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R. Bridgelall

ADVANCED AIR MOBILITY TO ENHANCE RURAL FREIGHT LOGISTICS

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16. Abstract

Freight transportation places substantial and growing stress on roads and bridges, particularly in rural and regional areas where heavy trucks travel long distances to serve dispersed communities. At the same time, progress in Advanced Air Mobility (AAM) to use new aircraft technologies for cargo transport creates an opportunity to move selected freight off the road and into the air. This project examined whether and how AAM can be used to improve freight logistics while preserving ground transportation infrastructure. This study integrates evidence on aircraft technology, freight demand, infrastructure availability, and regulatory readiness to identify practical, near-term opportunities for shifting freight from trucks to aircraft. The findings show that AAM is most effective when applied selectively. That is, focusing on high-value, time-sensitive, or safety-critical goods such as pharmaceuticals and hazardous materials, where demand is concentrated and reliability is essential. Rather than requiring new facilities, early deployment can rely largely on existing airports and hospital-related aviation assets. This enables faster and lower-cost implementation. While current aircraft performance is constrained by energy storage limitations, these constraints still allow meaningful substitution on short- and medium-range routes with repeatable demand. Overall, the project demonstrates that targeted use of AAM can reduce truck traffic on vulnerable roadways, enhance freight reliability, and extend the service life of transportation infrastructure. Targeted deployments of AAM can provide a practical foundation for future expansion as technologies and regulations continue to mature.

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Advanced Air Mobility to Enhance Rural Freight Logistics

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U.S. Department of Transportation (US DOT) Disclaimer

ABSTRACT

Freight transportation places substantial and growing stress on roads and bridges, particularly in rural and regional areas where heavy trucks travel long distances to serve dispersed communities. At the same time, progress in advanced air mobility (AAM) to use new aircraft technologies for cargo transport creates an opportunity to move selected freight off the road and into the air. This project examines whether and how AAM can be used to improve freight logistics while preserving ground transportation infrastructure. This study integrates evidence on aircraft technology, freight demand, infrastructure availability, and regulatory readiness to identify practical, near-term opportunities for shifting freight from trucks to aircraft. The findings show that AAM is most effective when applied selectively. That is, focusing on high-value, time-sensitive, or safety-critical goods such as pharmaceuticals and hazardous materials, where demand is concentrated and reliability is essential. Rather than requiring new facilities, early deployment can rely largely on existing airports and hospital-related aviation assets. This enables faster and lower-cost implementation. While current aircraft performance is constrained by energy storage limitations, these constraints still allow meaningful substitution on short- and medium-range routes with repeatable demand. Overall, the project demonstrates that targeted use of AAM can reduce truck traffic on vulnerable roadways, enhance freight reliability, and extend the service life of transportation infrastructure. Targeted deployments of AAM can provide a practical foundation for future expansion as technologies and regulations continue to mature.

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LIST OF KEY TERMS

Technology and Aircraft	Description
Advanced Air Mobility (AAM)	New ways of moving cargo or people using advanced aircraft, often electric or hybrid, at low altitudes.
Electric Vertical Takeoff and Landing (eVTOL)	An aircraft that uses electric power and can take off and land vertically without a runway.
Powered-Lift Aircraft	A regulatory aircraft category that includes eVTOLs and similar vehicles that rely on vertical lift.
Cargo Drone	An uncrewed aircraft designed specifically to transport goods instead of passengers.
Electrified Aircraft (EA)	Aircraft that use electric power for some or all propulsion functions.
Hybrid-Electric Aircraft	Aircraft that combine batteries with fuel-based engines or generators.
Hydrogen Propulsion	Aircraft propulsion that uses hydrogen as an energy carrier to extend range and reduce emissions.
Energy Density	The amount of energy stored per unit of weight; higher values allow longer range or heavier payloads.
Payload	The weight of cargo an aircraft can carry, excluding the aircraft itself and its energy source.
Range	The maximum distance an aircraft can travel on one charge or fuel load.
Propulsion Efficiency Index (PEX)	A metric used in the study to compare how effectively aircraft convert stored energy into useful range and payload.

Logistics and Markets	Description
Freight Logistics	The planning and movement of goods through transportation networks.
Middle-Mile Transport	The portion of a freight trip between major hubs such as airports, warehouses, or regional centers.
Last-Mile Transport	The final step of delivery from a hub to the end destination.
High-Value Freight	Goods with high economic value relative to their weight, such as electronics or pharmaceuticals.
Hazardous Materials (Hazmat)	Goods that pose safety risks during transport, such as chemicals or flammable substances.
Pharmaceuticals	Medicines and medical supplies that often require fast and reliable delivery.
Freight Corridor	A commonly used route that carries large volumes of goods between regions.
Truckload Equivalent	A measure that expresses freight volume in terms of full truck shipments.

Infrastructure and Networks	Description
Infrastructure Preservation	Reducing wear and damage to roads and bridges by lowering heavy truck traffic.
Node	A key location in a logistics network, such as an airport, hospital, or freight hub.
Underutilized Airport	An airport with low traffic that has capacity to support new uses such as cargo drones.
Hospital Airport (HA)	An airport designated as the closest or most suitable aviation access point for a hospital.
Multimodal Freight Hub (MFH)	An airport or facility where freight transfers between trucks and aircraft.
Truck Transfer Hub (TTH)	A location near major highways where truck freight shifts to air transport.
Vertiport	A ground facility designed for vertical-takeoff aircraft operations.
Metropolitan Statistical Area (MSA)	A geographic region centered on a large city, used to analyze economic and freight activity.
Pavement Wear	Deterioration of road surfaces caused by repeated heavy vehicle loads.

Data, Analysis, Methods	Description
Geographic Information System (GIS)	Software tools used to analyze and visualize spatial data such as routes and locations.
Freight Analysis Framework (FAF)	A national dataset that describes freight flows by commodity, mode, and region.
Hybrid Data Mining (HDM)	An approach that combines machine learning with spatial analysis.
Machine Learning (ML)	Computer algorithms that identify patterns and make predictions from data.
Unsupervised Machine Learning	Algorithms that group or cluster data without predefined labels.
Person-Years Saved (PYS)	A metric estimating total time savings across populations due to faster access or delivery.

Policy, Regulation, Governance	Description
Regulatory Readiness	The extent to which rules and oversight systems allow new aircraft operations.
Federal Aviation Administration (FAA)	The U.S. agency responsible for regulating civil aviation.
European Union Aviation Safety Agency (EASA)	The European authority responsible for aviation safety regulation.
International Civil Aviation Organization (ICAO)	A United Nations agency that sets global aviation standards.
Powered-Lift Rule	FAA regulations governing certification and operation of powered-lift aircraft such as eVTOLs.
Airspace Integration	The process of safely incorporating new aircraft into existing air traffic systems.
Detect-and-Avoid (DAA)	Technologies that help aircraft detect and avoid other airspace users.
Repeatable Operations	Flights that follow consistent routes and procedures, enabling reliable oversight and scaling.
Advanced Air Mobility National Strategy	A U.S. policy framework guiding coordinated AAM development and deployment.

EXECUTIVE SUMMARY

This report examines how advanced air mobility (AAM) can be deployed to enhance rural and regional freight logistics with the primary objective of preserving ground transportation infrastructure. The central premise is that selectively shifting appropriate freight from roads to air can reduce heavy-vehicle exposure on pavements and bridges, mitigate congestion at critical gateways, and lower the risk associated with transporting high-consequence goods. This approach will also deliver secondary benefits in reliability, safety, and access.

The analysis integrates findings from a comprehensive methodology that combines technology assessment, market analysis, infrastructure evaluation, and regulatory readiness. Across these dimensions, the results converge on a consistent systems-level conclusion. AAM is most effective as a freight solution when deployment aligns with four binding conditions: realistic energy density constraints, concentrated and repeatable freight demand, reuse of existing infrastructure nodes, and regulatory environments that support repeatable and scalable operations.

From a technology perspective, current and near-term aircraft performance is constrained primarily by energy density. Improvements in propulsion efficiency and airframe design enhance utilization of onboard energy but do not remove fundamental payload–range limits. Consequently, near-term AAM freight missions are best suited to short- and medium-range routes with predictable demand and high trip frequency. Hybrid and hydrogen-based pathways offer opportunities to expand this envelope over time but remain medium- to long-term options. Market analyses demonstrate that freight demand suitable for AAM is highly concentrated rather than diffuse. High-value, time-sensitive, and safety-critical commodities (particularly hazardous materials and pharmaceuticals) cluster in a limited number of regions and corridors. These markets exhibit strong willingness to pay for reliability and risk reduction. This makes them credible early candidates for aerial substitution. Both middle-mile and last-mile analyses show that a small set of nodes accounts for a disproportionate share of potential benefits.

Infrastructure evaluations indicate that physical infrastructure is not the primary barrier to early deployment. Existing assets, including underutilized airports, hospital-adjacent aviation facilities, and regional airfields, can support AAM operations with limited modification. A node-centric strategy that repurposes these assets enables rapid deployment, improves utilization, and supports scalability across rural, regional, and urban contexts without extensive new construction.

