A Multi-Dimensional Perceived Risk Assessment Framework for Urban Air Mobility Based on AHP

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Abstract. Urban air mobility (UAM) will place automated aircraft, low-altitude corridors, vertiports, data platforms and urban communities in a tightly coupled operating environment. To support proactive low-altitude safety governance, this paper develops a perceived-risk assessment framework combining the analytic hierarchy process (AHP) and a risk matrix. A literature-derived indicator system is established from UAM concept-of-operations, public-acceptance, cybersecurity and safety-management studies. Fifteen university experts evaluate six first-level dimensions and 19 second-level indicators. Results show that technical risk (27.89%) and policy risk (27.45%) dominate the overall structure. At the indicator level, policy implementation (20.13%), flight-control system reliability (13.81%), information leakage (8.92%), infrastructure environment (7.45%) and policy formulation (7.32%) are the principal risk drivers. The high weight of policy implementation is explained by the gap between rule formulation and enforceable low-altitude operations, as shown by FAA, EASA and Chinese UAV regulatory practices. The framework contributes a differentiated combination of multi-dimensional perceived risk, AHP quantification and low-altitude scenario application for UAM governance.

Keywords: Urban Air Mobility, Analytic Hierarchy Process, Perceived Risk, Risk Matrix, Low-Altitude Safety Governance

1 Introduction

UAM is moving from a technology vision toward an operational ecosystem that integrates electric vertical-takeoff-and-landing aircraft, unmanned logistics vehicles, low-altitude corridors, vertiports, digital traffic-management services, and local public authorities. Prior studies have emphasized that UAM deployment is not only an aircraft-design problem but also a system-level governance problem involving safety, communications, navigation, surveillance, ground infrastructure, demand, public acceptance, cybersecurity, and regulation [1]–[20]. In dense cities, low-altitude aircraft interact with buildings, electromagnetic environments, road traffic, emergency services, and residents; therefore, a risk framework limited to mechanical reliability is insufficient.

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Existing UAM risk and acceptance studies have mainly followed three routes: concept-of-operations and safety-management analysis, public-acceptance and stated-preference surveys, and technical hazard assessment of aircraft, communication or navigation subsystems [1]-[13], [16]-[20]. These studies provide important foundations, but many of them either describe risk categories qualitatively, focus on a single acceptance factor such as safety or privacy, or remain at the vehicle/subsystem level. The differentiated contribution of this paper is to integrate multi-dimensional perceived risk, AHP-based quantitative prioritisation and a low-altitude scenario application into one decision-support framework. This combination is intended to bridge public-perception concerns and operational governance decisions rather than merely ranking technical hazards.

Public acceptance studies consistently identify safety, security, noise, privacy, affordability, and environmental impacts as central concerns [8]–[13]. In parallel, concept-of-operations and safety studies show that UAM deployment depends on reliable flight control, command-and-control links, corridor management, contingency procedures, and effective regulatory enforcement [2]–[7], [16]. Motivated by these challenges, this study develops a multi-criteria perceived risk assessment framework for UAM using the analytic hierarchy process (AHP), enabling qualitative expert judgments to be transformed into comparable quantitative priorities. A literature-grounded risk taxonomy is established to capture technical, policy, environmental, social, performance, and infringement dimensions. Furthermore, the proposed framework integrates expert evaluation with hierarchical weighting analysis to identify critical risk drivers and provide decision support for phased UAM implementation, operational optimization, and adaptive low-altitude governance.

