAM Study Group (AAM SG) [12]. Recognizing the critical need for a global-

ly harmonized regulatory approach to prevent a fragmented international landscape, the AAM SG's primary purpose is to assist the ICAO Secretariat in formulating a holistic vision and strategic framework for AAM. Serving as the central advisory body for all AAM-related initiatives within ICAO, the AAM SG coordinates closely with other established aviation expert panels. Its overarching objective is to facilitate the robust development of the global AAM ecosystem while ensuring that the integration of these highly automated, novel operations into existing international airspace remains unequivocally safe, secure, efficient, and environmentally sustainable [3].

At the strategic behest of the ICAO, the International Forum for Aviation Research (IFAR) conducted in-depth analyses of the UAM domain. The Scientific Assessment for Urban Air Mobility (UAM), a landmark consensus document formulated by organizations representing 27 IFAR state members, has been developed. Delivered to the ICAO Council, this foundational assessment established an authoritative baseline for analyzing the technical, economic, and societal paradigms required to seamlessly integrate AAM aircraft designs into densely populated urban airspaces. By delineating 17 critical research focus areas – ranging from the aerodynamic implications of distributed electric propulsion to the exacting data requirements for cybersecurity and low-altitude meteorological sensing – the IFAR assessment serves as the scientific scaffolding for subsequent regulatory evolution. The revised version of the Scientific Assessment has recently been published [4].

A core component of this work is a granular update on the status quo of AAM domain development and on developments in the leading global aerospace markets [13]. The document is organized as follows: Section 2 gives an overview of the 10 groups of enablers, presenting the state of the art and the biggest challenges. Section 3 provides information on the notable State of the Art (SotA) of the country/region, the most important actions and processes, the key documents, and the biggest challenges. Section 4 highlights crucial findings and future perspectives as concluding remarks.

2. AAM Ecosystem

2.1 Policy, Governance, Strategy, and Economics

The comprehensive integration of Advanced Air Mobility (AAM) requires a cohesive multilevel governance framework that coordinates safety, efficiency, and sustainability across local authorities, national regulators, international aviation organizations, industry stakeholders, and the public [4]. Currently, the regulatory landscape remains highly fragmented, as differing national approaches across regions such as the United States, Europe, and Asia complicate market development and international harmonization efforts [4]. Comparative policy analyses emphasize that there is no universal regulatory blueprint for AAM; instead, countries must develop context-specific strategies that reflect their institutional and operational environments [14], while aligning safety regulation, airspace integration, infrastructure planning, and public acceptance across different administrative and sectoral levels [15], [16]. A particular challenge arises from the increasing importance of local and regional stakeholders operating within low-altitude airspace, including municipalities, ports, infrastructure operators, and emergency services. These actors often possess detailed operational knowledge and are directly affected by AAM activities, yet their interests and responsibilities may not always align with national aviation authorities, creating additional coordination and governance complexities. Strategic transportation planning must implement policies that support multimodal integration, ensuring AAM is no longer viewed as a standalone mode but rather as a complement to existing ground and rail networks within a fully integrated mobility ecosystem. Innovation is accelerated by establishing dedicated airspace test centers and regulatory sandboxes, where novel technological and operational procedures can be validated in risk-mitigated settings [4]. Furthermore, the transition to autonomous flight necessitates new accountability and liability frameworks to clarify responsibilities between manufacturers and service providers, supported by international agreements that standardize handling across jurisdictions [4], ultimately balancing the speed of innovation with strict safety assurance.

Beyond governance, economic viability and market readiness represent other critical challenges for the large-scale deployment of AAM [17]. The sector faces high aircraft development costs, expensive vertiport infrastructure, and considerable operational energy demands [17]. The strategic integration of AAM necessitates a governance framework that balances high regulatory

compliance costs with consumer affordability benchmarks, as profitability strongly depends on route density, fleet utilization, automation levels, and supportive regulation [4],[18]. For widespread adoption, AAM services must become profitable even at comparatively low ticket prices, requiring business models that move beyond premium niche markets and achieve substantial reductions in both direct and indirect operating costs [17]. Because market scenario analyses suggest that early commercialization may prove difficult, featuring limited initial growth followed by stronger expansion at later stages, manufacturers and operators will require significant financial resilience and long-term “staying power” during the market entry phase [19]. A robust economic framework is therefore necessary to foster market competitiveness, ensure open access to privately-owned infrastructure and Communication, Navigation, and Surveillance (CNS) services, and mobilize public-private partnerships [4]. Delays in policy development may not only hinder technological learning but also result in missed economic opportunities. Prolonged regulatory uncertainty can incentivize operators and manufacturers to relocate testing activities and early commercial operations to jurisdictions with more enabling regulatory frameworks, potentially leading to a loss of investment, innovation capacity, and competitive advantage for slower-adapting regions [20]. Finally, policy development must be informed by scientific studies on social equity and fair access to prevent the exclusion of broader population groups due to high initial investment costs [4], and to establish the global interoperability, cybersecurity, and scalable business models needed to transition AAM from demonstration projects to sustainable commercial operations.

2.2 Safety and Security Regulatory Environment

The global deployment and industrial scaling of Advanced Air Mobility (AAM) necessitate a unified, highly adaptable safety and security regulatory environment that transcends rigid national frameworks to prevent systemic fragmentation. This evolutionary process relies on establishing international mechanisms for mutual recognition and aligning airworthiness, personnel qualifications, and ground infrastructure standards, which together facilitate seamless cross-border operations and authorizations for foreign operators. To keep pace with rapid technological iteration, civil aviation authorities are actively modernizing legacy prescriptive rulemaking by adopting agile, operation-centric, and risk-based oversight structures that shift focus toward performance outcomes and flexible compliance pathways. During initial operational rollouts, this modernized framework relies heavily on structured waiver and exemption mechanisms to safely integrate remotely supervised uncrewed systems before fully mature autonomous legal structures are deployed. Crucially, as software-driven functionality becomes central to low-altitude transit, these regulatory frameworks must pioneer advanced digital validation criteria specifically tailored to certify automated flight software, collaborative air traffic management nodes, and adaptive platforms driven by artificial intelligence and machine learning.

Modernizing the regulatory environment requires a transition toward performance-based standards that can accommodate non-deterministic AI algorithms and increasingly automated systems. Scientific gaps exist in the verification of these algorithms and the quantification of advanced navigation technologies, both of which are essential for achieving safety levels equivalent to those of existing commercial aviation. Furthermore, regulatory evolution must shift from human-centric models to operation-centric frameworks that integrate lessons learned from initial cargo and disaster response trials [4]. The regulatory landscape must mature through three intersecting models of oversight: a top-down structural layer to enforce standardized civil aviation safety, a co-regulatory data protection structure to anchor operational accountability, and a middle-out coordination mechanism to support local legal experimentation and sandboxing [21]. This multi-layered approach helps legal authorities balance rapid technological iteration with data security and human rights protection, ensuring that unified regulatory policies foster technology advancement without compromising public trust. Complementing these foundational legal architectures are state-of-the-art technical meta-reviews focusing on the lifecycle safety of automated civil flight operations. Comprehensive safety risk analyses indicate that civil unmanned systems introduce novel operational challenges – such as ground-impact risks and navigation through dense urban obstacles – that are entirely distinct from the hazards managed by traditional aviation safety management processes [22]. While numerous theoretical modeling mechanisms

have been proposed to quantify low-altitude collision and infrastructure-damage parameters, there remains a critical operational gap in standardizing these risk-assessment definitions into practical, unified approval lifecycles across diverse international jurisdictions [22]. Consequently, engineering and regulatory research trends are rapidly converging on data-driven, lifecycle-wide safety models that integrate continuous operational updates, allowing state authorities to accurately gauge systemic risk margins and issue operational authorizations that preserve public trust while scaling commercial AAM enterprises.

2.3 Societal Acceptability and Environmental Sustainability

Societal acceptability and environmental sustainability are increasingly recognized as critical enablers for the successful implementation, broad legitimacy, and long-term viability of AAM. Beyond technological feasibility, AAM must achieve broad societal legitimacy by balancing operational benefits with environmental and social impacts. As AAM represents a complex socio-technical “system of systems”, interactions between aircraft, infrastructure, operational concepts, regulation, and urban integration directly influence public perception, stakeholder interests, and environmental impact [23]. Consequently, the overall system performance depends not only on technical efficiency but also on its acceptance by users, local communities, regulators, and society as a whole. Current research highlights that this social acceptance is shaped by three interrelated dimensions: socio-political acceptance, community acceptance, and market acceptance [23]. While policymakers and regulators focus primarily on safety, sustainability, and public welfare, local communities are deeply affected by localized disruptions, privacy concerns, land-use impacts, visual pollution, and systemic barriers to socio-economic equity.