Regulatory analysis highlights that institutional readiness is the dominant gating factor. Adoption depends on the ability to certify aircraft, approve operations, and integrate AAM into existing airspace systems in a repeatable manner. Recent progress in powered-lift certification frameworks and national AAM strategies reduces uncertainty. However, early deployment remains most feasible in jurisdictions with strong governance capacity and established aviation oversight. Taken together, the findings show that AAM can meaningfully preserve ground transportation infrastructure when applied selectively. The greatest impact arises from replacing repeated truck movements on fixed routes, particularly where pavement wear, bridge loading, congestion, or safety risks are highest. This research, therefore, positions AAM not as a universal replacement for trucking, but as a targeted, high-impact complement to surface freight systems. By aligning technology capabilities, market demand, infrastructure reuse, and regulatory readiness, decision-makers can unlock near-term benefits while laying the foundation for broader AAM integration as technologies and policies continue to mature.

1. INTRODUCTION AND BACKGROUND

1.1 Project Motivation

The emerging field of advanced air mobility (AAM) presents myriad opportunities for disrupting traditional modes of transport, including passenger travel to cargo logistics. Moving cargo by air instead of by truck at significant volumes can preserve road condition and reduce highway crash exposure. However, its path to full-scale adoption is fraught with regulatory, market, and logistical challenges.

1.2 Research, Objectives, and Tasks

This report presents a refined understanding of AAM's complexities and its potential for transformative impact, particularly to reduce the impacts on surface transportation degradation. The research employs data-driven methodologies, machine learning algorithms, and geographic information system (GIS) techniques to explore the AAM landscape. The objectives of these studies were to reveal the crucial role of regulatory frameworks and economic progress in the adoption of AAM, the importance of accurate market forecasting, and the value of identifying key commodities and geographical targets for cargo drones. Additionally, this study aims to highlight the potential of AAM in safely transporting goods to rural and underserved communities without heavy trucks traveling on highways. However, the successful integration of AAM into global transportation systems requires a multi-disciplinary and multi-stakeholder approach. Tasks to achieve the research objectives were:

- Systematic literature review of eVTOL development challenges and solutions
- Systematic patent review of eVTOL innovation trends
- eVTOL performance metrics and forecasting
- AAM freight market opportunities and commodity types
- Regulatory landscape assessment

1.3 Report Overview

This report evaluates the potential of AAM to enhance rural and regional freight logistics with the primary objective of preserving ground transportation infrastructure. It integrates evidence from technology assessment, market analysis, infrastructure evaluation, and regulatory readiness to identify where and how freight can be shifted from roads to air. Rather than treating AAM as a universal replacement for trucking, the report adopts a systems perspective that emphasizes energy constraints, demand concentration, infrastructure reuse, and regulatory feasibility. The analysis synthesizes results from multiple empirical studies (published by the principle investigator during the period of performance) to provide a coherent framework for targeted, high-impact AAM deployment and to inform future research and policy decisions.

2. METHODOLOGY

The four objectives of this research were as follows:

1. **Technology Assessment**: Conduct a thorough literature review and patent analysis to gauge current and future AAM technological capabilities, identify innovation trends, and develop AI models to predict eVTOL performance metrics.
2. **Market Analysis**: Utilize GIS to assess potential AAM networks by identifying gaps in existing infrastructure and highlighting economic opportunities, especially in remote and underserved areas, to support efficient cargo transport.
3. **Infrastructure Evaluation**: Investigate how existing transportation facilities can support AAM operations, identifying technical requirements and potential for multimodal integration and preserving highways.
4. **Regulatory Review**: Analyze AAM-related policies and regulations to identify adoption barriers and opportunities for regulatory alignment across different levels of government and sectors.

The subsections that follow describe the methodologies employed to achieve the above objectives and their outcomes.

2.1 Technology Assessment

The technology assessment defines the feasible performance envelope for AAM cargo operations intended to divert freight from highways and preserve surface transportation infrastructure. This subsection synthesizes evidence from thematic literature reviews, patent analyses, scientometric studies, and aircraft performance modeling to evaluate the maturity and limitations of AAM-enabling technologies. The assessment prioritizes freight-relevant performance metrics over passenger-centric considerations. These metrics include range, payload, efficiency, reliability, and scalability. The methodology integrates six peer-reviewed journal articles authored by the principle investigator during the period of performance. Each paper addressed a distinct but complementary dimension of AAM technology readiness. Together, these studies provide an empirically grounded basis for bounding expectations of near-, mid-, and long-term freight diversion potential.

The technology assessment employs a four-part analytical framework:

1) Thematic and bibliometric analysis to identify dominant research streams and persistent constraints in aircraft electrification
2) Patent-based innovation analysis to evaluate technological maturity, convergence, and unresolved engineering barriers
3) Scientometric trajectory analysis to quantify research momentum and knowledge concentration in energy storage technologies, which is the key technology for advancing performance
4) Performance modeling to translate technological attributes into freight-relevant operational limits

This framework avoids speculative forecasting and instead relies on observed innovation patterns and validated performance relationships.

2.1.1 Performance Metrics and eVTOL Efficiency Modeling

This subsection establishes energy density as the foundational determinant of aircraft performance in AAM. Energy density is positioned as the unifying constraint that governs subsequent discussions on electrification efficiency, battery technologies, and hydrogen propulsion. The analysis synthesized evidence from (Bridgelall, Askarzadeh and Tolliver 2023). It developed an aeronautically grounded framework to objectively compare eVTOL aircraft performance using publicly available specifications. The study demonstrated that, under fixed weight constraints, flight endurance and range scaled directly with the energy density of the onboard energy storage system regardless of aircraft architecture. While propulsion efficiency, aerodynamic design, and payload allocation influenced performance margins, the analysis showed that energy density ultimately bounded the feasible design space for range–payload combinations. This framing is critical for freight-oriented AAM because cargo missions prioritized endurance and payload mass over passenger comfort. This prioritization amplifies the sensitivity of system performance to energy storage characteristics (Bills, et al. 2020).

The methodological workflow, summarized in Figure 1**,** traces a transparent sequence from the literature synthesis and physics-based derivation to dataset assembly and statistical analysis. This figure anchored the technology assessment by demonstrating how first-principles flight physics translated into a reduced set of independent performance parameters. By grounding the analysis in cruise flight physics, the study isolated the portion of flight that dominated total energy consumption in mobility missions. This approach avoided confounding effects associated with short-duration hover and transition phases.

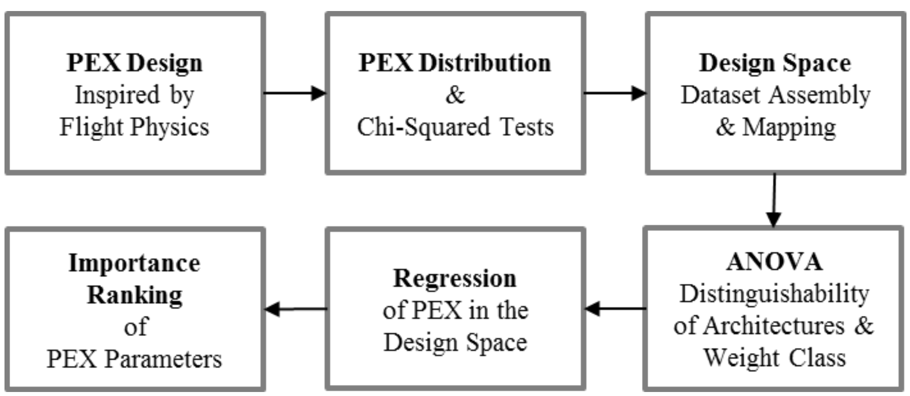


Figure 1: Workflow of the methods

The derivation of the propulsion efficiency factor showed that cruise range depended on four interacting elements: energy density, lift-to-drag characteristics, payload ratio, and propulsion efficiency. Figure 2 illustrates these interdependencies and explicitly identifies energy density as an exogenous constraint imposed by battery chemistry rather than airframe design. This figure is central because it clarifies that improvements in propulsion or aerodynamics could only partially compensate for low energy density. This conclusion is consistent with prior analyses of electric aircraft feasibility (Sahoo, Zhao and Kyprianidis 2020) (Warren, et al. 2019).

Building on this derivation, the study introduced the propulsion efficiency index (PEX) as a unitless metric that integrates three observable design parameters: altitude-normalized range, payload ratio, and airframe aspect ratio. By design, the PEX excluded energy density as an explicit variable because all manufacturers faced similar battery technology constraints at a given point in time. Instead, the index revealed how effectively each design utilized the available energy density. This distinction was essential for technology assessment because it separated energy availability from energy utilization. This theme appears later in discussions on electrification efficiency and hybrid propulsion strategies.

The empirical dataset assembled for the analysis comprised 45 eVTOL designs (winged types) drawn from public manufacturer disclosures. The data listed the aircraft specifications used to compute the PEX (Bridgelall, Askarzadeh and Tolliver 2023). The dataset captured a wide range of architectures, payload capacities, and ranges, enabling a cross-sectional view of the prevailing design space prior to commercial deployment.