1.1 Literature-based Risk Taxonomy

Table 1. Literature-derived UAM perceived-risk taxonomy

Dimension	Indicator focus	Typical concerns and sources
Environmental	Natural, living, infrastructure environment	Noise, weather, visual/ecological effects, vertiport siting [8], [9], [12]
Performance	Flight, payload, service performance	Range, reliability, demand fit, affordability, operating scenario [1], [4], [19]
Social	Pollution, public safety, defense, equity	Community integration, unequal access, safety exposure [2], [3], [8], [12]
Technical	Airframe, propulsion, CNS, flight control	Automation, C2/CNS reliability, hazard assessment [3]–[7]
Infringement	Economic loss, injury, information leakage	Liability, privacy, data misuse, cybersecurity [10]–[13], [18], [20]
Policy	Policy formulation and implementation	Regulation, oversight, SRM, corridor rules, enforcement [2], [3], [16]

The risk taxonomy was reconstructed from UAM and urban-drone literature rather than from an unpublished classroom fishbone diagram. The resulting hierarchy retains the six first-level dimensions in the original data but clarifies their research basis. Environmental risk captures noise, visual effects, weather exposure, ecosystem disturbance, and vertiport-environment compatibility. Performance risk concerns service reliability, range, payload, and scenario adaptability. Social risk reflects equity, public safety, national security, and broader community integration. Technical risk covers airframe, propulsion, communication-navigation, and flight-control reliability. Infringement risk represents third-party loss, injury, privacy invasion, and data leakage. Policy risk covers both the adequacy of rules and the effectiveness of enforcement. Table 1 summarizes the revised taxonomy and its supporting literature.

2 Methodology

AHP was selected because perceived risk involves intangible criteria that cannot be measured directly by operational statistics alone. AHP converts expert pairwise comparisons into ratio-scale priorities and provides a consistency test for judgment quality [14], [15]. In this study, 15 university-based experts and researchers familiar with air traffic management, UAV operation, transportation safety, and low-altitude governance were invited to complete pairwise comparisons. Individual judgments were aggregated by the geometric mean, which is commonly used for group AHP when multiple evaluators provide reciprocal matrices.

By the AHP method, raters compare each assessment index according to the scale. Furthermore, according to the scoring results, this research constructs an n*n judgment matrix, denoted as A, which is determined as:

$$A=\begin{bmatrix} 1 & a_{12} & \cdots & a_{1n} \\ \frac{1}{a_{12}} & 1 & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \frac{1}{a_{1n}} & \frac{1}{a_{2n}} & \cdots & 1 \end{bmatrix} \quad (1)$$

where a_{ij} represents the relative importance of element i relative to element j.

In the case that pairwise comparison involves excessive comparison elements, the rater's subjective cognition tends to be disturbed, thus affecting the accuracy of the assessment results. As revealed by past experience, the number of comparative elements in the range of 5 to 9 presents the optimal assessment effect, with 9 being regarded as the upper limit. Within this range, the 1-9 scale method is capable of reflecting the differences between elements more effectively. During practical operation, it is usually necessary to make n(n-1)/2 judgments on pairwise comparisons to obtain sufficient information. Concurrently, the scientific ranking results can be further achieved by repeated comparison of elements at different levels.

In the case of involving multiple raters, the usual practice is to perform an AHP analysis on the average scores of all experts, instead of implementing an independent AHP analysis on the scores of each rater.

Related to this, the Excel formula is determined as:

$$= POWER(number, 1/n)$$

where *number* denotes the value whose root is to be calculated, while n denotes the order of the root.

The specific calculation steps and formulas of the sum-product method are summarized as follows:

Step 1: Calculation of the Weight Vector

Normalization of each column is performed:

$$a_{ij}^{'}=\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \quad (2)$$

Subsequently, the average value of each line is calculated and used as the weight:

$$w_i=\frac{1}{n}\sum_{j=1}^{n} a_{ij}^{'} \quad (3)$$

Step 2: Consistency Test

The consistency index is calculated:

$$\lambda_{max}=\frac{\sum(Aw)_i}{nw_i} \quad (4)$$

where A stands for the judgment matrix, and w represents the weight, with n denoting matrix order.

$$CI=\frac{\lambda_{\max}-n}{n-1} \quad (5)$$

where λ_{max} represents the maximum eigenvalue of the judgment matrix.

Step 3: Calculation of the Consistency Ratio (CR)

The random consistency index RI is calculated, as presented in Table 2.