A significant hurdle to widespread social adoption is the public's sensitivity to acoustic profiles in urban settings, where operations can fuel community hesitancy regarding noise pollution if local benefits are not readily apparent. Long-term societal trust is predicated on the quantifiable mitigation of noise and emissions, with noise pollution identified as one of the most critical barriers to large-scale urban deployment, despite electric vertical take-off and landing (eVTOL) aircraft being quieter than conventional helicopters [4], [23]. Research indicates the need for psychoacoustic metrics that reflect human annoyance and health impacts, such as sleep disturbance, rather than standard single-point engineering measurements [4], [24]. Additionally, social trust depends on transparent communication about the full-lifecycle environmental footprint of AAM systems – including energy sources, infrastructure requirements, battery production, and local electricity grid carbon intensity – rather than on operational emissions alone [4], [23], [25]. The impact of tonal noise may prove to be crucial [26]. Strict environmental sustainability standards for noise and emissions reduction are required to minimize the environmental footprint of urban operations.

However, this community resistance varies by context; for instance, in tourism and scenic environments, an individual's environmental consciousness positively influences acceptance. When tourists perceive eVTOL technology as an environmentally friendly and sustainable innovation, their hedonic motivation and perceived usefulness increase, making them more willing to adopt it despite its local environmental footprint. Beyond acoustic profiles, societal acceptance is strongly affected by concerns regarding privacy and perceived surveillance [4], [23]. The operation of AAM aircraft at low altitudes over densely populated urban areas can generate public apprehension that onboard cameras and sensing systems could be used to record individuals or private property. Such concerns may persist even when sensors are employed exclusively for navigation, collision avoidance, and operational safety. Studies on public acceptance of AAM operations have identified privacy and surveillance concerns as important factors influencing trust and social acceptance, alongside safety, noise, and environmental impacts [27], [28]. At the same time, market acceptance depends on affordability, accessibility, and the perceived value of AAM services [29]. This hesitancy is further compounded by the challenge of equitable access, as consumer willingness to pay naturally restricts early discretionary air taxi trips to premium segments, raising valid social equity concerns that the infrastructure investment and the associated negative consequences of its integration (noise, visual impact, safety concerns) may serve only as an exclusive asset rather than an inclusive public transport alternative. In fact, studies indicate that

public support is significantly higher for applications with clear societal benefits, such as emergency response or medical transport, than for premium urban air taxi services [30], [31]. This demonstrates that societal value creation is a key determinant for long-term acceptance [32]. Accessibility and inclusivity are critical enablers, ensuring that AAM services cater to diverse populations and provide connectivity to remote or underserved regions.

Therefore, one of the greatest challenges remains the management of trade-offs among sustainability, operational efficiency, affordability, and community acceptance [23]. Consequently, building long-term public trust requires a strategic roadmap that explicitly mitigates urban noise, establishes stringent privacy safeguards, and democratizes access beyond niche commercial markets to align with the broader common good [30] [33]. Future AAM systems must not only be safe and economically viable, but also environmentally responsible, socially inclusive, and transparently integrated into existing urban mobility systems and broader urban planning strategies, supporting wider connectivity through connected cities and multimodal transport networks [23].

2.4 Personnel, Licenses, and Human Dimension

The profound shift from hands-on piloting to systems-level supervision requires new training, and the large-scale deployment and long-term viability of Advanced Air Mobility (AAM) necessitate a fundamental restructuring of human-system interaction, licensing paradigms, and systemic workforce readiness to safely support increasing levels of operational autonomy. This socio-technical transformation demands a profound shift in core human responsibilities, moving traditional hands-on flight crews toward system-level supervision and mission management roles designed to actively combat automation complacency, mode confusion, and dangerous proficiency loss. To ensure safety-critical competencies are systematically maintained, the entire ecosystem must establish comprehensive Competency-Based Training and Assessment (CBTA) frameworks that evaluate specialized technical and non-technical skills across all personnel categories, including pilots, remote supervisors, maintenance technicians, and regulatory oversight staff. This baseline workforce capacity is further expanded through targeted upskilling and reskilling pathways that provide foundational training in technology, regulation, and practical skills to new industry entrants and transitioning professionals. Supporting these entry pathways requires robust, ongoing professional development initiatives that utilize dynamic certification structures, structured workshops, and advanced seminars to help existing aviation professionals adapt fluidly to accelerating technology cycles. Concurrently, long-term economic scalability hinges on implementing competitive talent recruitment and retention models and dedicated diversity and inclusion strategies to optimize innovation by drawing on a broad spectrum of perspectives. Finally, to protect the overall safety thread of dense flight operations, organizations must elevate fatigue risk and alertness tracking from basic operational checklists into high-level strategic safety enablers integrated directly within system-wide risk management frameworks.

The advent of high-level autonomy requires a parallel paradigm shift in personnel qualifications, moving from single-aircraft handling to the systems-level supervision of multiple aircraft. Scientific assessments emphasize that human-automation teaming will remain a critical focus area, as autonomous systems currently lack the general intelligence necessary to replace human decision-making during complex, off-nominal contingencies [4]. Human-in-the-loop simulations investigating advanced airspace routing reveal that while subjective controller and operator workloads remain manageable during initial low-density rollouts, medium-to-high traffic densities quickly generate unmanageable cognitive overloads, requiring standardized operational agreements to minimize verbal communication and maintain safety [34]. To alleviate these operational bottlenecks, contemporary safety frameworks prioritize defining clear, optimized levels of automation between human pilots and advanced autopilots [35]. Empirical analyses indicate that implementing automated decision-making configurations – where both the pilot and autopilot concurrently monitor the system, but final optimization and execution are safely handled by the automation – requires a highly robust mitigation strategy against critical autopilot mode confusion and vertical navigation anomalies during high-stakes urban landings [35].

To systematically address these operational shifts, modern aerospace paradigms mandate a total

realignment of pilot training concepts away from traditional aviation contexts. Because proposed short-haul operations feature highly repetitive flight profiles, single-pilot configurations, and unique battery power-management parameters rather than conventional fuel tracking, legacy training mechanisms face significant limitations in preparing personnel for the behavior of automated systems [36]. As operators move into remote, multi-aircraft supervisory positions, they experience a substantial reduction in natural visual, auditory, and proprioceptive feedback, which dramatically increases their vulnerability to sudden automation surprises, overreliance, and complacency [37]. Mitigating these vulnerabilities requires integrating extensive empirical research to determine exactly how many aircraft a single remote manager can effectively supervise simultaneously before situation awareness degrades [37]. Consequently, targeting human factors research toward defining the precise boundaries of human performance and establishing continuous professional development pipelines remains a critical benchmark for validating systemic resilience across automated air mobility infrastructures [34], [35].

2.5 Aircraft Operations and Fleet Management

The institutional scaling and technological execution of modern flight operations require an integrated overhaul of aircraft capabilities and fleet management systems. This paradigm shift addresses the demands of high-level operational autonomy, driving critical changes to legal and oversight frameworks to successfully handle the complex challenges of liability, data governance, and systemic safety management. To implement successful operations without onboard or remote pilots, the ecosystem depends on sophisticated onboard systems capable of executing automated navigation, dynamic conflict avoidance, and decentralized real-time decision-making with minimal human intervention. To supplement these automated airframes, advanced ground-based infrastructure must be adapted to perform critical safety and efficiency functions that are not directly handled by the aircraft itself. Managing these complex environments requires high-throughput fleet management tools that can supervise several uncrewed aircraft simultaneously as a single operational unit, optimized by predictive analytics tools designed to forecast localized weather disruptions, traffic congestion, and maintenance requirements. This entire distributed framework is held together by an in-time performance assessment and decision-making system that continuously monitors operations against safety metrics and key performance indicators, enabling safety teams to enforce evidence-based oversight and implement proactive risk mitigation before traffic densities exceed human capacity. Operational efficiency is driven by deploying adaptive automation and predictive analytics to forecast weather disruptions and traffic congestion. Research focus areas highlight the complexity of managing high-cycle operations typical of urban ride-sharing, which necessitates real-time aircraft health monitoring and data-driven maintenance intervals. Fleet management enablers also include the development of information requirements and exchange protocols among pilots, vertiport managers, and air traffic controllers to support safe scaling [4].