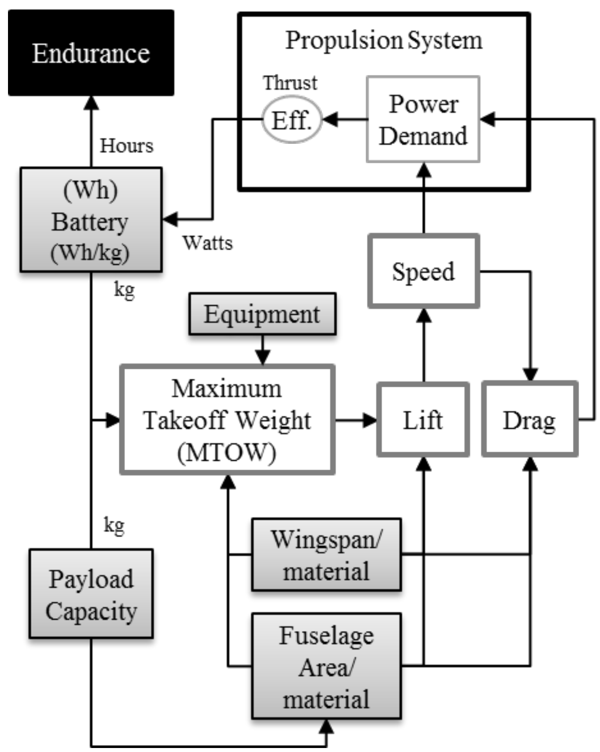


Figure 2: Interaction of aircraft design parameters

The distributional analysis revealed that unnormalized range exhibited substantially greater variance than payload ratio or aspect ratio. Figure 3 shows that range followed a lognormal distribution, whereas payload ratio and aspect ratio approximated normal distributions. Table 1 quantified these results and demonstrated that the spread in PEX values largely reflected the spread in range. This finding reinforced the central role of energy storage capacity in differentiating aircraft performance, even among designs with similar aerodynamic and structural characteristics.

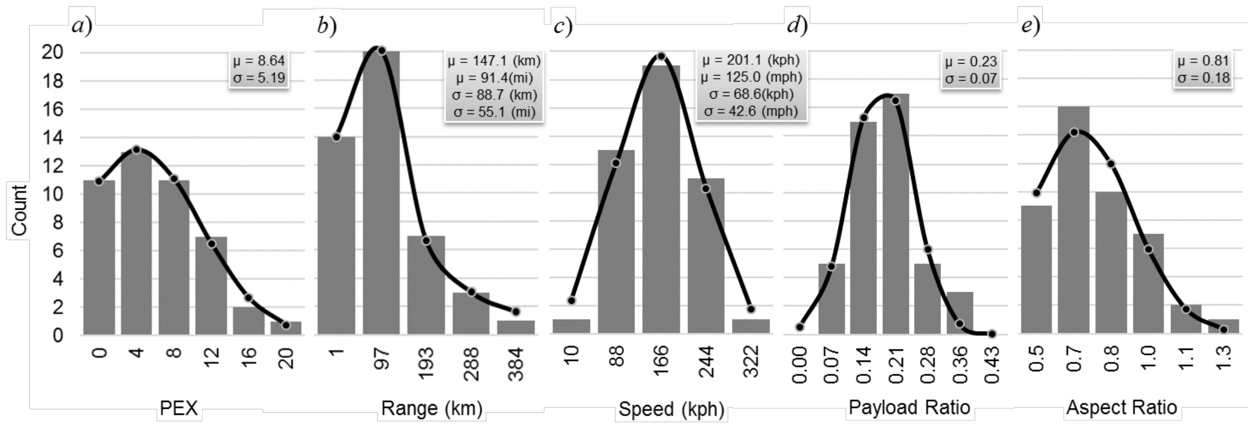


Figure 3: Distributions of a) PEX, b) Range, c) Speed, d) Payload Ratio (PR), and e) Aspect Ratio (AR)

Table 1: Parameters of the Performance Variable Distributions and Chi-squared Tests

Parameter	PEX	Range (km)	Speed (kph)	PR	AR
Mean	8.64	147.06	201.39	0.23	0.81
STD	5.19	88.66	68.66	0.07	0.18
Min	0.96	19.31	70.00	0.10	0.53
Max	23.25	462.99	350.00	0.37	1.30
CV	0.60	0.60	0.34	0.30	0.22
Skewness	0.74	1.33	0.07	0.13	0.56
Kurtosis	0.34	2.37	-0.69	-0.64	0.04
DOF	5	4	4	6	5
$\chi 2$ Statistic	0.28	0.25	1.25	7.20	2.50
$\chi 2$ p-value	0.99	0.99	0.87	0.31	0.77
H0	Normal	Lognormal	Normal	Normal	Normal
Reject H0	No	No	No	No	No

Architecture-level comparisons further highlighted this conclusion. Figure 4, Figure 5, Figure 6, and Table 2 show no statistically significant association between PEX values and mainstream eVTOL architecture types. These included fixed rotor (FR), tiltrotor (TR), transitioned-thrust (TT), folded wing (FW), and tilt-wing (TW) configurations.

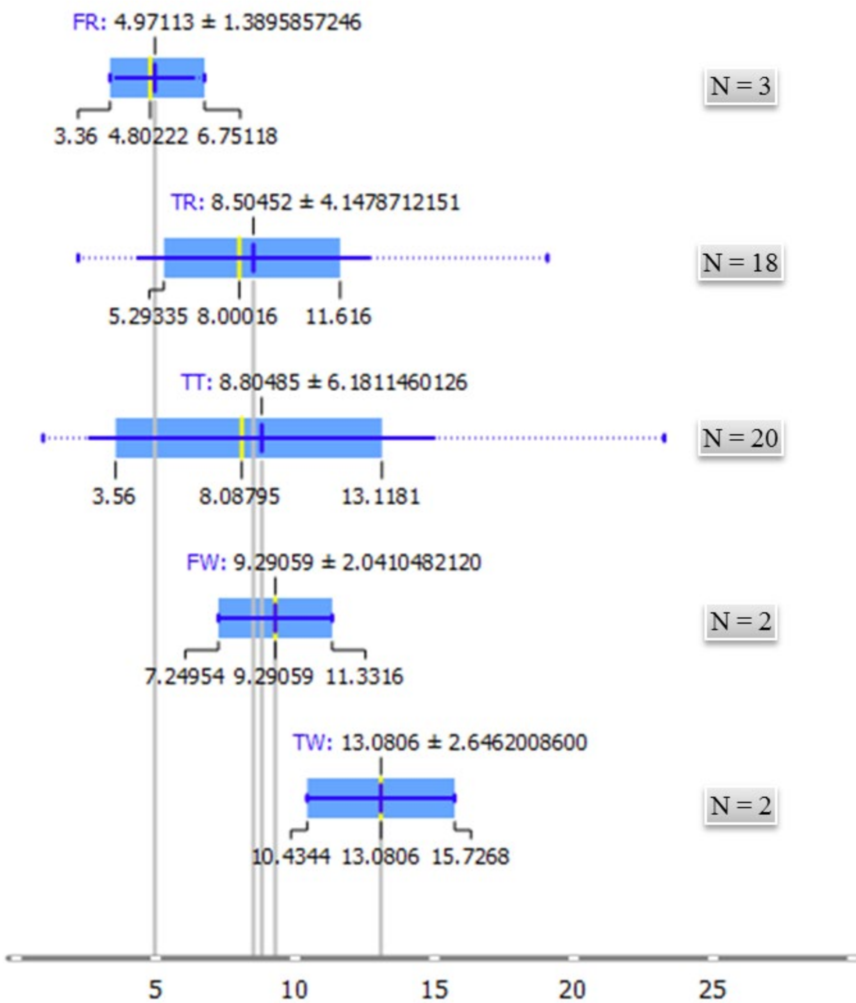


Figure 4: PEX distributions and ANOVA for the five drone architecture types

Similarly, weight-class analysis in Figure 7, Figure 8, and Figure 9 found no meaningful association between maximum takeoff weight and PEX. These results indicated that neither architecture choice nor aircraft size overcame the fundamental limitations imposed by available energy density.

Table 2: ANOVA Tests Across All Architecture Types

Parameter	ANOVA	p-value
PEX	0.740	0.570
Range	0.592	0.670
PR	0.706	0.593
AR	0.835	0.511

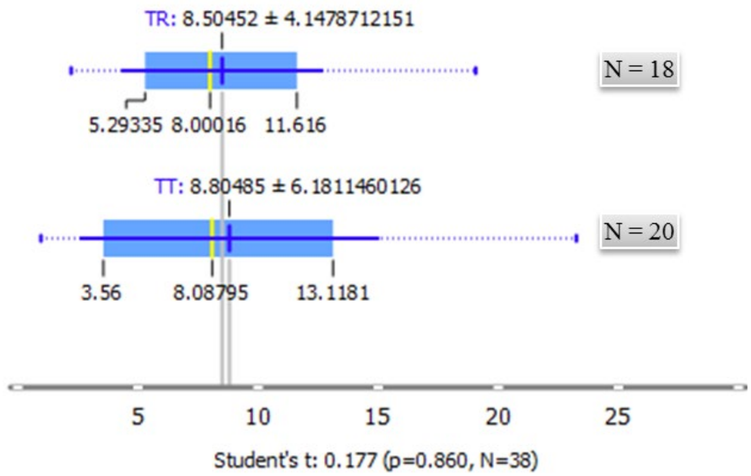


Figure 5: PEX distributions and t-test for the TR and TT drone architecture types