Table 2. Relationship between *RI* values and matrix order

Orders	1	2	3	4	5	6	7	8	9
Values	0	0	0.52	0.89	1.12	1.26	1.36	1.41	1.45

In this regard, the CR is defined as:

$$CR=\frac{CI}{RI} \quad (6)$$

When $CR < 0.1$, it can be determined that the consistency is acceptable.

Lastly, the comprehensive weight is equivalent to the product of secondary weights and the primary weight to which they belong.

A matrix is accepted when CR<0.10. After calculating local priorities for each group, global weights are obtained by multiplying a second-level local weight by its corresponding first-level weight. Finally, a risk matrix is used to map weighted indicators to practical risk scenarios. Because risk matrices may produce coarse rankings, they are used here only as a scenario-screening layer rather than as a substitute for AHP priorities [16], [17].

The panel-based design is consistent with the early stage of UAM deployment. When empirical accident rates and large-scale operational exposure data are limited, structured expert elicitation can identify which dimensions deserve immediate governance attention. The use of a consistency ratio does not eliminate subjectivity, but it reduces arbitrary judgments and improves the traceability of the ranking process. The resulting first-level weights and dominant second-level factors are summarized in Table 3.

Table 3. First-level weights and dominant second-level factors

Dimension	W	CR	Dominant second-level factors (global W)
Technical	27.89%	0.054	Flight control 13.81%; CNS 6.45%; propulsion 5.48%
Policy	27.45%	0.000	Implementation 20.13%; formulation 7.32%
Infringement	18.37%	0.085	Information leakage 8.92%; physical injury 6.05%
Environmental	12.16%	0.053	Infrastructure 7.45%; living environment 3.01%
Performance	8.83%	0.090	Service performance 5.05%; payload 2.45%
Social	5.30%	0.090	Social equity 2.10%; defense security 1.56%

3 Results and Discussion

The first-level ranking indicates that UAM perceived risk is dominated by technical and policy dimensions. Technical risk accounts for 27.89% of the total weight, confirming that public confidence in autonomous flight, flight-control algorithms, C2 links, navigation performance, and propulsion reliability is fundamental to low-altitude operation. Policy risk is nearly equal at 27.45%, showing that perceived safety depends not only on engineering maturity but also on credible implementation of laws, standards, airspace procedures, and emergency-response responsibilities. Together, these two dimensions contribute more than half of the overall perceived risk, which suggests that UAM safety governance should be designed as a combined technology-regulation problem rather than as a purely operational problem.

Policy implementation ranks highest at the indicator level because domestic and foreign UAM practices all show that the bottleneck has shifted from whether rules exist to whether they can be implemented in dense, low-altitude operations. In the United States, the FAA Innovate28 implementation plan links AAM deployment with aircraft certification, operational approval, airspace integration, infrastructure, community engagement and interagency coordination [4]. In Europe, EASA has developed regulatory material for innovative air mobility and stresses both safe ATM integration and citizen acceptance [5]. In China, UAV flight management has moved toward classified management, collaborative supervision, operator requirements, real-name registration and mandatory standards, while low-altitude economic growth increases the pressure for enforceable corridor approval, identification, data reporting and local coordination [21], [22]. These practices indicate that public trust is strongly affected by whether responsibilities, enforcement boundaries and emergency coordination are operationally credible, not simply by the publication of policy documents.

Infringement risk ranks third with 18.37%. This result reflects the salience of third-party rights in urban low-altitude operations. Information leakage has a global weight of 8.92%, which is higher than economic loss and most environmental or social indicators. The result is consistent with privacy and cybersecurity research showing that drones and UAM platforms generate concerns about sensing, tracking, data access, and unauthorized use [10]–[13], [18], [20]. Environmental risk, with a first-level weight of 12.16%, is driven mainly by infrastructure-environment compatibility. This indicates that vertiport location, charging facilities, emergency landing areas, and integration with dense urban land use may shape perceived risk as strongly as direct environmental externalities. The global ranking of all second-level risk indicators is presented in Table 4.

