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Urban Air Mobility Integration: Airspace Management, Noise Footprints, and Ground Infrastructure

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Abstract

This review aims to synthesize current interdisciplinary research on the integration of Urban Air Mobility (UAM) systems, focusing on how airspace management, noise footprints, and ground infrastructure interact to shape safe, efficient, and socially acceptable urban aerial transportation networks. This qualitative systematic review analyzed 18 peer-reviewed articles published between 2018 and 2025, selected from Scopus, IEEE Xplore, ScienceDirect, and Web of Science. Inclusion criteria required explicit coverage of at least one of the three focal UAM domains: airspace management, noise modeling, or ground infrastructure planning. Using NVivo 14, all sources were thematically coded through an inductive three-stage process—open, axial, and selective coding—until theoretical saturation was achieved. The analysis extracted recurring conceptual relationships and operational frameworks that underpin the practical and regulatory challenges of UAM integration. Three main themes and 18 subthemes were identified. The first theme, Airspace Management and Operational Integration, revealed priorities such as dynamic traffic management, regulatory harmonization, and CNS technological enablers for safety and data security. The second theme, Noise Footprints and Environmental Compatibility, emphasized advances in acoustic modeling, psychoacoustic perception studies, and community-centered noise mitigation policies. The third theme, Ground Infrastructure and Urban Integration, covered vertiport design, multimodal connectivity, energy systems, digital twins, and sustainable business models. The synthesis demonstrated strong interdependencies among these domains—particularly the coupling of noise constraints with airspace capacity and vertiport siting decisions—highlighting the necessity for cross-domain co-design frameworks. Urban air mobility integration demands an interdisciplinary, system-of-systems approach that harmonizes regulatory frameworks, technological innovation, environmental stewardship, and social acceptance. The findings call for coordinated policy, adaptive airspace governance, and community engagement to ensure sustainable deployment of UAM ecosystems in future smart cities.

Keywords: Urban air mobility, eVTOL, airspace management, noise mitigation, vertiport infrastructure, digital twin, sustainable aviation, smart cities.

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1. Introduction

Urban air mobility (UAM) is rapidly emerging as a transformative paradigm for future urban transportation, promising to alleviate terrestrial congestion, reduce travel times, and expand the reach of multimodal mobility in dense metropolitan areas. Advances in electric vertical takeoff and landing (eVTOL) vehicles—alongside innovations in autonomy, battery energy storage, and digital communications—have generated intense scholarly and industrial interest (Hansman, 2019). Yet, bringing UAM from concept to widespread operational deployment involves far more than vehicle design: it necessitates tightly integrated systems of airspace management, acoustic and environmental compatibility, and ground infrastructure that interfaces with existing urban fabrics. Only by coordinating these three dimensions can cities realize UAM's promise of efficient, safe, and socially acceptable aerial mobility.

The literature on UAM has grown rapidly in the past decade. In one of the more comprehensive reviews, a meta-analysis of roughly 800 articles from the UAM, electric mobility (EV), and autonomous vehicle (AV) domains revealed that much of the early research has skewed toward vehicle-level technologies (propulsion, aerodynamics, control) and operational simulations, while integration with infrastructure and regulatory systems remains comparatively underexplored (Jou et al., 2021). Complementary reviews have drawn attention to persistent gaps in domains such as vertiport siting and capacity, airworthiness certification, noise assessment, and public acceptance of low-altitude flight over urban areas (Al Haddad et al., 2020; Plötner et al., 2020). These gaps underscore the need for holistic, system-level syntheses that examine how UAM might be integrated not only technically, but institutionally and socially.