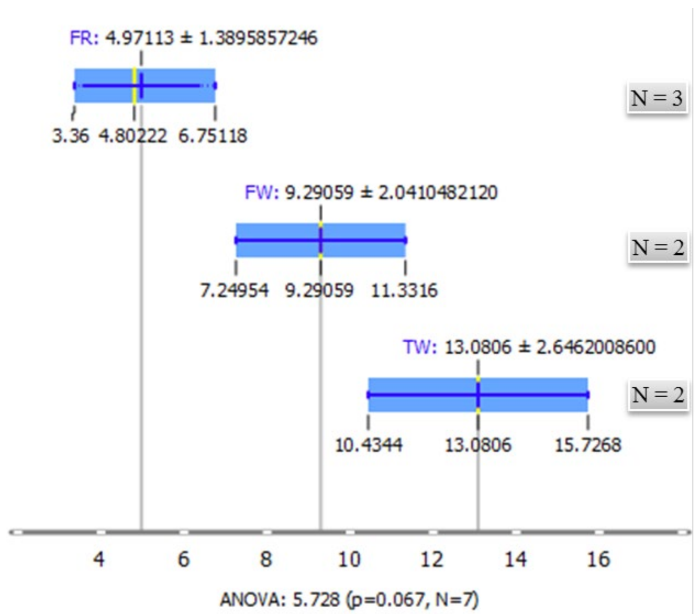


Figure 6: PEX distributions and ANOVA for the FR, FW, and TW drone architecture types

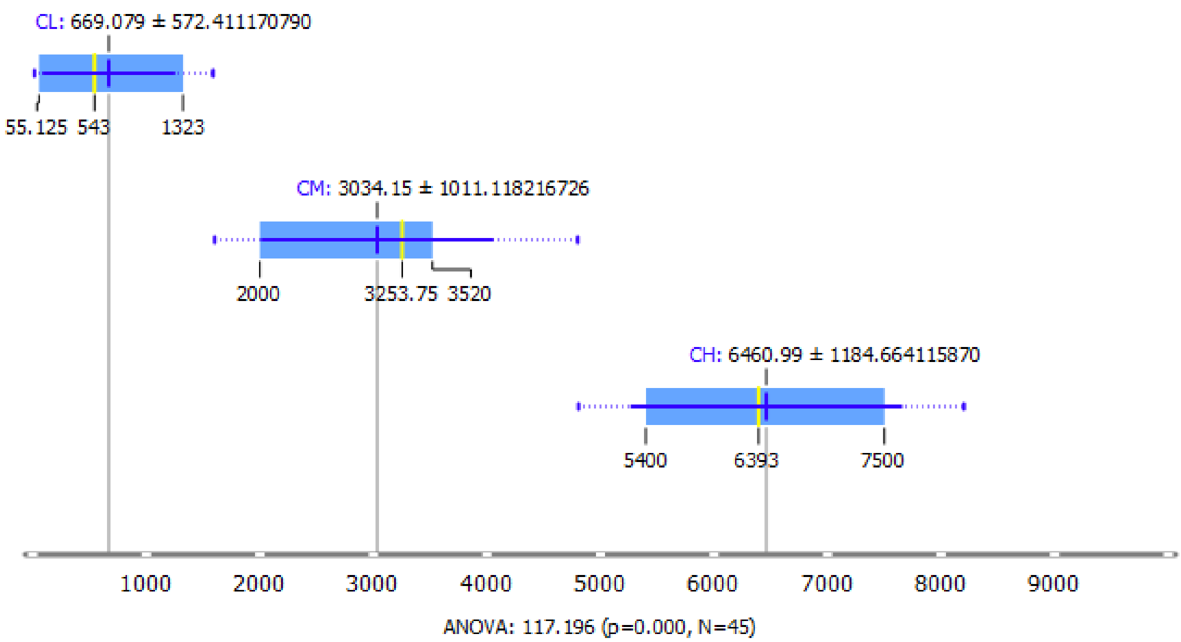


Figure 7: Box plot of MTOW (pounds) by weight class: low (CL), medium (CM), high (CH)

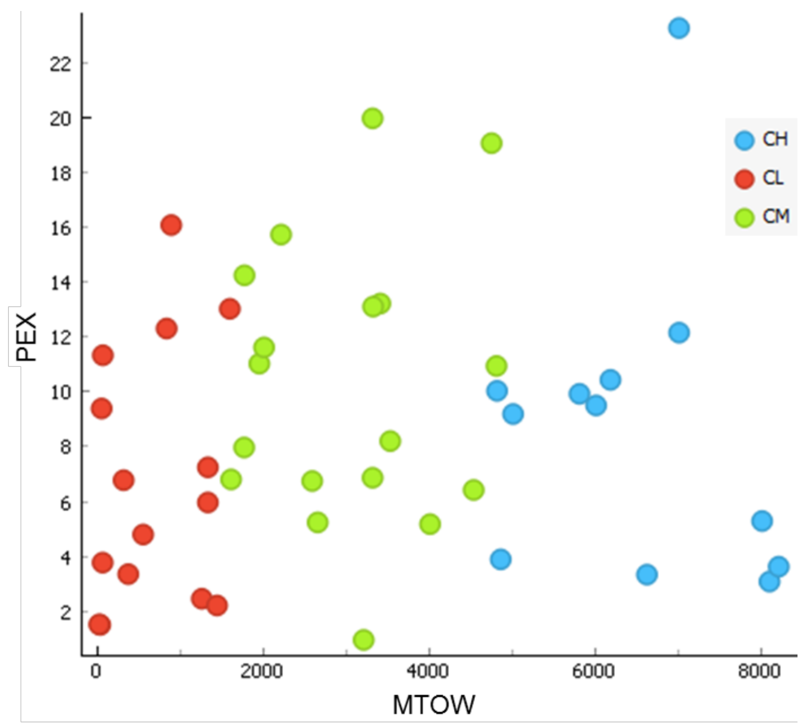


Figure 8: Scatter plot of PEX against MTOW by weight class

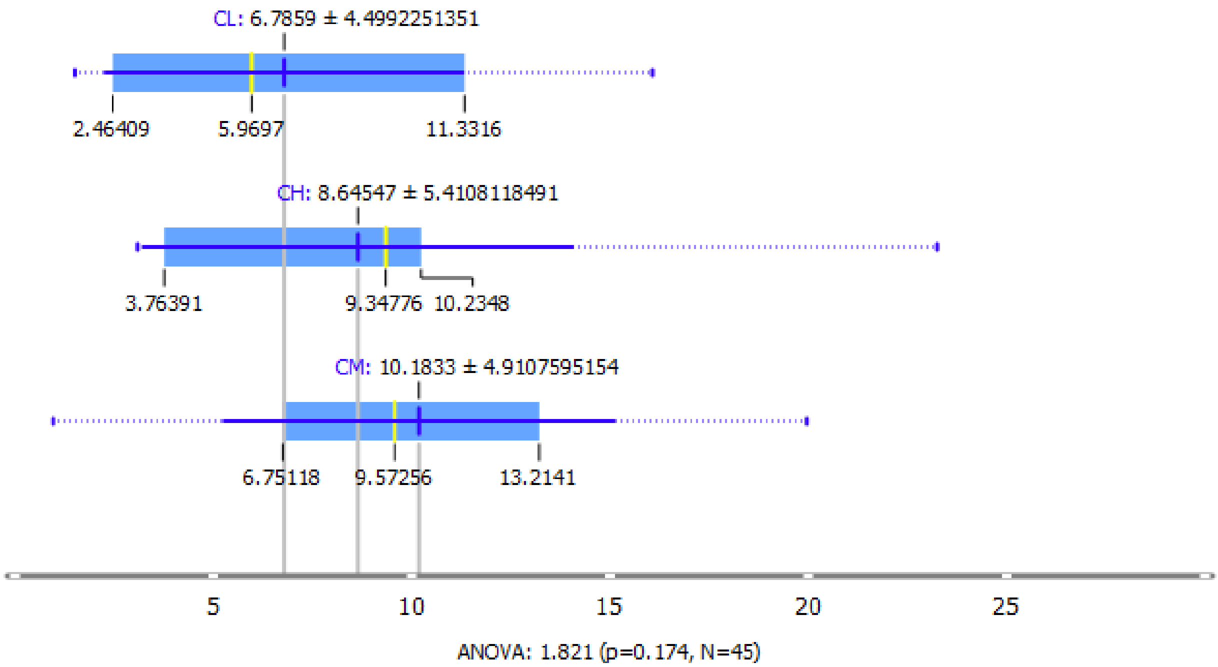


Figure 9: Box plot of PEX by weight class

Regression analysis provided additional clarity. Table 3 reports that altitude-normalized range (RA) accounted for the largest share of explained variance in PEX, followed by payload ratio (PR) and aspect ratio (AR). Together, these three parameters explained more than 90% of the variation in the observed design space. The dominance of range in the regression ranking empirically confirmed that performance differentiation in eVTOL designs remained primarily energy-limited rather than architecture-limited (Lee, Tullu and Hwang 2020) (Zong, et al. 2021).