Table 4. Global ranking of second-level risk indicators

Rank	Indicator	Global W
1	Policy implementation	20.13%
2	Flight control system	13.81%
3	Information leakage	8.92%
4	Infrastructure environment	7.45%
5	Policy formulation	7.32%
6	Communication and navigation system	6.45%
7	Physical injury	6.05%
8	Propulsion system	5.48%
9	Service performance	5.05%
10	Economic loss	3.40%
11	Living environment	3.01%
12	Payload performance	2.45%
13	Airframe structure	2.15%
14	Social equity	2.10%
15	Natural environment	1.70%
16	National defense security	1.56%
17	Flight performance	1.34%
18	Public safety	1.07%
19	Environmental pollution	0.57%

The second-level ranking further clarifies the governance priorities. Policy implementation is the highest single factor, with a global weight of 20.13%. This means that the perceived credibility of supervision, enforcement, emergency coordination, and responsibility allocation is more influential than the mere existence of regulations. Flight control system reliability follows at 13.81%, highlighting the importance of redundant control architectures, algorithm validation, and fail-safe behavior under abnormal conditions. Information leakage, infrastructure environment, policy formulation, and CNS reliability form the next tier of indicators. Although several social and environmental indicators have relatively low weights, they should not be ignored. Low current priority may reflect limited public exposure during early-stage deployment; as operations scale, cumulative noise, public-safety incidents, and equity conflicts may become more prominent.

Sensitivity analysis was conducted by perturbing the judgment-matrix scale and recalculating priorities. The resulting change in major weights remained within 5%, indicating acceptable robustness for screening and prioritization. However, the model should be updated dynamically as operational data, accident reports, community complaints, and regulatory practices accumulate. For example, the high ranking of policy implementation may decrease if mature airspace-management rules become widely accepted, while environmental and social indicators may increase as UAM services enter residential communities.

4 Empirical Application

To illustrate how the weighted indicators can support low-altitude corridor management, a UAV logistics corridor in a dense urban area is considered. The corridor is assumed to connect a logistics hub, several delivery nodes, and emergency landing locations while operating near residential blocks and elevated infrastructure. The case does not aim to predict a single accident probability; instead, it demonstrates how AHP priorities can be combined with scenario severity and exposure to identify where supervision and technical safeguards should be concentrated.

As shown in Table 5, extreme weather with sensor degradation receives the highest scenario priority. This is because adverse weather simultaneously affects perception, navigation integrity, vehicle controllability, and emergency landing feasibility. Collision-avoidance delay in a high-density corridor also receives a high priority, reflecting the interaction between flight-control reliability and traffic-density management. Electromagnetic interference is another critical scenario because it can reduce the availability of command-and-control communication and navigation updates, especially in corridors close to high-rise buildings and complex radio environments.

Table 5. Illustrative high-priority risk scenarios for a UAV logistics corridor

Scenario	Weight	Governance response
Extreme weather with sensor degradation	0.32	Weather minima; sensor redundancy; emergency landing zones
High-density corridor with avoidance delay	0.27	Algorithm verification; capacity limits; dynamic spacing
Electromagnetic interference causing C2 interruption	0.21	Protected links; interference monitoring; contingency routing
Vertiport conflict with residential environment	0.12	Siting buffer; noise control; public consultation
Unauthorized access to trajectory/user data	0.08	Encryption; access control; audit trails; privacy-by-design

The scenario analysis demonstrates the operational meaning of the AHP weights. A regulator can use the results to define corridor access conditions, weather minima, capacity limits, communication-performance requirements, and emergency-response drills. Operators can use the same results to allocate verification resources to high-weight subsystems, including flight-control algorithms, sensor fusion, link protection, and privacy-by-design data management. Thus, the model acts as a bridge between perceived-risk assessment and actionable governance measures.

5 Recommendations

Technical assurance should be placed at the center of UAM risk governance. The flight control system requires redundant sensing, verified control-law envelopes, robust anomaly detection, and scenario-based testing in adverse weather, high-density traffic, and degraded-CNS environments. Communication and navigation systems should be designed with link diversity, interference monitoring, timing and positioning integrity checks, and clear contingency modes. Propulsion and energy systems should be monitored through predictive maintenance and fault-tolerant power-management strategies. These measures are necessary because a failure in a single technical subsystem can cascade into collision risk, service interruption, public distrust, and regulatory restrictions.