Transitioning to fully automated operations requires moving past classical, offline safety paradigms to embrace dynamic, data-driven system oversight. Central to this vision is the concept of an In-Time Aviation Safety Management System (IASMS), which operates as a continuously aware digital nervous system designed to ingest high-density, real-time operational streams from both aircraft and ground components to detect threats to safety before they develop into hazardous incidents [38]. Because legacy exceedance-based safety monitoring methods rely on rigid, predefined variables that cannot capture the complex interplay of unexpected microscale anomalies, contemporary frameworks utilize advanced machine learning algorithms to perform continuous, real-time risk characterization across dense urban airspace corridors. By automating the safety assurance cycle at second- and minute-by-minute intervals, these predictive architectures enable operators and automated traffic controllers to dynamically adapt operational volumes, impose preemptive constraints, and maintain systemic airspace integrity in highly complex, rapidly changing environments. Complementing system-wide safety monitoring is the challenge of optimizing large-scale fleet operations under tight energy constraints. Unlike conventional fossil-fuel aircraft, whose performance margins remain stable until fuel exhaustion, electricity-powered AAM aircraft experience a progressive reduction in maximum power delivery

capabilities as their state of charge drops, which creates severe operational risk during energy-intensive vertical landings at vertiports [39]. Furthermore, because high-density urban air networks suffer from lower vertiport capacities due to synchronized boarding, landing, and surface charging constraints, real-time fleet operations rely heavily on reinforcement learning frameworks and simulation-optimization models to manage dispatch and charging decisions under stochastic demand patterns and wind variability [40].

2.6 Aircraft, Systems, and Technology

The technological maturation and regulatory integration of AAM aircraft architectures rely on the shift of conventional international airworthiness standards toward an operation-centric, risk-based certification framework. This evolution is heavily centered on validating innovative propulsion technologies – specifically electric, hybrid-electric, and hydrogen fuel cell configurations – by systematically targeting and dismantling legacy regulatory barriers. To optimize low-altitude airspace capacity and enable higher traffic densities, aircraft must deploy enhanced onboard sensors, data analytics pipelines, and advanced digital situational awareness instruments that reduce operator cognitive load while accurately mapping local tactical hazards such as wake vortices. This operational complexity requires an agile certification environment capable of validating critical sub-components, including high-density battery packs, precision vertiport landing configurations, landing-hazard detection tools, and fully autonomous environments in which the underlying safety case certifies the system-level software logic rather than simply the physical aircraft. Furthermore, this technical network integrates comprehensive human-factors oversight, crisis and contingency plans, emergency landing zones, real-time battery-health tracking, and rapid-response firefighting protocols. Mitigating societal and ecological externalities requires the holistic deployment of environmental impact-reduction technologies, while maintaining low hyper-local acoustic and visual profiles through proactive land-use planning. Finally, to safely enable dense operations including flights beyond visual line of sight, the system incorporates performance-based wake and downwash classification criteria alongside advanced detect-and-avoid capabilities that provide an automated, multi-layered safety backup during close-proximity flight maneuvers.

Technological enablers for AAM aircraft focus on electrification, energy density, and situational awareness to overcome payload and range limitations. Research identifies the gravimetric energy density of current lithium-ion batteries as a primary bottleneck, driving the need for continued research into hydrogen fuel cells and hybrid-electric systems. Furthermore, aircraft must incorporate distributed electric propulsion (DEP) for noise reduction and advanced DAA sensors to safely navigate dense low-altitude environments populated by both cooperative and non-cooperative objects. [4]

The critical bottleneck in validating autonomous flight control systems lies in the fundamental incompatibility between legacy, deterministic aerospace verification standards and the probabilistic, non-deterministic behaviors inherent to artificial intelligence (AI) architectures [41]. Because proving absolute software correctness across infinite low-altitude urban edge cases is mathematically impractical, operational validation cannot rely on pre-flight simulation alone; instead, it structurally depends on deterministic runtime assurance frameworks – rigid, rule-based safety guardrails that wrap around complex control loops to continuously monitor the aircraft and instantly execute an automated fallback maneuver the moment an unmodeled state or sensor anomaly is detected [2].

The safe co-existence of traditional crewed aircraft and automated uncrewed systems within low-altitude airspaces is fundamentally challenged by the systemic vertical discrepancy between pressure-derived Barometric Altimeter Settings (QNH) and satellite-tracked Global Navigation Satellite System (GNSS) geometric elevations [42]. Because isobaric pressure surfaces warp dynamically across local weather fronts, complex topographies, and urban heat gradients, an uncrewed aircraft and a crewed rotorcraft maintaining the exact same physical height will register highly contradictory vertical readings, introducing severe risks of mid-air collision and airspace non-conformance [43]. To bridge this data gap without requiring traditional aviators to install additional cockpit hardware, modern U-space frameworks utilize a digitized Common Altitude Reference

System (CARS); this system acts as a real-time translation matrix that continuously converts satellite ellipsoidal coordinates into equivalent barometric pressure levels, ensuring an absolute, mutually understood vertical safety thread across all collaborative airspace participants [42].

2.7 Safety Management, Accident Investigation, Security, and Facilitation

The systemic operationalization and scalability of advanced air networks are anchored upon an integrated, multi-layered oversight paradigm comprising adaptive safety management, threat mitigation, and digital facilitation architectures. State-of-the-art literature reviews confirm that scaling these low-altitude networks introduces complex, system-of-systems dynamics, requiring systematic analysis of legacy vertical-lift and urban helicopter accident profiles to translate historical operational hazards into predictive constraints for AAM airframes [44], [45]. To support increasing operational complexity and high levels of automation, the state safety ecosystem mandates scalable Safety Management Systems (SMS) and State Safety Programs (SSP) that can actively identify hazards, assess risks, and execute continuous safety assurance actions. This predictive logic relies on a global learning ecosystem that standardizes event-reporting taxonomies, including the ICAO Accident/Incident Data Reporting (ADREP) taxonomy [46], and promotes uniformity in system nomenclature to track human-automation interaction hazards and safety precursors across international regions. To ensure cross-regional statistical normalization and effective trend analysis, this taxonomic framework is increasingly deployed in advanced, API-driven reporting environments such as the ECCAIRS 2 architecture, which enables multi-tenant networks to ingest and classify safety data by specific aircraft autonomy tiers and human-supervisory modalities.

This proactive capability is increasingly achieved via an In-Time Aviation Safety Management System (IASMS) archetype to address compressed operational decision timelines [47]. Designed to transcend the structural limitations of historically reactive and retrospective SMS, the IASMS concept of operations integrates continuous data fusion, prognostic machine learning models, and real-time risk characterization to optimize the safety thread across both airborne assets and distributed vertiport infrastructures [47]. This digital safety ecosystem functions by ingesting continuous data streams from both flying airframes and ground infrastructure to immediately identify risk precursors, validate battery pack thermal health profiles, and execute automated fallback maneuvers before an operational anomaly escalates into a catastrophic physical failure. Ultimately, robust safety enablers require implementing scalable SMS that explicitly accounts for the unique data integrity, software verification, and network availability risks inherent to highly automated environments, recognizing that latent vulnerabilities in operational technology can directly propagate into immediate physical flight hazards [4].

2.8 Infrastructure and Support Services

The physical deployment and systemic configuration of Advanced Air Mobility (AAM) are structurally dependent upon a comprehensive, highly automated infrastructure and support services network. This institutional layout demands the strategic engineering and modernization of smart vertiports and ground facilities, capable of adapting existing aerodromes and heliports to accommodate high-throughput traffic fluctuations while fully accommodating passengers with reduced mobility. To ensure operational safety and resilience, these facilities integrate automated vertiport management systems to coordinate arrivals and departures, as well as shared databases that track real-time emergency landing zones and specialized firefighting services. Meeting the massive energy demands of alternative propulsion architectures requires expanding electrical grid capacities and establishing standardized charging or refueling pipelines for electricity, hydrogen, and sustainable aviation fuels. The framework unifies high-resolution digital mapping tools and precise, low-altitude weather-forecasting networks that integrate aircraft- and ground-based sensors into a federated nowcasting ecosystem capable of predicting localized urban wind fields and turbulence.

Reliable CNS infrastructure enablers must provide ubiquitous connectivity and accurate positioning in complex environments where the GNSS may be degraded or denied. Research highlights the need for surveillance technologies that recognize non-AAM objects and provide coverage in urban

canyons where traditional radar is insufficient. Infrastructure development must address micro-weather challenges in urban canyons, where localized wind-speed gradients and building-wake shear significantly affect aircraft stability. Vertiport design enablers include standardized energy distribution for rapid recharging and standardized markings that support both piloted and autonomous operations. Furthermore, the successful integration of vertiports into city infrastructure requires research into zoning, fire codes, and environmental impacts to ensure equitable community placement [4].