Table 3: Parameters of the Regression Model

Coefficients	Unnormalized	[0, 1]	Std. Err.	t-statistic	p-value
Constant	-12.20	-4.04	0.71	-5.68	10^{-5}
RA	0.08	23.09	1.21	19.05	10^{-5}
PR	29.86	8.01	0.91	8.85	10^{-5}
AR	7.84	6.02	1.04	5.79	10^{-5}

Collectively, this section establishes energy density as the first-order constraint governing AAM aircraft performance. This subsection, therefore, framed the remainder of the technology assessment. Subsequent discussions on electrification and propulsion efficiency addresses how designers sought to maximize performance within fixed energy density limits. The sections on solid-state batteries and hydrogen propulsion examine whether emerging energy carriers could relax this binding constraint in the medium to long term. By establishing this hierarchy, the analysis establishes a coherent and physics-consistent progression through the technology readiness evaluation for freight-oriented AAM.

2.1.2 Electrification and Propulsion Readiness

This subsection assesses the readiness of aircraft electrification and propulsion technologies for freight-oriented AAM by synthesizing evidence from a cross-sectional thematic and bibliometric analysis of the electrified aviation literature (Bridgelall 2024). The objective is to establish how current research trajectories, integration challenges, and persistent technical constraints have bounded feasible AAM cargo performance, particularly for applications intended to divert freight from highways and preserve surface transportation infrastructure.

The assessment treats peer-reviewed publications as an observable proxy for technology maturity and constraint severity. The underlying workflow shown in Figure 10 applies a structured sequence of database querying, record cleaning, subject-matter expert screening, OpenAlex enrichment, and natural-language processing. This transparent pipeline supports traceability and replicability, which are essential when inferring technology readiness from research patterns rather than prototype demonstrations (Donthu, et al. 2021) (Eck and Waltman 2024).

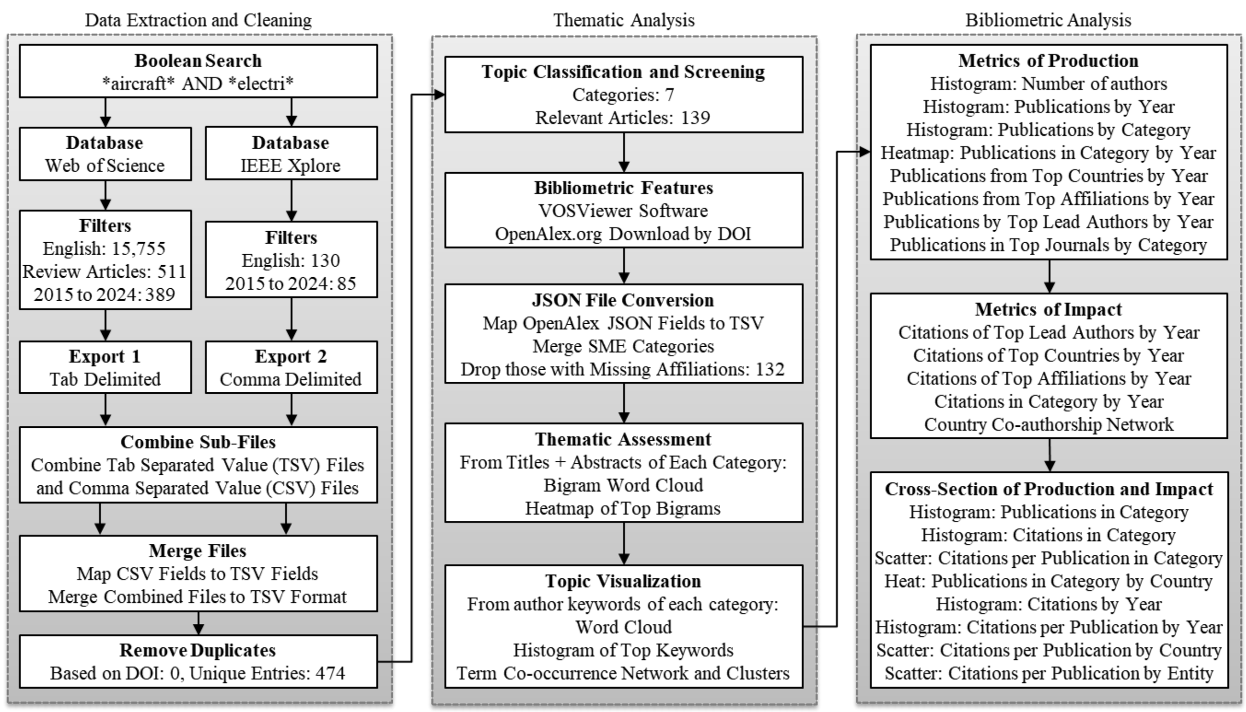


Figure 10: The analytical workflow developed in this study

Using a Boolean wildcard query applied to titles and abstracts, the study retrieved electrified aircraft publications from Web of Science and IEEE Xplore covering 2015–2024. After duplicate removal and expert screening, the final corpus included 132 relevant articles. The analysis then classified these articles into the seven electrification subsystems summarized in Table 4. The categories are electric machines, propulsion, power distribution, energy management, multidisciplinary design, materials, and thermal management. This taxonomy anchored the technology assessment by linking research emphasis to subsystems that directly govern range, payload, efficiency, and reliability in freight operations.

The thematic analysis applied NLP-based bigram extraction to identify dominant technical concerns within each subsystem. Figure 11 presents bigram word clouds by category, showing strong emphasis on terms such as power density**,** thermal management**,** fuel cell**,** battery, and distributed propulsion. These terms correspond directly to freight-relevant constraints, as payload capacity and sustained power delivery depend on efficient energy conversion and effective heat rejection (Sarlioglu and Morris 2015) (Madonna, Giangrande and Galea 2018) (Deisenroth and Ohadi 2019).

Figure 12 quantifies these patterns by reporting bigram frequency distributions. It revealed that energy management and propulsion-related terms dominated multiple categories. This evidence supports treating electrification readiness as an integrated propulsion–energy problem rather than a collection of independent component improvements (Yang, et al. 2021) (Viswanathan, et al. 2022).

Table 4: Electrification Subsystems Discussed in the Selected Literature

Category	Description
Electric Machines	The electrification of various moving parts on an aircraft, such as flaps, ailerons, rudders, landing gears, brakes, generators, rotors, and hydraulic pumps.
Electric Propulsion	The use of electric power for aircraft propulsion, including all-electric, hybrid-electric, and distributed electric propulsion systems. Includes the development of electric motors, power electronics, and integration for improved efficiency and reduced emissions.
Electrical Power Distribution	The design and implementation of electrical systems to efficiently distribute power throughout the aircraft. Includes high-voltage DC systems, power electronics for conversion and control, and smart power management strategies to optimize energy use across various aircraft systems.
Energy Management	Strategies and technologies for optimizing the use, storage, and generation of electrical energy onboard aircraft. Encompasses battery systems, fuel cells, energy harvesting techniques, and intelligent algorithms for balancing power demands across different flight phases.
Multi-disciplinary Design Analysis	The integrated approach to aircraft design, considering the complex interactions between electrical systems, aerodynamics, structures, and propulsion. Includes computational tools and methodologies for optimizing aircraft performance while incorporating electrification technologies.
Novel Aviation Materials	The development and application of new materials specifically suited for electrified aircraft. Includes lightweight composites for structural components, advanced conductors for electrical systems, and innovative materials for insulation and electromagnetic shielding.
Thermal Management	Technologies and strategies for managing heat generated by electrical systems in aircraft. Includes cooling systems, heat exchangers, thermal materials, and design approaches to ensure optimal performance and safety.

Cross-category integration challenges emerge more clearly in the keyword intersection analysis. Figure 13 displays a heatmap of the top five author keywords across subsystems, showing that terms such as motor optimization and propulsion recur across multiple categories. This recurrence indicates strong coupling between electrical, thermal, and structural design decisions. For freight AAM, such coupling constrains achievable payload and range and justifies system-level modeling approaches over component-level optimization (Zhang, et al. 2022) (Cano, et al. 2021) (Roboam 2023).

The term co-occurrence network further exposes latent structure in the research landscape. The study applied a data-driven threshold selection method, documented in Figure 14, to avoid arbitrary network construction. The resulting network, shown in Figure 15, reveals three dominant clusters: computational and optimization methods, propulsion and energy conversion, and materials and sensing. The presence of a distinct propulsion–energy cluster confirms that energy storage, power electronics, and thermal constraints jointly govern electrified aircraft feasibility. For freight operations, this finding reinforces that range and payload limits arise from system-level interactions rather than isolated propulsion efficiency gains (Kiesewetter, et al. 2023) (Ciliberti, et al. 2022).

Bibliometric production metrics provide additional context for readiness assessment. Figure 16 shows publication growth by year and subsystem category. It demonstrated rapid expansion in electrification research after 2018. Energy management and multidisciplinary design emerged as leading categories. This growth reflected sustained research investment but also signaled continued attention to managing, rather than eliminating, fundamental energy constraints (Fakhreddine, et al. 2023) (Raoofi and Yildiz 2023).