Policy governance should move beyond rule drafting toward implementation capacity. A cross-departmental platform should connect aviation regulators, urban-planning authorities, emergency-management agencies, public-security departments, and operators. This platform should clarify approval procedures, corridor access rules, data-sharing standards, emergency responsibilities, and enforcement boundaries. Pilot programs should be used as regulatory learning environments: operational data from freight, medical-response, inspection, and passenger-trial services can be used to iteratively update performance requirements, operating limitations, and community-protection measures.

Data security and rights protection require institutional as well as technical safeguards. UAM operations collect trajectory, image, sensor, user, and maintenance data, and the assessment results show that information leakage is a core perceived-risk indicator. Operators should implement encryption, minimum-access authorization, data-retention limits, privacy-impact assessment, and accountable audit trails. In parallel, liability and compensation mechanisms should define the process for handling physical injury, property loss, privacy intrusion, and service interruption. A transparent compensation mechanism can reduce public uncertainty and improve trust even before large-scale commercial operation begins.

Infrastructure planning should be adaptive and community-sensitive. Vertiports, charging sites, emergency landing points, and logistics depots should first be deployed in transportation hubs, industrial parks, hospitals, and other locations where operational benefits are clear and conflicts with residential life can be controlled. Environmental compatibility should be incorporated into design through low-noise propulsion, green-energy supply, visual-impact management, and safe separation from sensitive land uses. Social risks should be addressed through public hearings, simulation demonstrations, disclosure of safety cases, and cooperation with national-defense and public-security authorities. These measures transform perceived-risk governance from passive response to proactive prevention.

6 Limitations and Future Work

Several limitations should be noted. The AHP results are based on expert perception rather than directly observed accident frequencies. This is appropriate for early-stage UAM systems, where large-scale operational statistics are unavailable, but it also means that the weights should be interpreted as priority signals rather than as absolute probabilities. The expert panel is university-based and technically informed; future studies should include regulators, emergency responders, operators, community representatives, and potential passengers to test whether different stakeholder groups assign different weights to safety, privacy, noise, and affordability. The aggregation of individual judgments by the geometric mean also assumes that the panel can be treated as a single decision-making body, which may mask disagreement among subgroups.

Future work should integrate the present perceived-risk framework with simulation and operational data. For instance, flight-control and CNS indicators can be connected with failure-mode analysis, Monte Carlo trajectory simulation, and separation-assurance performance. Environmental and social indicators can be linked to noise exposure, visual impact, land-use conflicts, and public-comment records. Policy implementation can be evaluated through compliance audits, incident-response drills, and interagency coordination performance. Such integration would allow the AHP model to evolve from a static expert-priority tool into a dynamic decision-support system for low-altitude safety governance.

7 Conclusion

This paper develops a literature-supported UAM perceived-risk assessment framework that combines a multi-dimensional perceived-risk taxonomy, AHP-based quantification and a low-altitude scenario application. Compared with existing UAM risk assessment studies that primarily emphasise operational concepts, public acceptance or subsystem hazards, the proposed framework quantifies how technical, policy, infringement, environmental, performance and social dimensions jointly shape perceived risk and translates the results into corridor-management priorities. The AHP results show that technical and policy risks dominate the overall structure, while policy implementation, flight-control reliability, information leakage, infrastructure compatibility and policy formulation are the most important second-level factors. The high priority of policy implementation is consistent with FAA, EASA and Chinese regulatory practices, which all demonstrate that credible enforcement, interagency coordination, operational approval, data governance and emergency responsibilities are decisive for public trust in low-altitude operations. The findings suggest that

UAM safety governance should combine technical assurance, enforceable regulation, data protection, adaptive infrastructure and transparent community engagement. Future research should expand the expert panel, integrate real operational data and compare AHP results with probabilistic safety assessment and simulation-based risk metrics.

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