The scalable rollout of AAM faces profound bottlenecks across its physical and digital infrastructure layers, driven primarily by a critical lack of standardization in vertiport design and fragmented communication networks [48]. On the physical side, the absence of standardized, performance-based metrics to evaluate vertiport Level of Service (LoS) and airside capacities creates severe structural constraints, leading to unpredictable ground-handling bottlenecks that limit network throughput [49]. Digitally, legacy air traffic systems are structurally constrained and unable to seamlessly ingest high-volume automated data feeds, thereby limiting overall airspace capacity near complex urban hubs [50]. To counter airframe-induced signal shadowing and multi-path fading within urban canyons, the ecosystem relies on a transition toward next-generation, cellular-based routing architectures [51]. Ultimately, resolving these vulnerabilities requires deploying unified, xG-based Integrated Communication, Navigation, and Surveillance (ICNS) networks. By binding these distinct capabilities into a spectrum-efficient digital matrix, the framework achieves the ultra-low-latency, deterministic data delivery, and structural resilience necessary to securely manage high-density autonomous flight operations [52].

2.9 Digital Information and Data Management

The scaling of AAM operations is structurally dependent on a seamless, multi-layered digital information and data management framework. In the pre-flight strategic phase, this digital pipeline coordinates four-dimensional trajectory intents and operational volume reservations to preemptively deconflict shared airspace volumes. Once operations transition into active, in-flight phases, the data ecosystem evolves into high-throughput, ultra-low-latency streams that process real-time position telemetry and state vectors to deliver automated conflict-resolution commands under strict deterministic timelines. Underpinning this entire framework is a federated meteorological data layer that captures microscale wind-flow profiles, urban boundary turbulence, and hyperlocal atmospheric disturbances, thereby transforming distributed Internet of Things (IoT) sensors and flying AAM platforms into ad hoc weather stations. Concurrently, managing high-throughput vertiport logistics introduces a complex, multi-tenant personal data environment in which strict privacy requirements must be explicitly balanced against safety-critical pre-flight weight-and-balance verifications. To streamline onboarding without compromising human dignity, systems deploy high-velocity biometric authentication pipelines that isolate passenger bio-information within localized hardware security modules or permissioned distributed ledger environments, transmitting only cryptographically signed validation tokens. This safety-critical thread is further supported by technology-agnostic data repositories that protect sensitive corporate fleet logs and proprietary commercial routing preferences from unauthorized exposure. Ultimately, this multi-tenant network achieves comprehensive system resilience by modernizing aeronautical charts, providing electronic conspicuity to reinforce shared traffic awareness, enforcing standardized altitude reference metrics, and applying System Wide Information Management (SWIM) services to ensure a trusted, highly interoperable digital infrastructure.

The transition to digital messaging and aircraft-to-network radio transmission supports collaborative air traffic management and automated deconfliction. Shared traffic awareness is improved through Electronic Conspicuity (E-Conspicuity) and the management of reliable 4D micro-scale atmospheric data. Data governance is maintained through open, technology-agnostic data management and the application of SWIM services. Data protection focus areas emphasize protecting information in transit through robust encryption and transitioning to quantum-resistant public key infrastructure (PKI) models to avoid future operational disruption. Simultaneously, safeguarding this information-centric network requires enforcing stringent cybersecurity protocols and data protection frameworks that insulate critical airframe-to-ground data exchanges while

preserving the individual privacy of communities living near AAM operations areas [4]. The increasing density of low-altitude airspace operations poses broader resilience and security challenges in detecting, identifying, and tracking both cooperative and non-cooperative airspace users. Since certain categories of airspace users may operate without mandatory transponders or equivalent electronic identification systems, maintaining comprehensive situational awareness and implementing effective counter-UAS measures will become increasingly important for safeguarding critical infrastructure and ensuring secure AAM operations [53].

The meteorological data ecosystem required for AAM demands an unprecedented degree of microscale spatial-temporal resolution to safely manage the strict airworthiness boundaries of AAM aircraft. Conventional legacy aviation weather structures, which rely on localized Meteorological Aerodrome Reports (METAR), twice-daily vertical soundings, and scattered Pilot Reports (PIREPs), deliver coarse macroscopic snapshots that are fundamentally inadequate for resolving the hyper-local variations found in urban environments [54]. To build dependable weather-aware flight-planning networks and dynamic Four-Dimensional (4D) geofences, the low airspace manager requires robust microscale wind-flow modeling capable of mapping turbulent wind flows, severe wind shear, and unpredictable urban-canyon effects created by building clusters [55]. These fine-scale meteorological phenomena introduce severe operational vulnerabilities, including abrupt flight path deviations, critical battery drain due to rapid thrust corrections, and safety certification challenges, making it necessary to classify localized Atmospheric Disturbances (AD) using advanced methodologies such as the Microscale Handling Qualities Rating Method (MHQRM) to establish reliable dynamic weather corridors [55]. To counter the acute lack of real-world urban atmospheric data, modern network paradigms integrate distributed Internet of Things (IoT) sensors alongside low-cost ground stations and UAS acting as ad-hoc flying weather stations to ingest continuous, high-density streams of ambient temperature, humidity, pressure, and wind vectors along active operational segments [56].

The processing of passenger personal data within AAM networks introduces a complex, multi-tenant digital environment where strict data privacy requirements must be carefully balanced against safety-critical weight, balance, and security protocols. Managed across integrated networks of fleet operators, Vertiport Automation Systems (VAS), and AAM service providers, this data pipeline captures standard Personally Identifiable Information (PII), transactional histories, and real-time indoor location tracking to streamline high-throughput urban transit. However, unlike traditional commercial aviation, the highly constrained payload and energy storage envelopes of AAM aircraft require precise physical mass measurements for accurate pre-flight calibration and automated Weight and Balance (W&B) verification. To maintain passenger psychological comfort and dignity while satisfying these packaging airworthiness requirements, systems must utilize Privacy by Design frameworks that immediately anonymize or tokenize raw weight measurements at the vertiport gate, passing only aggregated mass totals to the flight planning system. Furthermore, to support the rapid turnaround times vital to the economic viability of urban air networks, smart vertiports rely extensively on high-velocity biometric authentication pipelines – including facial recognition data and iris scans – to handle continuous ticketing, security screening, and boarding without human intervention [57]. Because this creates a high-value target for digital exploitation, handling these sensitive biometric and physiological data vectors requires strict compliance with overarching legal frameworks, such as Europe's General Data Protection Regulation (GDPR) and the Federal Aviation Administration (FAA) privacy mandates. Consequently, modern AAM network architectures isolate raw passenger bio-information within localized hardware security modules or permissioned Distributed Ledger Technology (DLT) systems; these networks distribute only cryptographically signed validation tokens across multi-tenant service interfaces, protecting passenger identity from edge-node breaches while ensuring a secure, continuous digital thread from booking to destination [58].

2.10 Air Traffic Management

Traffic management evolves through the implementation of UAS Traffic Management (UTM) capabilities that support safe access to both segregated and integrated airspaces. Integrated systems manage both AAM and traditional aviation through open data exchanges under the

supervision of a single authority. New flight rules and evolved airspace classifications address the requirements of digitally native, trajectory-based operations (TBO). Automated conflict management tools and advanced trajectory negotiation allow for dynamic adjustments without constant human intervention. Airspace design transitions from structured segregation to fully integrated, performance-based access. Finally, real-time adaptive management and demand-capacity balancing tools optimize traffic flow in complex urban and regional environments. Scalable traffic management relies on federated digital architectures that leverage cooperative intent sharing and management-by-exception to reduce controller workload. Given the current state of AAM development, a critical need for standardized separation minima between AAM aircraft and traditional air traffic has been identified [4]. At present, significant differences in performance characteristics, operational capabilities, and levels of automation among aircraft types can reduce both safety and operational efficiency in mixed-traffic operations [59]. Therefore, before the full integration of air operations is achieved, airspace structures such as corridors, lanes, layers, or zones must be developed and validated to enable high-density flight operations without burdening existing global ATM systems [4].