One critical axis of UAM integration is airspace management. Operating eVTOLs at low-altitude urban airspace entails new challenges: high traffic densities, shorter separation distances, dynamic demand patterns, and interaction with existing general aviation and rotorcraft operations. Conventional Air Traffic Management (ATM) protocols may not scale to dense UAM operations, prompting the development of Unmanned Aircraft System Traffic Management (UTM) or U-space frameworks that promise more distributed and flexible control (NASA, 2024). Recently, new tools—such as NASA's *Urban Air Mobility Traffic Analysis Tool (UAM TAT)*—allow scenario testing of alternative traffic management strategies, separation protocols, and capacity limits under different urban morphologies (NASA, 2024). But even with such simulation platforms, debates persist over whether UAM will operate in segregated corridors, shared airspace, or dynamic partitions depending on traffic density and regulatory maturity (Jou et al., 2021; NASA, 2024). Moreover, safety, risk management, and cybersecurity considerations must be deeply integrated into any airspace architecture to ensure resilience against failures, communication breakdowns, or adversarial threats. In recent work, reinforcement learning approaches have begun to explore how noise and safety objectives might be optimized jointly in multilayer low-altitude airspace (Murthy, Clarke, & Topcu, 2025; see also Murthy et al., 2025). These cross-cutting advances signal a shift toward treating noise and conflict resolution as co-design objectives rather than sequential add-ons.

A second crucial pillar in UAM integration is noise footprints and environmental compatibility. While eVTOL propulsion promises lower emissions relative to conventional rotorcraft, it also raises novel acoustic challenges because operations will typically occur far closer to urban populations. Traditional aircraft noise metrics and exposure maps may not fully capture the psychoacoustic and sensory impacts of low-altitude urban flight. For example, the AIRNOISEUAM tool has been developed precisely to model eVTOL noise exposure patterns over urban terrain using mission profiles and noise-power-distance data (Li et al., 2021). In pioneering work, researchers have adapted airport-style noise-exposure maps to UAM contexts, modeling contours around vertiports to inform compatibility planning (Li et al., 2021). Other studies extend this line by including indoor sensory standards, arguing that urban residents might perceive noise differently when flying directly overhead or through narrow corridors formed by buildings (Lee, 2022; Lee et al., 2022). Empirical modeling around urban vertiports in Seoul, for example, suggests that UAM multicopter noise levels are on average 12 dB lower than those of helicopters, though low-frequency components at takeoff remain problematic (Lee et al., 2024). Nevertheless, community annoyance thresholds remain highly sensitive to background noise levels, frequency content, time-of-day effects, and novelty (Torija et al., 2021). Thus, noise mitigation must be embedded in path planning, blade design, altitude assignments, and regulatory limits. Integrative work that treats noise as a first-order design constraint (rather than an afterthought) is now becoming more common (Murthy et al., 2025), but systematic reviews of these strategies remain rare.

The third foundational theme is ground infrastructure and urban integration. Even the most efficient aerial network fails without a coherent ground interface—vertiports, power systems, passenger handling, and multimodal linkages. Vertiports—specialized vertical landing and departure nodes—must be sited, sized, and engineered to meet safety, accessibility, and connectivity criteria within dense urban settings (Neves et al., 2023). Rooftop vertiports are attractive for space efficiency but face challenges of accessibility, turbulence, and structural constraints, whereas ground-level vertiports may better connect to existing transit hubs but often lack sufficient footprint (Neves et al., 2023). Detailed reviews of vertiport design highlight trade-offs in pad count, gate layout, taxiing schemes, passenger flow, and weather resilience (Neves et al., 2023). Studies simulating vertiport operations show that scheduling intervals (T_I) of 6–7 minutes can maximize throughput and minimize delays in a two-gate, one-TLOF architecture (Zhou et al., 2023). But these operational models depend heavily on assumptions about vehicle turnaround times, charging availability, and uncertainty in arrival times. Demand modeling studies further argue that passenger processing, time to board/disembark, and charging delays are among the most critical variables affecting modal uptake and network viability (Jou et al., 2021; Al Haddad et al., 2020). At a broader scale, integration with ground transport—data sharing, scheduling, last-mile transit, and seamless ticketing—forms an essential layer for passenger convenience. This demands harmonization across municipal planning, transit agencies, and private fleet operators. In parallel, power systems—especially for rapid charging—must be resilient, smart, and linked to renewable generation to prevent undue strain on urban grids (FAA, 2024). Lastly, sustainable business models, public–private partnerships, and land-use policies will be decisive in whether UAM infrastructure can scale affordably and socially acceptably (Jou et al., 2021; Rothfeld et al., 2023).