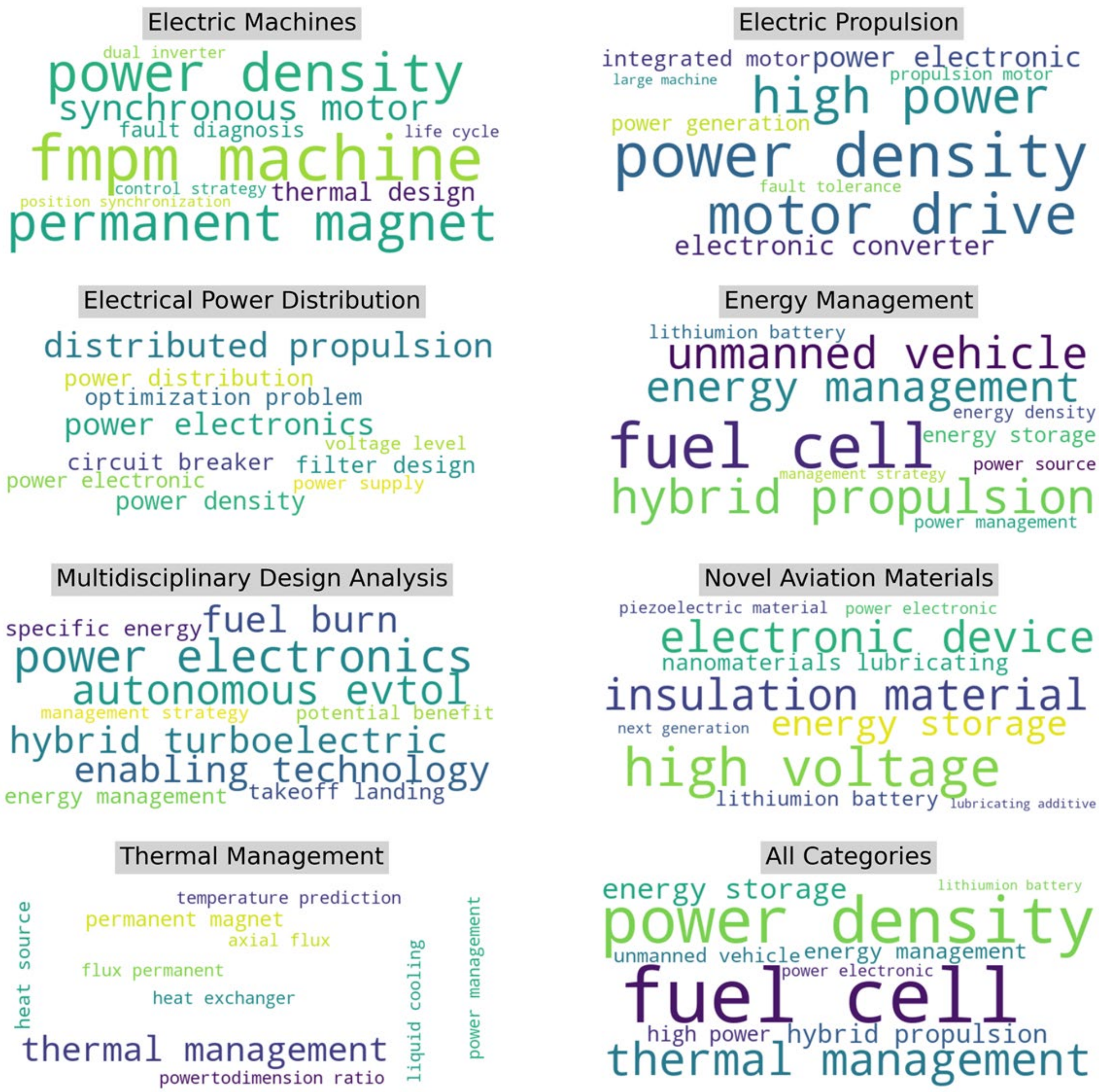


Figure 11: Bigram word cloud within categories

Figure 17 identified leading authors, countries, affiliations, and journals. It indicated that electrified aircraft research concentrated within a relatively small set of institutions and venues, which shapes innovation diffusion and standard-setting dynamics. Impact metrics further clarify where the field derives its foundational knowledge. Figure 18 shows that the most highly cited work concentrated on energy management and multidisciplinary design categories. This citation pattern confirms that influential research prioritizes integration, optimization, and constraint management over isolated propulsion breakthroughs (Cano, et al. 2021) (Zhang, Roumeliotis and Zolotas 2022).

Collaboration analysis in Figure 19 and Table 5 demonstrates extensive international co-authorship. This implies that future AAM freight deployment will depend on globally coordinated supply chains, certification practices, and technology standards (Donthu, et al. 2021)

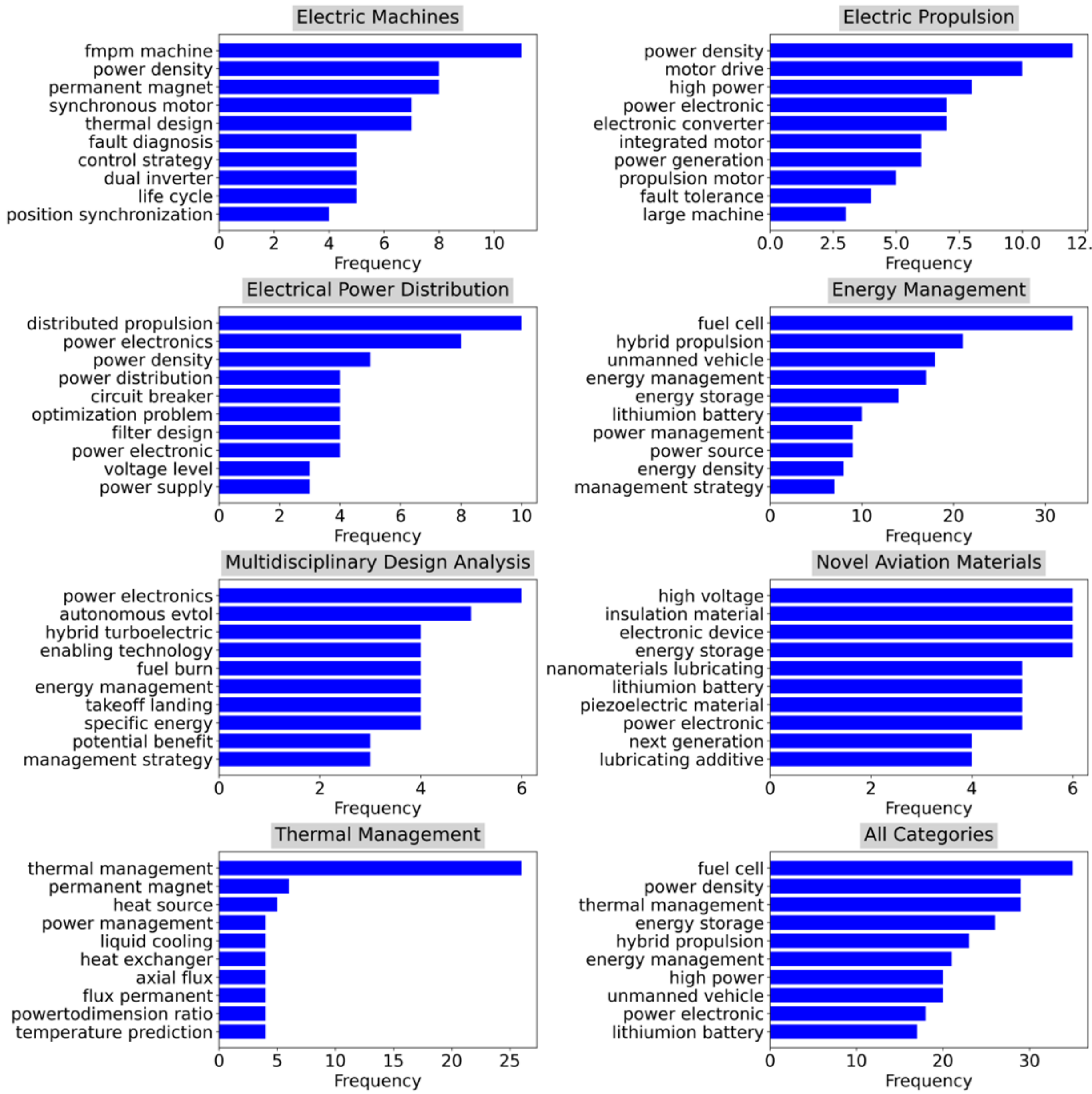


Figure 12: Bigram word frequency within categories

Taken together, the figures, tables, and cited literature in this paper establish a coherent picture of electrification and propulsion readiness. The evidence shows sustained growth and convergence toward efficiency-driven, integrated design approaches. The study consistently reaffirmed that energy storage, thermal management, and system integration remain binding constraints. For the broader technology assessment, this subsection provides a defensible basis for bounding near-term AAM freight missions to short- and medium-range applications and for prioritizing system-level performance metrics when estimating the potential to divert freight from highways.