One approach is to define airspace cells that can be flexibly allocated between the AAM and ATM domains, allowing the two types of traffic to operate in these cells based on demand, particularly for AAM operations such as UAS [60]. Accordingly, ATM must remain fully aware of the operational implications of delegating airspace cells to anticipate and manage resulting changes with minimal impact on conventional traffic. Conversely, such AAM services as UTM must ensure that all traffic can safely and efficiently vacate airspace whenever control needs to be returned to ATM. The operational process for enabling airspace delegation is called Dynamic Airspace Reconfiguration (DAR) [61]. In particular, the related infrastructure and interface developments enable the required flexibility by enhancing communication among all actors involved on both the AAM and ATM sides. Where full automation in complex traffic situations is not yet possible, a so-called DAR Manager (DARM) may coordinate DAR changes and communicate them to affected tactical controllers. An investigation of contingency scenarios revealed that different situations require tailored DAR approaches, underscoring the complexity of integrating diverse traffic types within shared airspace structures [62]. The current DAR concept, including its implementation via developed ATM and UTM interface prototypes, still needs improvements to increase situational awareness for all actors, reduce the workload for tactical controllers, and present coherent, accurate information on DAR activations and UAS movements. Especially in rapidly changing situations, when missions and flight plans change, greater clarity on impending airspace changes will be required. Furthermore, for further development, it will be critical that regulators provide clear definitions of separation distances between different types of traffic and buffer areas between AAM- and ATM-controlled airspace. Also, the prioritization of UAS flights and AAM traffic in general remains an open issue. There is a need to regulate the use of shared airspace cells by aircraft with a certain priority under given operational circumstances, which may contribute to enhanced automation [63]. High-impact macro-level surveys emphasize that because the projected traffic volume of passenger air taxis for daily urban commutes vastly exceeds the processing capacity of traditional centralized human operators, high-level system automation is an absolute structural prerequisite [64].

Current research formalizes the flight-safety threat using Digital Flight Rules (DFR) and advanced trajectory-optimization algorithms. Under the newly proposed DFR paradigm, flight path separation is achieved cooperatively by sharing operational intents and arrival schedules at Constrained Waypoints (CWPs) within three-dimensional air corridors [65]. This scheduling problem can be mathematically modeled using linear dynamical systems to define non-overlapping estimated time of arrival (ETA) intervals, thereby optimizing throughput while strictly preventing near mid-air collisions (NMAC) at corridor intersections [65]. Concurrently, when managing wider regional and urban networks, strategic traffic flow management employs mixed-integer programming (MIP) within centralized configurations to minimize global delay costs across conflicting vertiport pairs [66]. In multi-provider settings where distinct service entities manage overlapping airspaces, this framework scales into a bi-level optimization model leveraging cooperative game theory, allowing individual providers to iteratively negotiate 4D trajectories, update routing strategies, and

dynamically enforce service priority classifications (regular, express, and medical emergency) without compromising fair airspace equity [66]. However, the long-term vision for AAM should be full integration into the airspace rather than local segregation. This will be achieved through gradually increasing levels of digitalization and automation in both the AAM and ATM domains, culminating in their convergence, thereby supporting the full integration of commercial, general, and AAM aviation operations [3], [67].

3. Examples from Countries and Regions

3.1 Brazil

Brazil has emerged as one of the most significant AAM markets in the world, driven by a mature aviation industry, an increasingly congested urban mobility system, especially in large metropolitan regions like São Paulo and Rio de Janeiro, and a proactive regulatory approach. The primary regulatory authorities are the National Civil Aviation Agency (ANAC) and the Department of Airspace Control (DECEA), with the former regulating aircraft certification, airline operations, airports, and personnel licensing, and the latter regulating and managing the Brazilian Airspace Control System (SISCEAB).

In 2023, ANAC published the document “Advanced Air Mobility - Panorama and Perspectives”, which presents the state of the AAM ecosystem and the challenges for certification, pilot qualification, infrastructure, and air traffic management [68]. Eve Air Mobility, an Embraer spinoff, stands out as the major industrial player in the domestic AAM market. In late 2024, ANAC published the final airworthiness criteria for Eve’s EVE-10 aircraft model, a critical milestone enabling Eve to define its means of compliance and advance toward type certification [69]. Besides Eve’s eVTOL certification work, ANAC granted an Experimental Flight Authorization Certificate (CAVE) to China’s EHang pilotless eVTOL in 2024 and is also working on the validation of other aircraft models, such as Valo from Vertical Aerospace. More recently, in May 2025, ANAC launched a new sectoral consultation on safety objectives for Powered-Lift Certification Level 2 aircraft, covering models with two to six passengers and a maximum weight of 5,670 kg. On the drone side, ANAC proposed a comprehensive restructuring of UAS regulations through the new RBAC no 100, which replaces RBAC-E no 94/2017 and introduces SORA-based risk analysis [70]. Brazilian companies such as Moya Aero and Speedbird Aero are pursuing a cargo-first AAM strategy, using both drones and eVTOLs, to gain a faster path to deployment and public trust by prioritizing freight over passenger operations.

Regarding pilot certification, ANAC is developing specific licensing and training requirements for eVTOLs and is proposing adjustments to RBAC no 61 to create a specialized category for vertical-flight aircraft. For vertiport infrastructure, ANAC approved a 2-year regulatory sandbox based at São Paulo/Campo de Marte Airport and São José dos Campos Airport, with two consortia led by VertiMob Infrastructure and PRS Aeroportos selected and announced in Feb 2025. The sandbox focuses on physical infrastructure, firefighting systems, noise requirements, and airspace access. Regarding airspace integration, DECEA is advancing regulatory frameworks to increasingly support low-altitude drone operations and enable eVTOL integration in busy urban airspace such as São Paulo. DCA 351-6/2022 (BR-UTM) Concept of Operations (ConOps) presents DECEA’s high-level vision for UAS Traffic Management, defining the concepts, capabilities, and infrastructure for unmanned aircraft operating at low altitudes [71]. Building on this foundation, PCA 351-7/2024 presents the national UAM ConOps, which address the integration of eVTOL operations into urban airspace [71]. It acknowledges that a new airspace classification beyond current ICAO categories may be required and foresees the provision of UAM services by DECEA or authorized public or private entities within a synchronized, interoperable central system. It also proposes new digital flight rules to reduce segregation and support automated conflict resolution in high-density phases, in line with international frameworks. At the access level, the updated ICA 100-40 (effective July 2026) consolidates all UAS airspace access rules into a single document, mandates prior SARPAS authorization for all unmanned aircraft regardless of weight, and sets specific criteria for operations within UTM Zones [72]. These instruments are operationalized through DECEA’s SIRIUS program via two dedicated working groups: BR-UTM, which covers low-altitude drone operations, and BR-UAM, which focuses on eVTOL operations.

At the policy level, the Ministry of Ports and Airports, through the Secretariat of Civil Aviation (SAC), launched a public consultation in March 2026 to gather contributions from citizens and specialists from academia, government, and industry toward the formulation of a National Advanced Air Mobility Policy, structured around seven thematic axes, including key environmental and social aspects [73].

Despite these efforts, Brazil faces systemic challenges common to all AAM markets as well as domestic structural challenges. The multi-agency regulatory landscape, spanning ANAC, DECEA, and state and municipal authorities for land use, adds significant complexity to operational approval for any AAM operator. The integration of BR-UTM and BR-UAM efforts into a unified traffic management framework is also a relevant challenge. Vertiport infrastructure regulation remains absent, with reliance on the ongoing sandbox to support future standards. The energy infrastructure required to support eVTOL operations, including charging systems at vertiports and grid capacity in dense urban areas, poses an additional challenge that has received limited attention to date. Finally, public acceptance, equitable access, and noise tolerance in dense Brazilian urban environments represent societal dimensions that the regulatory framework has only begun to address.

3.2 Canada

With respect to the development of the AAM sector, Canada builds on its strong aviation history and uses its large geography to its advantage. Most of the work has been done by three Canadian organizations: Transport Canada (TC), the federal Civil Aviation Authority (CAA), the National Research Council Canada (NRC), the federal research agency, and NAV CANADA, the private, non-profit company that runs the country's air navigation system. The past seven years show how these three have supported Canada's AAM sector.

In 2019, Transport Canada published Statutory Order and Regulation (SOR)/2019-11 in the Canada Gazette Part II [74]. This added Part IX to the Canadian Aviation Regulations and gave Canada its first drone-specific regulations, covering all drones weighing between 250 g and 25 kg flown within visual line of sight (VLOS). A year later, in 2020, the Canadian Advanced Air Mobility Consortium (CAAM) was set up in Vancouver. CAAM is a national non-profit organization, co-founded with the NRC, that brings industry, government, and communities together. The next year brought digital tools to go with the new TC regulations. In 2021, NAV CANADA launched NAV Drone, an app for getting permission to fly drones in controlled airspace. Pilots use a mobile or web interface to plan a flight, request permission, and obtain approval. A November 2025 update added support for medium drones (25–150 kg) and for flights done under an SFOC-RPAS. NAV CANADA is also building Remote and Uncrewed Traffic Management (RTM/UTM) services for low-altitude flying. This will be Canada's version of what Europe calls “U-space”.

Attention then moved from drones to bigger questions about AAM infrastructure and "clean" aircraft operations. In November 2024, Canada launched H2CanFly. It is a national group, led by the NRC, that works on bringing hydrogen-powered aircraft to market and supports Canada's net-zero plans.