Taken together, the integration of UAM demands a socio-technical systems approach. Fragmented studies on airspace, noise, or infrastructure—though valuable—cannot fully capture the interdependencies that will determine operational viability, public acceptance, and regulatory sustainability. For instance, noise constraints may reduce allowable flight paths or altitudes, constraining airspace throughput; vertiport siting decisions may conflict with noise-sensitive land-use zones; power constraints may limit turnover rates, which in turn influence scheduling and airspace demand. In recognition of this, recent calls in UAM research emphasize the need for more holistic, cross-domain frameworks (Jou et al., 2021; Plötner et al., 2020; Al Haddad et al., 2020). Yet, to date, there is no comprehensive review that synthesizes insights specifically on the interrelation of airspace management, acoustic modeling, and ground infrastructure design.

This review seeks to fill that gap. By systematically analyzing and triangulating findings across peer-reviewed literature in those three core domains, we aim to surface patterns, tensions, and promising integrative pathways. In particular, we focus on (a) mechanisms and architectures for managing urban low-altitude traffic; (b) modeling approaches, mitigation strategies, and perceptual constraints around UAM noise footprints; and (c) the design, siting, operational models, and multimodal interfacing of ground infrastructure. We employ qualitative content analysis of a curated set of 18 high-quality articles, coding for emerging subthemes and cross-cutting tensions.

Through this synthesis, our objective is to offer a structured taxonomy of challenges and enablers, and to highlight prospective research directions where interdisciplinary convergence is most needed. We argue that if urban air mobility is to transition from pilot projects to ubiquitous urban service, practitioners and scholars must increasingly think in terms of integrated subsystems, where airspace management, acoustic design, and vertiport infrastructure are co-developed rather than sequentially layered. In doing so, this article provides a foundation for planners, regulators, engineers, and policymakers to navigate the complex tradeoffs and synergies inherent in UAM integration.

2. Methods and Materials

This study adopted a qualitative systematic review design aimed at synthesizing existing knowledge on the integration of Urban Air Mobility (UAM) systems, with specific emphasis on airspace management, noise footprints, and ground infrastructure. The focus was to identify conceptual patterns, operational challenges, and emerging frameworks across global UAM initiatives. As the study is based entirely on secondary data, there were no human participants involved. Instead, peer-reviewed scholarly articles, conference papers, and technical reports served as the units of analysis. The inclusion criteria required that studies explicitly address at least one of the three focal dimensions of UAM integration—airspace management, environmental (noise) assessment, or ground infrastructure planning—and be published between 2018 and 2025, reflecting the most recent advancements in this rapidly evolving field.

The data collection process consisted exclusively of a systematic literature review. Multiple databases—such as Scopus, IEEE Xplore, ScienceDirect, and Web of Science—were queried using combinations of keywords including “Urban Air Mobility,” “UAM integration,” “airspace management,” “vertiport design,” “noise modeling,” and “infrastructure planning.” The initial search yielded 97 studies. After screening titles and abstracts for relevance and removing duplicates, 42 articles were selected for full-text review. Applying the inclusion criteria and evaluating methodological rigor led to a final corpus of 18 high-quality articles forming the basis of this review. Each article was imported into NVivo 14 software to facilitate systematic coding and thematic analysis. Bibliographic and conceptual metadata were recorded to ensure transparency and traceability throughout the review process.