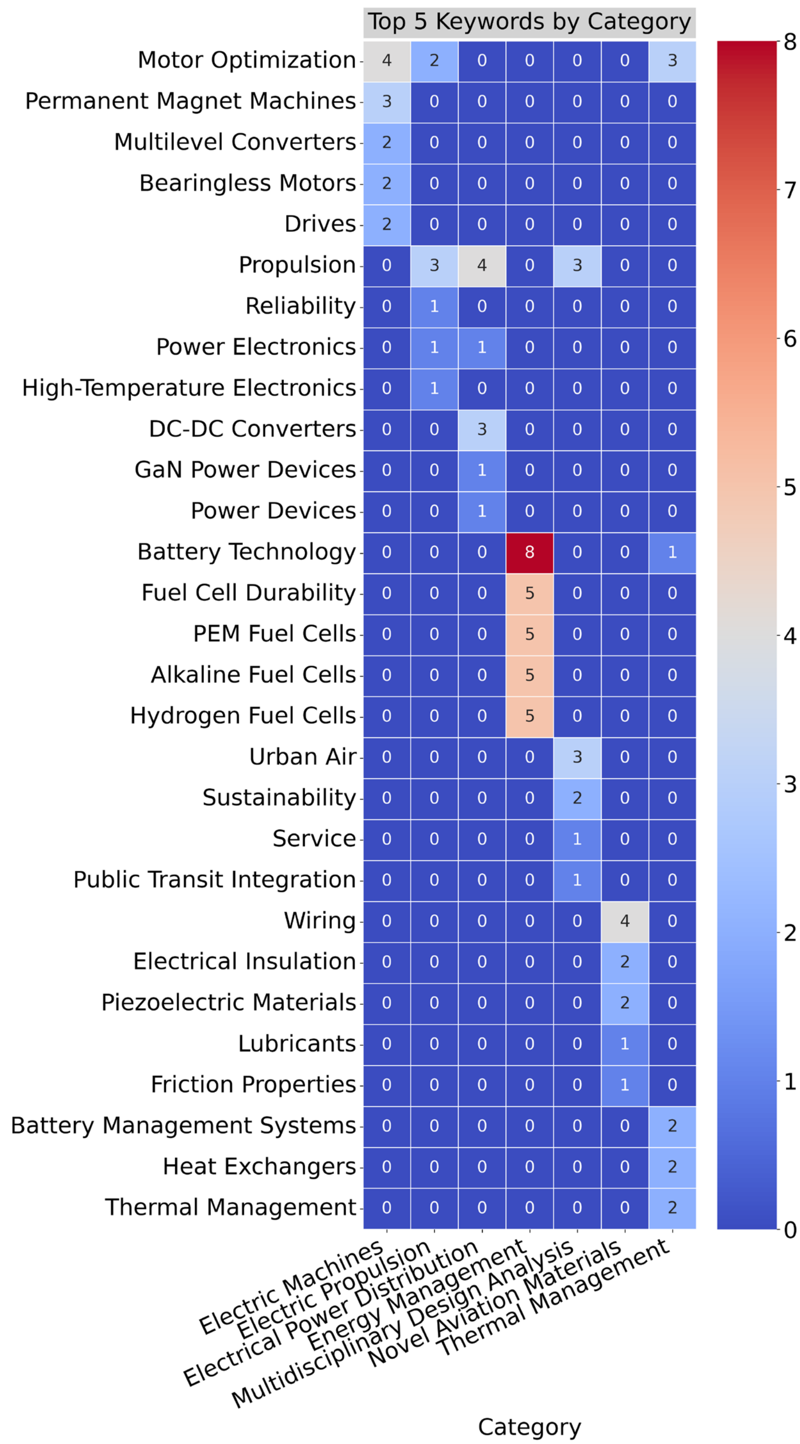


Figure 13: Top 5 author keywords within categories

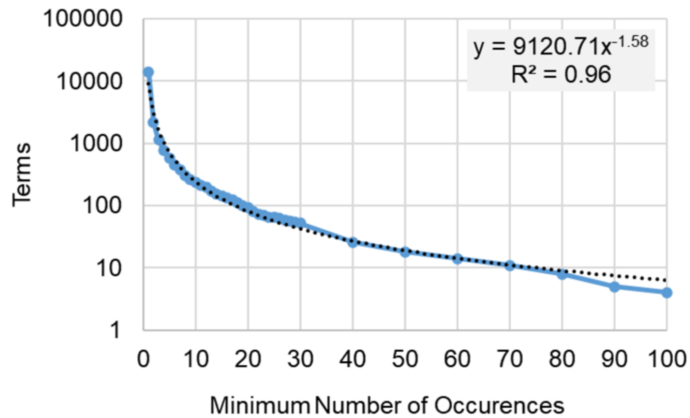


Figure 14: Number of terms as a function of their minimum number of occurrences in the corpus

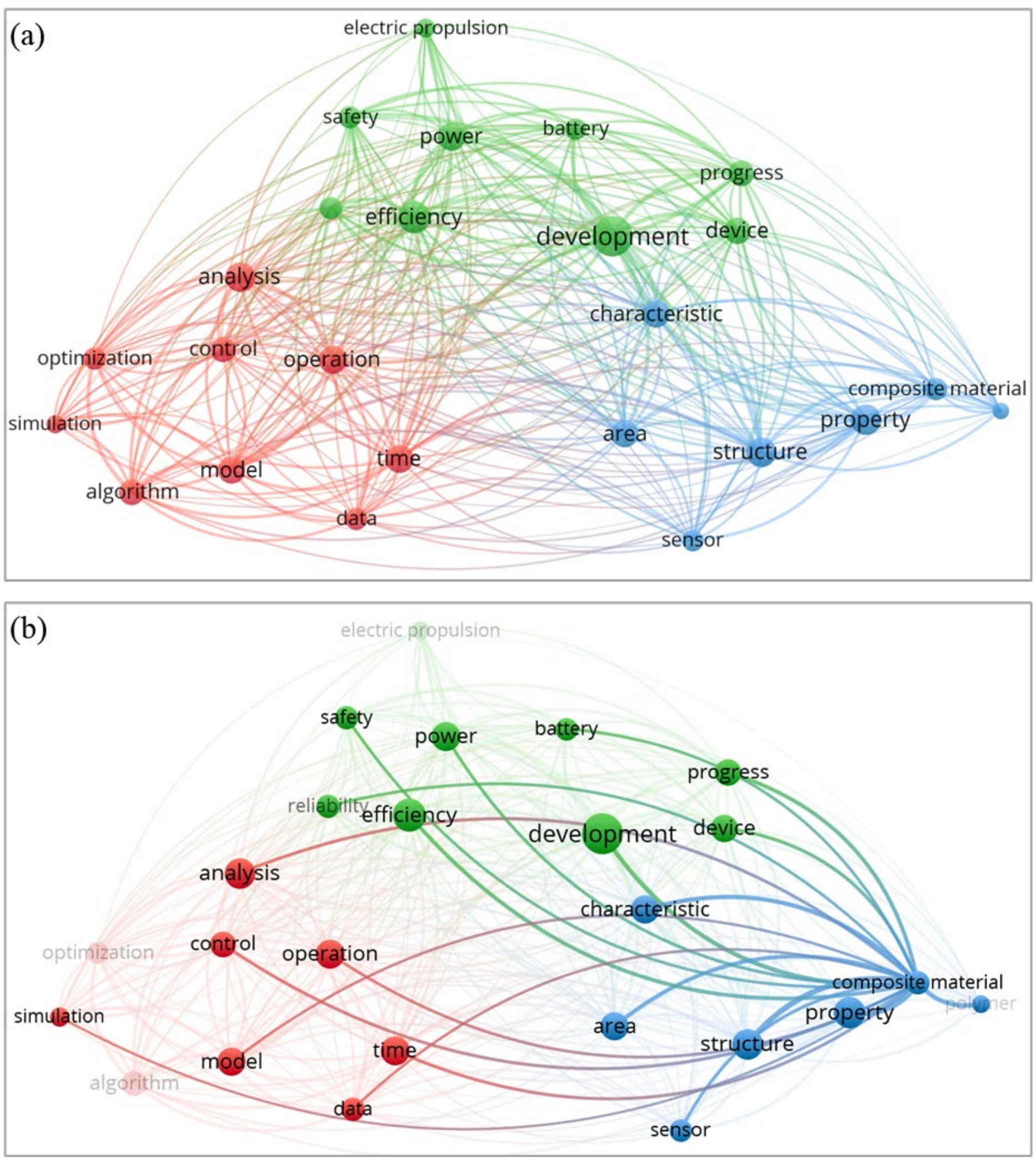


Figure 15: a) term co-occurrence and clusters, and b) highlighted example of "composite material"