The busiest year for new regulations was 2025. In March 2025, SOR/2025-70, also called “RPAS – Beyond Visual Line-of-Sight and Other Operations”, was published [75]. The new regulations allow lower-risk Beyond Visual Line-of-Sight (BVLOS) flights to happen without an SFOC each time. They also created two new credentials: the Level 1 Complex Pilot Certificate and the RPAS Operator Certificate (RPOC), and opened flights for medium drones (25–150 kg). By April 2025, attention shifted from the domestic rules to the international ones. The National Aviation Authorities (NAA) Network, an international group of five regulators that includes Transport Canada alongside the FAA (Federal Aviation Administration), the UK CAA, Australia's CASA (Civil Aviation Safety Authority), and the NZ CAA, published the first edition of its Roadmap for Advanced Air Mobility Aircraft Type Certification [13]. The roadmap sets out a shared approach to certifying AAM aircraft, organized as a "crawl-walk-run" progression from piloted to remotely piloted to fully autonomous flight.

The most recent step came in 2026, when the NRC opened its Drone Innovation Hub. The Hub operates in two cities and three research areas: drone and counter-drone systems, and a drone "living lab" in Montréal, and autonomous flight systems in Ottawa. The goal is to help Canadian

drone companies move from research prototypes to working products, and to shrink the gap between what Canadian labs can show and what is flying around the world.

Canada's AAM sector faces three main challenges. First, a certification gap: the current aircraft certification framework was designed for conventional aircraft and does not yet fully accommodate electric, hybrid-electric, or hydrogen-powered platforms. Second, infrastructure remains underdeveloped, including vertiports, electric charging, hydrogen refueling, and connections to existing transit systems. Third, projected growth in low-altitude operations will exceed the capacity of today's ATC system, requiring next-generation UTM/RTM capabilities. Addressing these gaps will determine how quickly Canada moves from demonstration flights to routine commercial AAM operations.

3.3 European Union

While the term AAM is widely used internationally, the European ecosystem explicitly prefers the term Innovative Air Mobility (IAM), reflecting a stronger emphasis on systemic integration, sustainability, and regulatory innovation. The IAM concept encompasses UAM, regional air mobility, emergency medical services, and tourism operations involving larger aircraft, including those capable of transporting humans. UAS operations are a subject of Innovative Aerial Services (IAS), such as consumer and specific delivery, social and entertainment, firefighting, Search and Rescue (SAR), agriculture, law enforcement, and data acquisition services. The ecosystem is shaped by a broad set of stakeholders, including regulators, industry, and research organizations [5]. The European Union Aviation Safety Agency (EASA) plays a central role, ensuring harmonized safety regulation across Europe. EUROCONTROL supports member states and civil and military stakeholders in achieving safe, efficient, cost-effective, and environmentally friendly aviation operations. The Single European Sky ATM Research 3 Joint Undertaking (SESAR 3 JU) accelerates the implementation of the Digital European Sky strategy [76] through research activities and innovation. This results in a coordinated yet heterogeneous implementation landscape, in which the EU defines overarching frameworks, and Member States handle national operationalization.

The European regulatory framework for U-space, a similar concept to UTM, is built around a package of three Commission Implementing Regulations adopted on 22 April 2021: (EU) 2021/664 [77], 2021/665 [78], and 2021/666 [79] – which together govern airspace designation, the obligations of relevant service providers, and the rules for manned aviation operating alongside drones. Regulation (EU) 2023/203 [80] introduces information security requirements for the digital infrastructure underpinning U-space services. Strategic direction is further reinforced by the European Commission's Drone Strategy 2.0 [81] to shape technical innovations into a regulated, safe, secure, and sustainable drone market in Europe.

Central to the European IAM framework is EASA's pioneering work on the Special Condition for VTOL [55], establishing the certification pathway for (electric) vertical take-off and landing aircraft. Furthermore, EASA has published the prototype technical specification, PTS-VPT-DNS, for the design of VFR vertiports, mainly derived from existing heliport regulations [83].

However, despite Europe's comparatively advanced regulatory framework, several major challenges still hinder large-scale IAM deployment. Europe increasingly pursues an ecosystem-oriented implementation approach in which regulatory development, technological testing, stakeholder participation, and societal integration evolve simultaneously rather than sequentially. The developmental trajectory of AAM within the European ecosystem is distinguished by a societally oriented paradigm that prioritizes stringent safety thresholds, environmental sustainability, and community integration over purely market-driven expansion. Rather than relying on prescriptive legacy rules, European oversight bodies have pioneered a performance- and risk-based regulatory framework. To scale this ecosystem effectively, the primary challenge is establishing a standardized interpretive logic that smoothly translates high-level risk criteria into specific, actionable operational requirements. To guarantee absolute systemic integrity in the absence of long-term operational history, early rule sets frequently incorporate highly conservative safety buffers. While these extensive margins ensure a robust baseline of safety, they present a clear opportunity for regulatory refinement, where constraints can be progressively streamlined as

empirical flight-test data and automated telemetry metrics mature. From an economic perspective, existing European strategic roadmaps focus extensively on establishing safety and compliance baselines rather than actively cultivating, originating, and facilitating commercial market demand. This structural emphasis leaves early-stage business cases relatively ambiguous, making it complex for operators to project long-term financial balancing. Furthermore, this commercial landscape is shaped by a sparse presence of domestic European AAM aircraft manufacturers. This industrial reality highlights a strategic imperative for regional policy to prioritize developing, funding, and scaling local industrial capacity to foster technological sovereignty and secure the regional supply chain.

To address these challenges and support the transition from research to operational deployment, several European coordination and implementation initiatives have emerged. One important example is the IAM Hub [84], initiated by the European Commission and EASA, which connects policymakers, authorities, industry, and research institutions across Europe to harmonize implementation approaches and exchange best practices. In this context, the city of Hamburg, Germany, represents a notable example of regional IAM implementation through close cooperation between public authorities, industry, and academia, resulting in the city's dedicated Urban Air Mobility strategy [85]. At the Port of Rotterdam, the dedicated airspace management and BVLOS drone operations are being tested in a real-world industrial environment [86]. The first operational U-space was established in Italy, and several are close to deployment in Spain, Belgium, and Switzerland, with many more under development in other countries. The U-space ConOps and Architecture [87] and the Implementation Handbook [88] have been published. There is increasing interest in the availability and capabilities of test centers in the European Union. For this purpose, the European UAS Test Centers Alliance, consisting of 35 organizations from 17 European countries, aims to establish a collaborative platform that facilitates communication and knowledge sharing among European UAS test sites, ultimately supporting the growth of the European UAS ecosystem and promoting synergies for both civil and defense applications [89]. These initiatives are complemented by an increasing number of U-space test areas, living laboratories, and real-world test environments that support the validation of IAM technologies and operational concepts under realistic conditions.

3.4 India

According to studies and reports by the National Institution for Transforming India (NITI) Aayog [90], 40% of India's population will live in urban areas by 2030. India has initiated a phased approach for Advanced Air Mobility (AAM) deployment. From an operations perspective, the Indian certification agency, DGCA, has introduced the ”Digital Sky (DigiSky)” platform for dynamic airspace management of drones with up to 500 kg AUW. This web-based portal serves as a single-window system for registering, operating, and monitoring all drone operations in India. In terms of technological innovations, a unique technology in the Indian context is the proposed application of ”Navigation with Indian Constellation“ (NavIC) for more accurate and reliable urban navigation [91]. NavIC algorithm, developed by the Indian Space Research Organization, is India's independent regional satellite navigation system. Another system deployed for drones is the automated ”No Permission No Take-off” (NPNT) protocol. This system is designed to prevent the takeoff of any unregistered or unauthorized drone.

To realize the AAM ecosystem, India introduced a conservative regulatory framework with the “Digital Sky” platform and NPNT-compliant operations in 2021. All drones weighing less than 500 kg must be registered through the DigiSky portal and must be equipped with the NPNT digital chip. This approach is taken to address security and privacy issues. Further, DGCA's DigiSky platform uses a color-coded (red, orange, and green zones) airspace map for safety and efficient traffic management [92]. However, the current limitation is that the ceiling altitude permitted for UAS operations is below 400ft. Further, another notable breakthrough towards AAM realization in India is the plan for a pilot-scale deployment during 2026-2028 for AAM operations between Gurugram and Noida International Airport (Jewar) corridor, which is about 65 - 75 km in length [93].