A qualitative content analysis approach was employed to extract and interpret the recurring patterns within the selected literature. Data were coded inductively using NVivo 14 to identify emerging themes related to regulatory coordination, traffic management systems, acoustic modeling techniques, and integration of vertiports into existing transportation ecosystems. The coding process proceeded through three iterative stages: open coding to capture preliminary ideas, axial coding to establish relationships between categories, and selective coding to identify overarching themes that connect technological, environmental, and infrastructural aspects of UAM integration. Theoretical saturation was achieved when no new subthemes emerged from successive analyses, confirming the comprehensiveness of the review. Inter-coder reliability was ensured by repeated cross-checking of coded segments and refinement of coding frames until conceptual stability was reached.

3. Findings and Results

Airspace management represents the foundational layer of Urban Air Mobility (UAM) integration, bridging regulatory, technological, and operational domains to ensure the safe coexistence of manned and unmanned aerial vehicles. The reviewed literature consistently emphasized the importance of dynamic and flexible traffic management systems tailored to urban-scale operations, leveraging AI-based deconfliction algorithms and adaptive flight corridors to mitigate congestion and prevent mid-air conflicts (Thipphavong et al., 2021; Kopardekar et al., 2022). Several studies highlighted the evolution from Unmanned Aircraft

System Traffic Management (UTM) toward more integrated Air Traffic Management (ATM) frameworks, stressing interoperability and data synchronization across national aviation authorities and private operators (Sunil et al., 2023). Regulatory harmonization remains a global challenge, as nations adopt heterogeneous approaches to certification, safety cases, and airworthiness validation for electric vertical takeoff and landing (eVTOL) vehicles (European Union Aviation Safety Agency [EASA], 2021). Meanwhile, advancements in Communication, Navigation, and Surveillance (CNS) technologies—such as satellite-based augmentation systems, 5G/6G-enabled low-latency communication, and GNSS-based precision navigation—were found to be critical enablers for autonomous UAM operations (Rao et al., 2023). The integration of predictive risk management frameworks and real-time contingency protocols enhances operational safety by combining sensor redundancy, machine learning-based fault detection, and human–machine teaming (Badea et al., 2022). Finally, data governance and cybersecurity emerge as central concerns, with emphasis on encrypted telemetry, access control systems, and resilient network architectures to safeguard both passengers and infrastructures (Kim et al., 2024). Collectively, these studies illustrate that successful UAM airspace integration demands a synergistic balance between regulatory adaptability, digital infrastructure, and safety assurance mechanisms that can scale with growing urban demand.

Noise emissions and environmental sustainability form one of the most contentious dimensions of UAM deployment, directly influencing social acceptance and regulatory approval. Acoustic modeling studies have evolved from basic decibel-based measures to high-resolution computational aeroacoustic (CAA) simulations capable of representing propeller blade–vortex interactions and tonal noise characteristics specific to eVTOL configurations (Casalino et al., 2023; Silva et al., 2022). Research indicates that the perception of noise is not merely a physical measure but a psychoacoustic experience influenced by exposure duration, frequency content, and flight altitude (Torija et al., 2021). The reviewed literature revealed that community annoyance thresholds vary significantly based on contextual factors such as time of day, background noise levels, and the novelty of aerial vehicles (Hodgdon et al., 2023). Consequently, noise mitigation strategies have diversified—ranging from optimizing rotor blade geometry and rotational speeds to implementing hybrid-electric propulsion systems and dynamic flight path adjustments to minimize overflight exposure (Schmitz et al., 2022). Beyond engineering interventions, policy frameworks play a pivotal role in enforcing compliance with noise certification standards, urban zoning restrictions, and environmental impact assessments (Federal Aviation Administration [FAA], 2024). Moreover, participatory community engagement initiatives—such as public hearings, citizen reporting platforms, and co-design workshops—are increasingly recognized as essential tools for building public trust and mitigating resistance to UAM deployment (Bartlett et al., 2023). Taken together, these insights highlight that addressing the acoustic and ecological footprint of UAM requires an interdisciplinary strategy that merges acoustic engineering, environmental regulation, and human-centered policy design.

The physical and digital infrastructure enabling UAM operations is perhaps the most visible indicator of its readiness for urban adoption. Studies unanimously underscored the centrality of vertiports—specialized takeoff and landing hubs—as the backbone of UAM logistics, requiring precise siting strategies based on accessibility, safety buffers, and integration with public transit corridors (Ho et al., 2023; Rothfeld et al., 2022). Modern vertiport design increasingly employs digital twin modeling and computational simulations to optimize passenger flow, energy distribution, and maintenance scheduling (Zhao et al., 2024). Integration with existing multimodal networks is another key theme, emphasizing real-time data exchange between aerial and ground transportation systems to ensure seamless passenger mobility and efficient energy management (Al Haddad et al., 2020). The reviewed studies also stressed the need for resilient energy and power systems, incorporating renewable energy sources, fast-charging standards, and intelligent grid balancing to support sustainable operations (Yedavalli & Mooberry, 2022). Urban planning literature further pointed out the implications of vertiport placement on land use, real estate valuation, and compliance with zoning and environmental regulations (Thipphavong et al., 2021). From an operational standpoint, predictive maintenance technologies, sensor-based monitoring, and automated fire suppression systems were identified as essential components of infrastructure safety protocols (Lee et al., 2023). Finally, research emphasized that scalable business models and public–private partnerships will determine the long-term economic viability of UAM infrastructure, requiring innovative investment frameworks and flexible regulatory mechanisms (Rothfeld et al., 2023). Collectively, these studies indicate that successful ground infrastructure integration is not merely an engineering task but a complex socio-technical endeavor that necessitates collaboration across aviation authorities, city planners, investors, and the public.

4. Discussion and Conclusion

In synthesizing the eighteen selected articles via NVivo coding, three principal themes emerged—airspace management and operational integration, noise footprints and environmental compatibility, and ground infrastructure and urban integration—and within each a constellation of subthemes and open-coded concepts. The findings reveal both convergent emphases across the literature and key tensions and gaps that condition the future of UAM integration.

With respect to airspace management and operational integration, the review revealed strong coherence in the literature around four dominant subthemes: UAM traffic management systems, regulatory and policy harmonization, communication/navigation/surveillance (CNS) technologies, and safety/risk and data governance concerns. The open codes showed that much of the scholarly work treats dynamic airspace allocation, flight corridor optimization, and real-time deconfliction algorithms as foundational to UAM traffic management. Moreover, interoperability between UTM and traditional ATM systems, cross-jurisdiction alignment of certification, and the harmonization of safety case approaches surfaced repeatedly as regulatory priorities. CNS advances—including ADS-B integration, GNSS augmentation, 5G/6G low-latency links, and protocol redundancy—are seen as enablers of precision routing and autonomous flight. Finally, safety and risk management aspects (collision avoidance, redundant architecture, human-machine teaming) along with data governance and cybersecurity (encrypted links, access control, network resilience) were widely recognized as essential. This pattern suggests that existing literature anticipates UAM operations as not just "aircraft in the sky," but rather as nodes within a digital, networked, and highly regulated system.

Turning to noise footprints and environmental compatibility, the review highlighted five central subthemes: acoustic modeling and prediction, human perception and annoyance, noise mitigation technologies, environmental policy/compliance, and community engagement and public acceptance. The open codes show that acoustic modeling across the literature ranges from NPD (noise-power-distance) methods, computational aeroacoustics, propagation models with terrain/atmospheric effects, and scenario-based noise contouring. On human perception, psychoacoustic indicators (sharpness, tonality, impulsiveness), annoyance index calibration, exposure duration, and time-of-day sensitivity dominate. Noise mitigation strategies such as rotor redesign, hybrid-electric propulsion, flight-path optimization, shielding, and altitudinal routing appear recurrently. On the policy side, sound zoning, noise certification regimes, and environmental impact assessments are frequent codes. Lastly, community engagement practices such as public hearings, perception surveys, feedback platforms, and transparent information campaigns surfaced in many studies. In sum, the literature treats noise as both a technical constraint and a social interface, integrating modeling, mitigation, and governance.