In line with efforts to establish an AAM ecosystem in India, several regulatory and policy documents have been issued by stakeholders, including the Director General of Civil Aviation

(DGCA) and the Confederation of Indian Industry (CII). A few prominent documents from DGCA include AD AC 01 on Aerodrome Advisory for Vertiport [94], AEAC 01 on Aircraft Engineering Advisory Circular for Type Certification [95], and FCL 01 on Guidance material for training and endorsement rating [96] of VCA. In addition to these, the key report from CII is “Skyways to the Future: Operational Concepts for Advanced Air Mobility in India.” [97] and “Navigating the future of advanced air mobility in India.” [93]. Apart from this, the Government of India publishes many notifications related to AAM on the Press Information Bureau web portal. Apart from these documents of Indian origin, one of the key international documents in the Indian context of AAM that needs mention is a report by the International Air Transport Association (IATA) titled “Aviation in India.” Sustaining – and growing – a dynamic air transport market.” [98].

For India, it is important to identify the key specific challenges before proceeding with the implementation of AAM operations. India has a subtropical climate with cold, high-altitude areas, dry deserts, and a corrosive coastal climate with episodes of tropical cyclones during the post-monsoon months. These wide variations in climatic conditions across India pose a challenge to designing a universal AAM platform that can operate optimally nationwide. Apart from the climatic conditions, the strong ionospheric disturbance over the Indian sub-continent often distorts the GPS signals. Yet another anthropogenic challenge in India is that, due to the limited number of operational civil helicopters (about 250 to 280 registered), there are infrastructure deficits for VTOL Urban Air Mobility platforms. Apart from this, regulatory policies are still being evolved by DGCA, Government of India, for the AAM ecosystem. From an operational perspective, the emergence of the Urban Air Transport Management System and the evolving last-mile connectivity ecosystem bring further challenges to the implementation of AAM in India. An inclusive approach by all Indian stakeholders, like DGCA, the Government of India, Research Organizations like CSIR, Academic institutes, Local Governing bodies, and law and order enforcement bodies, is imperative. Furthermore, India is a very price-sensitive market, and all Urban Air Taxi Operations need to achieve economies of scale to be affordable to the traveling public, a challenging prospect given the technological uncertainties and the social acceptance of Advanced Air Mobility.

3.5 Japan

In Japan, the development and social implementation of AAM have been promoted through coordinated public–private initiatives led by the Public-Private Committee for Advanced Air Mobility, established in 2018. The Roadmap for the Air Mobility Revolution provides a phased implementation strategy from demonstrations to commercialization. The latest revision [99] specifies the initiation of commercial operations in 2027–2028 and outlines subsequent phases involving new traffic management systems, remote operations, and partial automation in the 2030s. Complementing this, the AAM ConOps [100] defines a structured transition from low-density operations within existing airspace to higher-density and more automated operations.

In addition to these policy and technical developments, Japan has actively promoted industry participation and real-world demonstrations. Notably, at Expo 2025 Osaka, Kansai, Japan, multiple eVTOL aircraft, including those developed by SkyDrive and Joby Aviation, conducted demonstration flights, highlighting both domestic industrial efforts and international collaboration. These activities have also supported the development of regulatory frameworks, including guidelines for vertiport implementation and certification frameworks for aircraft, operators, pilots, and maintenance personnel. At the same time, regional and local governments, including those in Tokyo, Osaka, Aichi, Shizuoka, Ishikawa, Yamanashi, and Oita, have initiated efforts toward AAM deployment, such as vertiport planning and infrastructure development. Among industrial players, SkyDrive aims to launch domestic commercial operations, while the Japan-based manufacturer Honda is also advancing overseas aircraft development. These developments underscore the integration of regulatory frameworks, operational concepts, and emerging market players within Japan’s AAM ecosystem.

The principal documents underpinning Japan’s AAM strategy include the Roadmap, the ConOps, and outputs from research and development initiatives. Among these, the ReAMo (Realization of Advanced Air Mobility) project, funded by the New Energy and Industrial Technology Development Organization (NEDO), supports the implementation described in the Roadmap and ConOps. One

of the central focus areas of ReAMo is the design and validation of UATM (Urban Air Traffic Management) functions for AAM, including flight plan coordination, vertiport resource management, and conformance monitoring under dynamic constraints. In addition, particular emphasis has been placed on interoperability between UATM and UTM systems, reflecting the need to manage mixed operations involving AAM aircraft in low-altitude airspace. Demonstration activities have provided initial validation of the developed traffic management functions, highlighting both their feasibility and their relevance for emerging operational scenarios [101].

Building on these results, several challenges remain. A primary issue is the robustness of AAM operations under uncertainty and irregular disruptions, such as departure delays, demand fluctuations, and temporary vertiport closures. These disruptions can propagate across interconnected operations, affecting the stability and reliability of the overall system. Addressing this requires traffic management approaches that maintain operational continuity through flexible coordination and resilient resource management. These capabilities must be integrated with existing airspace and air traffic management frameworks. Additional challenges include the development of regulatory frameworks, infrastructure, and public acceptance, as well as environmental impact. Future deployment will depend on advances in automation and distributed traffic management with an emphasis on operational resilience aligned with the Roadmap and ConOps.

In summary, Japan's AAM initiative is characterized by strong alignment among policy, operational concepts, and R&D, with Expo 2025 serving as a key validation milestone; however, further work is required to achieve scalable and integrated operations.

3.6 Korea

The Republic of Korea is actively pursuing policy and technology development to commercialize AAM, led by the Korea Aerospace Administration (KASA) and the Ministry of Land, Infrastructure, and Transport (MOLIT). Since the establishment of the "K-UAM Roadmap" in 2020 [102], [103] the government has been implementing a phased commercialization strategy, targeting demonstration and early commercialization in 2025, followed by full-scale commercialization by 2030. MOLIT is advancing an integrated ecosystem strategy encompassing the ConOps, Urban Air Traffic Management (UATM), vertiport infrastructure, and the development of a certification framework. Established in 2024, KASA serves as the national authority for aerospace R&D coordination and is currently focusing its investment on developing future AAM aircraft and localizing eco-friendly propulsion systems.

The K-UAM Grand Challenge is a representative national demonstration program to validate Korean UAM technologies [103]. The program conducts integrated testing of aircraft safety, air traffic management, communications, and vertiport operations, with participation from major private consortia such as Hyundai Motor Group, Korean Air, and SK Telecom. The primary objective of this initiative is to verify operational safety and feasibility prior to commercialization through real-world urban flight scenarios [104]. In addition, KASA has initiated construction of the "Green UAM-AAV Core Component Test and Evaluation Center" in Seosan, Chungcheongnam-do, with completion and operation scheduled for the second half of the year [105]. This facility is expected to provide essential infrastructure for the reliability and safety verification of key components of next-generation eco-friendly aircraft, such as electric motors and hydrogen fuel cell stacks, thereby supporting technological self-reliance within domestic industries. Furthermore, Korea is developing an AAM industrial ecosystem centered on eVTOL development, communication-based UAM traffic management, precision navigation, and AI-based air traffic management technologies. Leading industrial actors, including Hyundai Motor Group (Supernal), Hanwha Systems, and Korean Air, are driving aircraft and systems development, while collaboration with public institutions is enhancing overall technology maturity.

Similar to other countries, Korea faces several key challenges in AAM implementation. Because AAM aircraft operate at lower altitudes in complex urban environments, existing aviation certification frameworks are insufficient to ensure safety. Significant technical uncertainties remain regarding eVTOL battery safety, emergency landing capabilities, and collision-avoidance technologies [106]. Moreover, AAM requires establishing a new Urban Air Traffic Management

(UATM) system distinct from conventional air traffic management. Key requirements include dynamic air corridors, automated traffic management, and real-time data integration for high-density urban operations. In addition, the development of vertiport siting, power infrastructure, charging systems, and 5G/6G-based communication networks is essential. However, current infrastructure remains limited to selected metropolitan areas, and nationwide expansion is still in its early stages. Finally, public acceptance remains a critical challenge due to concerns regarding noise, safety risks, and operational costs. In particular, reducing high operational costs during the early commercialization phase is a key determinant of industrial scalability and market expansion [107].

In summary, Korea's AAM development is progressing rapidly under a government-led structured roadmap supported by large-scale demonstration programs. While the technological and institutional foundations are gradually maturing, significant challenges remain in safety certification, traffic management integration, infrastructure development, and public acceptance.

3.7 The USA

In the United States, several organizations have taken an active role in developing the AAM domain. The Department of Transportation (DoT) led an integrated working group to develop a comprehensive national strategy covering key aspects, including airspace, infrastructure, security, community planning and engagement, workforce, and automation [108]. One of the interesting aspects of this national strategy is collaboration among 19 different federal agencies to comprehensively identify research and policy needs. These needs were also mapped to federal entities for their ownership. Such a national strategy, comprehensive plan, and collaboration among various entities could serve as a model to any nation that would like to plan and prepare towards advanced air mobility implementation. The Federal Aviation Administration (FAA) is primarily responsible for certification, regulation, and operational implementation of AAM operations in the airspace. One of the key aspects of airspace integration is avoiding overload of the existing air traffic management system. The FAA developed a concept of operations for urban air mobility operations that included cooperative airspace operations. Cooperative operations are similar to UTM and can be supported by third-party services known as Providers of Services for Urban Air Mobility (PSU) [109]. NASA is primarily responsible for conducting research related to autonomy, aircraft design and safety, noise modeling, airspace operations, and safety considerations, and the outcomes are used by the FAA, industry, and standardization bodies.

After a decade of research and collaboration among NASA, the FAA, and industry, and following multiple pilot studies and field tests, the FAA established a key site operation in the Dallas area to initiate limited BVLOS operations for small drones. The FAA released a Notice of Proposed Rule Making (NPRM) in August 2025. It includes Part 108, which sets out requirements for operating BVLOS on a routine basis, and Part 146, which offers a regulatory framework for automated data service providers (or third-party service suppliers) to enable BVLOS flights. The most relevant for AAM is Part 146, which provides a pathway for third-party services known as Automated Data Service Providers (ADSPs). All of these will be highly applicable to the AAM industry if it wants to scale these operations without overloading the air traffic control system and/or without requiring the government to invest in the entire infrastructure needed to support the operations, where such infrastructure does not exist.

One of the interesting aspects of the United States ecosystem is the role of venture capitalists, private equity, or corporate investors. Many AAM start-ups were funded by such investments. The availability of capital has allowed many start-ups to continue to mature technically viable aircraft designs or airspace service providers. The FAA is the responsible agency for certification and safe operation of these aircraft. They have rigorous processes and data requirements before certification can be issued. Specialized certification pathways for powered-lift and hybrid-electric aircraft are being considered [110]. The DOT and FAA also initiated an electric Vertical Take-off and Landing Integrated Pilot Project (eIPP) to accelerate testing and operationalization of the AAM aircraft. Eight multi-state projects have been selected to collect data for future regulations.

Complementing these policy roadmaps, NASA's Airspace Operations and Safety Program (AOSP) establishes a shared baseline for the international research community by addressing open

scientific gaps and systemic bottlenecks [84]. While autonomous flight control certification remains a significant technical barrier, NASA treats remotely piloted and increasingly autonomous operations as a gating capability for viable business use cases. NASA's portfolio addresses a layered set of operational barriers: implementing digital clearance exchanges and machine-readable procedures to replace voice workflows; integrating multi-sensor fusion and Artificial Intelligence (AI) algorithms for hazard perception across surface, terminal, and en-route domains; ensuring navigation accuracy and integrity for precise approach and landing; and validating Detect-and-Avoid (DAA) performance across diverse operational regimes. System architectures, off-nominal handling, and supervisor workloads are evaluated through human-in-the-loop simulations and flight tests to provide empirical evidence to standard-setting bodies, including the Radio Technical Commission for Aeronautics (RTCA) Special Committee 228 (SC-228) and the European Organization for Civil Aviation Equipment (EUROCAE) Working Group 105 (WG-105).

Because regulatory evolution must accommodate non-deterministic systems, NASA is developing a tailorable, performance-based safety framework and novel verification methods for learning-enabled algorithms. This research spans learning assurance and overarching system properties to establish an evidentiary path to airworthiness and operational approval, complementing parallel international initiatives, such as EASA's AI rulemaking and scientific activities at IFAR institutions. In the ATM domain, NASA addresses mixed-aviation integration by investigating strategic trajectory management, Trajectory-Based Operations (TBO) across heterogeneous equipage, automated flow management under increasing automation, and the role of AI agents in supporting human traffic controllers within federated, distributed simulation environments. Additionally, NASA's research into PSU capabilities, cooperative airspace design, and DAR procedures informs candidate data exchanges that align with international frameworks. In parallel, NASA's Higher Airspace Traffic Management (HATM) research extends this cooperative-services paradigm into stratospheric regimes, driving early international research alignment to ensure next-generation aviation standards – including SWIM, E-Conspicuity, common altitude reference metrics, and PKI data protection focus areas.

4. Discussion and Future Perspectives

The global operationalization of AAM exposes a complex socio-technical tension between rapid, decentralized technological iteration and highly fragmented international governance frameworks. Comparative analysis of regional strategies – ranging from the market-capitalized, interagency approach of the US DoT to the safety-oriented, risk-based philosophy of the EASA – reveals that no single regulatory blueprint exists. This global divergence introduces significant friction for international market development and cross-border type certification. Furthermore, localized structural and environmental realities complicate universal implementation. For instance, Brazil's multi-agency regulatory landscape must integrate extensive low-altitude drone operations with urban vertical-flight frameworks in dense metropolitan areas, while India faces profound geographical and physical bottlenecks, including severe ionospheric distortions of satellite navigation signals and subcontinental microclimatic extremes.

Compounding these regulatory misalignments are deep economic and infrastructural bottlenecks that challenge long-term commercial viability. The sector is constrained by high aircraft development costs, expensive vertiport infrastructure, and significant energy demands, which conflict with consumer affordability expectations. Because early market phases are projected to exhibit restricted initial growth before achieving scale, manufacturers and fleet operators require substantial financial resilience and long-term "staying power". This economic uncertainty highlights a critical operational gap: the absence of standardized, performance-based metrics for evaluating vertiport Level of Service and airside capacities, leading to unpredictable ground-handling bottlenecks. Additionally, the transition from traditional fossil-fuel aviation to electric architectures introduces unique physical flight hazards. Unlike legacy airframes with stable performance profiles until fuel exhaustion, battery-powered aircraft experience a progressive decline in maximum power as their state of charge drops, thereby increasing risk during energy-intensive vertical landings in highly constrained urban canyons.

At the intersection of technology and human factors, the evolution from human-centric piloting to

remote, system-level supervision over multiple aircraft introduces unmodeled cognitive risks. Human-in-the-loop simulations demonstrate that while operator workloads are manageable during initial low-density rollouts, medium-to-high traffic densities generate severe cognitive overload, exposing remote managers to automation surprises, mode confusion, and dangerous proficiency loss due to diminished natural sensory feedback. On a societal level, public acceptance remains highly contingent on localized externalities. While communities demonstrate a strong willingness to adopt AAM for high-utility, mission-critical use cases such as Emergency Medical Services or disaster response, market acceptance of premium urban air taxi services is constrained by legitimate social equity concerns. If services remain restricted to discretionary premium segments, public infrastructure risks becoming an exclusive asset rather than an inclusive transport alternative, undermining the societal legitimacy required for large-scale urban integration.

The scalability of the next-generation low-altitude aviation ecosystem depends on shifting from local, structured airspace segregation to full, performance-based airspace integration. Overcoming the cognitive limits of traditional centralized human air traffic control requires a transition to federated digital architectures driven by Digital Flight Rules (DFR) and automated trajectory-negotiation algorithms. Concurrently, the digital infrastructure must evolve to handle non-deterministic artificial intelligence algorithms and massive, multi-tenant data streams while maintaining absolute data integrity and individual privacy. Because proving absolute software correctness across an infinite number of low-altitude edge cases is mathematically impractical, operational validation will rely on deterministic runtime assurance frameworks to continuously monitor flight control loops and execute automated fallback maneuvers the moment an unmodeled state is detected.

Moreover, the physical resilience of future operations requires an unprecedented resolution in microscale environmental forecasting. Future airspace networks must build a federated, low-altitude nowcasting matrix that transforms distributed Internet of Things (IoT) sensors, ground stations, and flying airframes into ad-hoc weather stations. Ingesting these continuous, high-density streams will enable advanced methodologies to map hyper-local urban boundary-layer turbulence, building-induced wake shear, and severe wind gradients in real time. Finally, to secure this information-centric infrastructure against cyber-physical threats and systemic disruptions, data protection focus areas must prioritize implementing quantum-resistant Public Key Infrastructure models, robust transit encryption, and secure-by-design principles.

AAM represents a paradigm-shifting socio-technical system-of-systems that cannot scale through independent technological or infrastructure innovations alone. Its successful operationalization demands the seamless convergence of adaptive safety oversight, robust economic models, and global standardizations that transcend legacy national boundaries. To support this global safety loop, international standardization organizations must promote absolute uniformity across all elements of the AAM ecosystem and all its enablers. Ultimately, the long-term viability of AAM will not be dictated solely by engineering airworthiness or aircraft automation milestones. Instead, its maturity depends on establishing a transparent, accessible, and environmentally responsible digital fabric that successfully integrates with existing multimodal public transport networks to serve the broader common good.

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