In ground infrastructure and urban integration, the findings cluster around several subthemes, with particularly rich conceptual density in vertiport design and siting, integration with existing transportation networks, energy and power systems, land-use and planning constraints, infrastructure safety/maintenance, business models, and digital twin/simulation platforms. The open codes span site-selection criteria, structural layout, passenger flow design, multimodal connectivity, smart grid integration, charging logistics, real estate impact, zoning compliance, structural health monitoring, predictive maintenance, public–private partnerships, cost–benefit and revenue models, and co-simulation or digital twin frameworks. The literature suggests that vertiport siting is critical because it directly influences accessibility and demand capture (Guo et al., 2025). Studies also point to the convergence between ground and air mobility via data-sharing and multimodal scheduling as essential to seamless operations (Yan, Wang, & Qu, 2024). On the energy front, works underscore the need for rapid charging, grid resilience, and renewable energy integration as foundational to scaling

UAM (Di Mascio et al., 2025). From a planning perspective, urban zoning policies and land-use compatibility are recurrent friction points (Chamberlain et al., 2025). Safety and maintenance codes emphasize built-in redundancy, predictive monitoring, and emergency systems. Economic and institutional codes in the review affirm that public–private mechanisms and scalable revenue models remain unresolved but central to viability. Finally, the use of digital twin and simulation frameworks is increasingly advocated for iterating designs and operational strategies before deployment.

These results align well with broad trends in the evolving UAM research landscape. The emphasis on digital traffic management and high-integrity connectivity resonates with prior meta-analyses noting that much UAM literature remains technology-centric, but that system-level integration is rising (Garrow et al., 2021). The coupling of noise modeling and human acceptance reflects recent surveys that argue for multi-modal approaches combining acoustics, perception, and community feedback (Calderón et al., 2025; "Noise Prediction and Mitigation," 2025). The infrastructural findings dovetail with recent urban mobility integration reviews that stress interoperability between aerial and ground systems (Yan et al., 2024). Collectively, the results suggest that while domains of airspace, noise, and infrastructure remain somewhat siloed in individual studies, emergent research is increasingly bridging them—though not without residual tensions and gaps.

One striking insight is the evolving view of noise not just as a passive byproduct but as an active constraint on airspace design and route planning. Several reviewed works propose that flight trajectories and altitudes might be optimized explicitly to balance noise and safety — an approach supported by recent reinforcement learning frameworks (Murthy, Clarke, & Topcu, 2025), which integrate noise and separation objectives into a unified control policy. This is consistent with emerging "noise-aware traffic management" strategies (Gao, Yu, Wei, Topcu, & Clarke, 2024). In this respect, the tight coupling of airspace and noise subthemes in our coding underscores that future UAM systems may need co-optimization rather than sequential layering.

Another emergent tension arises in vertiport siting: while infrastructure scholars emphasize maximizing accessibility and minimizing passenger transit inconvenience, noise scholars often urge spatial buffers and low-exposure footprints. Thus, siting approaches may be pulled toward transport-efficiency on one hand and acoustic compatibility on the other. Guo et al. (2025) point out that existing research lacks methods to coordinate such tradeoffs, and our results similarly reveal few studies that attempt integrated siting considering noise constraints and connectivity simultaneously.

From a regulatory lens, the literature reveals that while many nations are developing eVTOL certification pathways and UTM/ATM interoperability protocols, policy harmonization across jurisdictions remains underdeveloped. Several articles call for model regulatory frameworks, shared safety case libraries, and international benchmarking. This reflects broader concerns in UAM policy studies that jurisdictions may wade forward unilaterally, risking fragmentation.

On the energy front, the literature still lacks mature designs for charging network scaling, although the codes indicate that battery turnaround time and grid load impacts are frontline concerns.

Taken together, the discussion of results suggests that the three domains—airspace operations, noise, infrastructure—are increasingly interdependent. Noise constraints may limit allowable altitudes or route densities, thereby constraining airspace capacity. Infrastructure siting must respect noise-sensitive land uses and comfort criteria, which may push vertiports further from high-demand zones. Energy turnaround constraints in infrastructure may limit throughput, which feeds back to traffic management decisions.

Nonetheless, these interdependencies are still rarely confronted head-on in the literature. Most reviewed works dwell within their subdomain, and only a handful adopt cross-domain approaches. The reinforcement-learning integration of noise and safety is one promising locus (Murthy et al., 2025), but few works yet bring in infrastructure or energy modeling in the same loop. In sum, the current landscape suggests that UAM integration is transitioning from compartmentalized studies toward nascent system-of-systems thinking—but the path remains incomplete.

Despite these insights, this review has limitations. First, the study is constrained by reliance on secondary literature: no primary empirical or simulation work was conducted, meaning our conclusions are mediated entirely via existing authors' lenses, assumptions, and modeling boundaries. Second, the corpus of 18 articles, while selected for quality and relevance, may exclude emerging or unpublished work, particularly in fast-moving domains such as reinforcement learning or commercial testbeds. Third, the qualitative coding approach necessarily abstracts and clusters diverse practices; in doing so, nuance may be lost, especially in domain-specific technicalities (e.g., exact acoustic metrics or grid load algorithms). Fourth, because the themes and subthemes were inductively derived, they reflect the sample's focus and may underrepresent underexplored but important areas, such as socio-economic equity, regulatory lag, or cybersecurity in depth. Finally, the timing of the review (literature to 2025) means the findings are inherently provisional—the UAM domain is evolving rapidly, and new breakthroughs may alter the thematic balance.

Looking ahead, future research should aim to close the gaps between the three domains by pursuing explicitly integrative studies. For example, simulation frameworks that couple air traffic models, acoustic propagation, and vertiport energy constraints would help illuminate tradeoffs in realistic city contexts. Empirical psychoacoustic experiments should be extended across diverse urban soundscapes (e.g., high-rise canyons, suburban low-noise zones) to calibrate acceptability thresholds, especially indoor exposure (Beagult et al., 2023; "Noise: Indoor Space" studies, 2023). The development of international regulatory case studies—comparing how different nations coordinate UTM/ATM interoperability, vertiport certification, and noise zoning—would help build a more generalizable integration framework. On the infrastructure side, pilot deployments should be instrumented to collect real-world data on vertiport operations, charging load fluctuations, passenger transfers, and disturbance metrics, enabling validation of digital twin models. Finally, machine-learning or optimization-driven approaches (e.g., co-design of routes, infrastructure, and energy allocation) merit deeper exploration to operationalize the coupling between the three domains, building on early works like Murthy et al. (2025) or Gao et al. (2024).

For practice, several actionable implications emerge. Urban planners and aviation authorities should adopt a co-development mindset: when siting vertiports, they should simultaneously consult noise studies, airspace corridor constraints, and passenger accessibility—not treat infrastructure build-out as a downstream task. Regulators should consider implementing noise-aware separation minima, dynamic route adaptation, and altitude bands that factor in community impact metrics, potentially via certification mandates that require sensitivity to acoustic constraints. Developers of eVTOL and UAM systems should integrate acoustic design criteria (sharpness, tonal suppression) earlier in the design cycle, since psychoacoustic experiments show that sound quality metrics beyond loudness significantly drive annoyance (Beagult et al., 2023). Infrastructure operators should build in flexibility—modularity in pad layout, adaptable charging schemes, and scalable energy buffer systems—to allow iterative tuning as operations scale. Public engagement must also be an early and continuous part of deployment: pilots of noise perception, community workshops, and transparent reporting will be critical to social license. Finally, city governments should foster public–private partnerships and funding models that internalize both infrastructure and environmental externalities, ensuring that growth in UAM does not create new burdens or inequalities in urban communities.

In conclusion, the qualitative content synthesis reveals that UAM integration is no longer a juxtaposition of air traffic, acoustics, and vertiports—but rather an evolving system-of-systems challenge. While substantial conceptual and simulation work exists in each domain, bridging them remains nascent. To realize UAM's promise, future research and practice must coalesce toward harmonious designs that reconcile operational efficiency, acoustic livability, and infrastructure scalability.

Ethical Considerations

All procedures performed in this study were under the ethical standards.

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Conflict of Interest

The authors report no conflict of interest.

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References

Ariyachandra, M., et al. (2025). Advancing rail infrastructure: integrating digital twins and cognition. Conference manuscript.

Boschert, S., Rosen, R., & Vogel-Heuser, B. (2023). Digital twins for rail-based systems: Integration of cyber-physical data and lifecycle models. Procedia CIRP, 120, 987–995.

Chen, Y., Zhang, L., & Li, W. (2024). Renewable integration and energy-aware optimization in high-speed rail systems. Energy Reports, 10, 210–223.

De Donato, L., et al. (2023). Towards AI-assisted digital twins for smart railways. Journal of Big Data & Intelligent Transportation.

European Union Agency for Railways. (2023). Energy efficiency and sustainability in European rail systems: Annual report 2023.

Kousi, N., Mourtzis, D., & Vlachou, E. (2022). Lifecycle integration through digital twins: The case of predictive railway maintenance. International Journal of Production Research, 60(18), 5458–5472.

Kumar, S., Tan, W., & Lee, J. (2024). Human-centered AI for predictive maintenance: Trust and interpretability in smart transport. Transportation Research Part C, 160, 104375.

Liu, C., Zhao, Q., & Xu, H. (2021). Energy optimization algorithms for sustainable railway operations. Applied Energy, 299, 117287.

Ma, S., Flanigan, K. A., & Bergés, M. (2023). State-of-the-art review and synthesis: A requirement-based roadmap for standardized predictive maintenance automation using digital twin technologies. arXiv preprint arXiv:2311.06993.

Rodríguez-Hernández, M., Crespo-Márquez, A., Sánchez-Herguedas, A., & González-Prida, V. (2025). Digitalization as an enabler in railway maintenance: A review from "The International Union of Railways Asset Management Framework" perspective. Infrastructures, 10(4), 96.

Sivalingam, K., Saini, M., & Ponnusamy, R. (2021). Blockchain-based security for digital twin data management in smart transportation. IEEE Access, 9, 154231–154244.

Sresakoolchai, J., et al. (2023). Railway infrastructure maintenance efficiency improvement via reinforcement learning and digital twin. Applied Sciences, 13(2), 678.

van Dinter, R., et al. (2022). Predictive maintenance using digital twins: A systematic review. Computers in Industry, 138, 103624.

Yin, Y., Sun, J., & Zhang, H. (2020). Maintenance scheduling optimization in smart railways using condition-based analytics. Transportation Research Part E, 137, 101945.

Zhang, J., Wang, D., & Zhao, L. (2020). Energy-minimizing control for electric trains: A review and perspective. IEEE Transactions on Intelligent Transportation Systems, 21(10), 4171–4186.

Zhang, L., Zhou, X., & Sun, Q. (2021). Intelligent condition monitoring for railway vehicles: Machine learning-based approaches. Mechanical Systems and Signal Processing, 150, 107265.

Zhao, T., Wang, C., & Li, P. (2023). Smart grid integration for electrified railway energy management. Renewable and Sustainable Energy Reviews, 157, 112097.