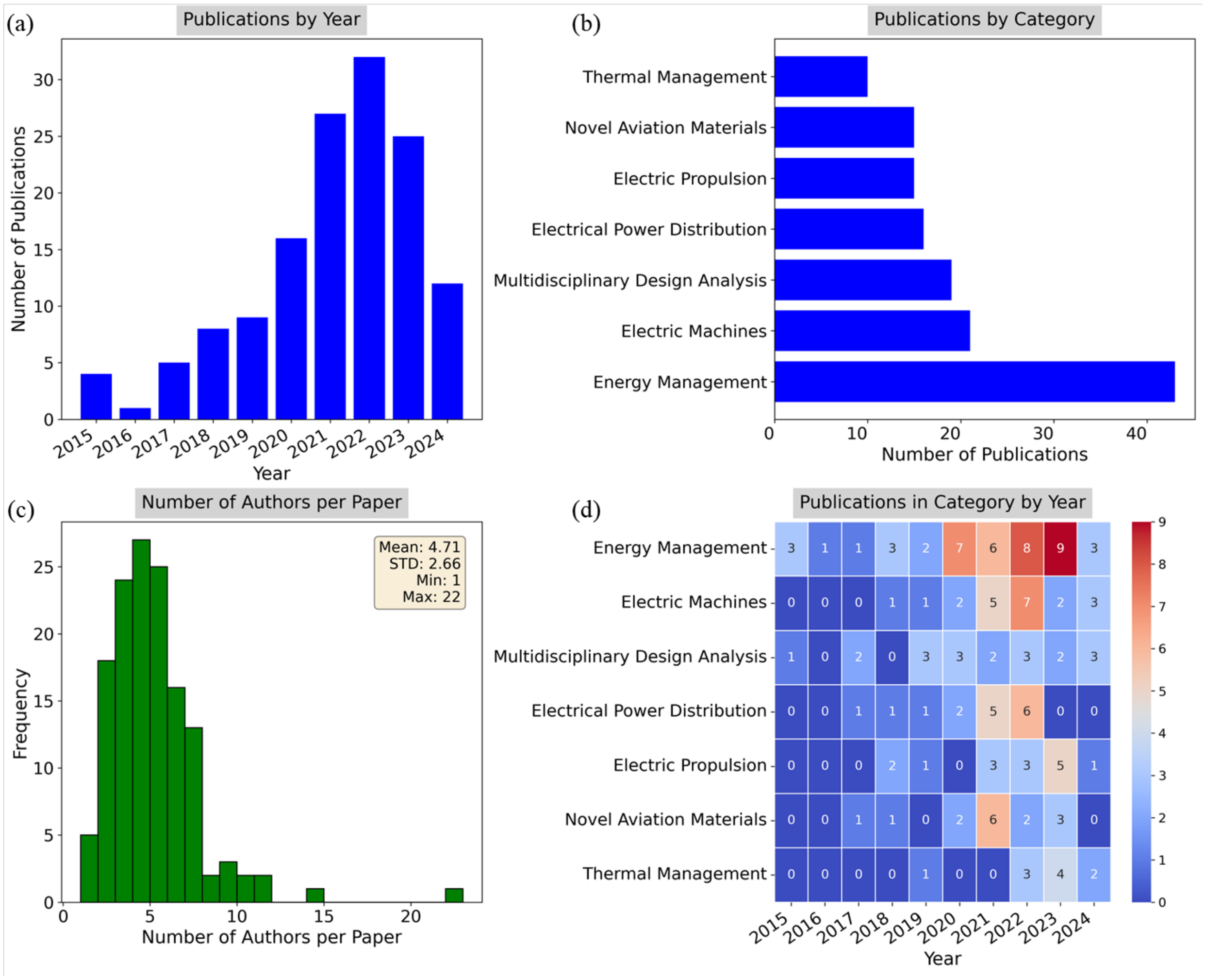


Figure 16: Publications by a) year, b) category, c) author count distribution, and d) category

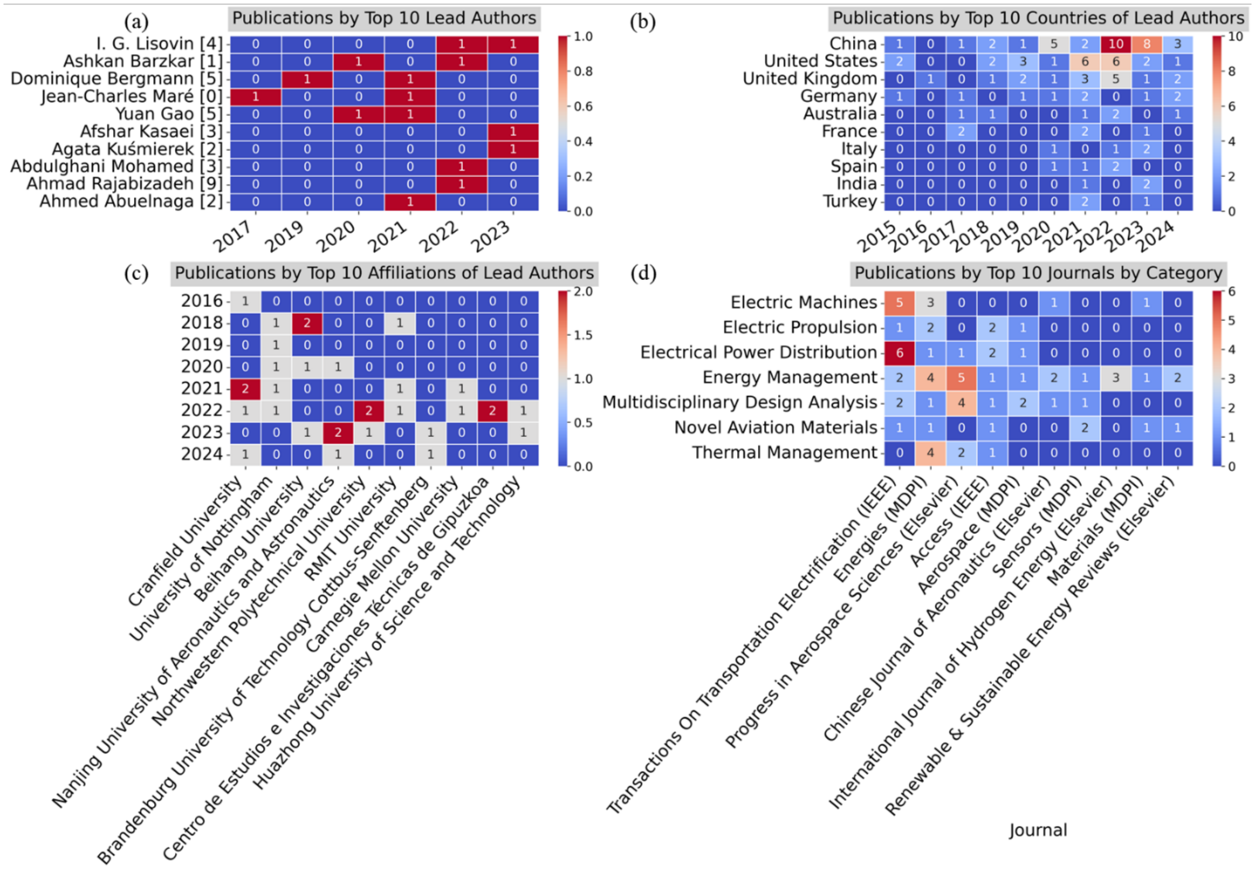


Figure 17: Publications by top 10 a) lead authors, b) countries, c) affiliations, and d) journals

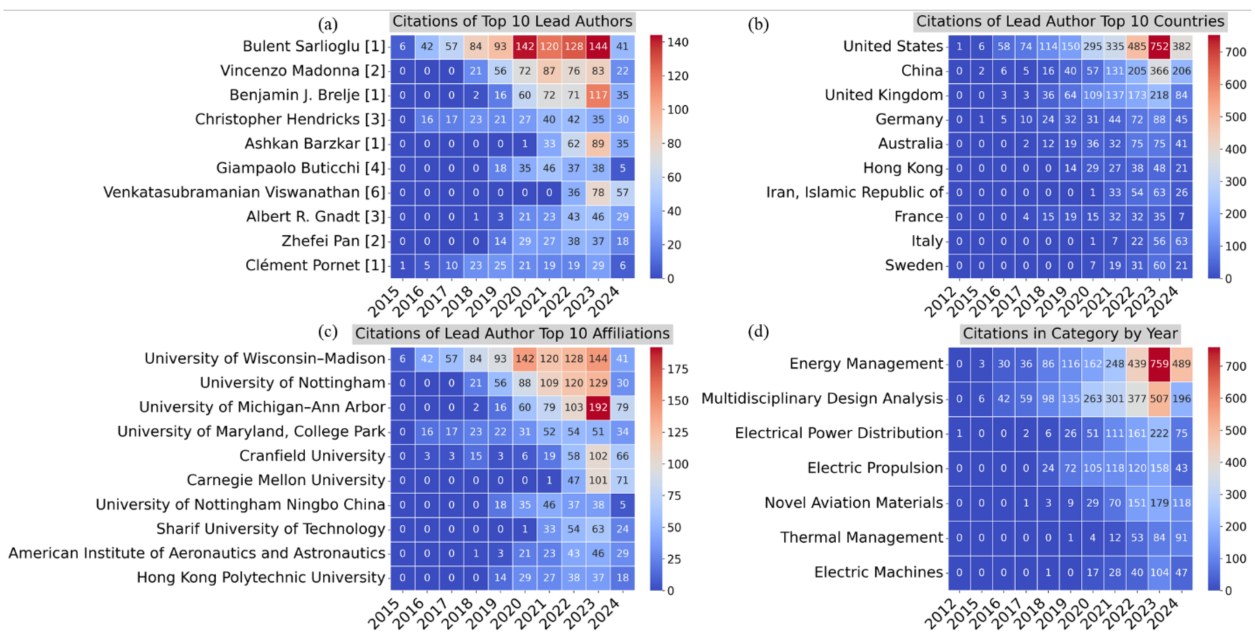


Figure 18: Citations a) of top 10 lead authors, b) of lead author in top 10 countries, c) of lead author in top 10 affiliations, and d) in category by year

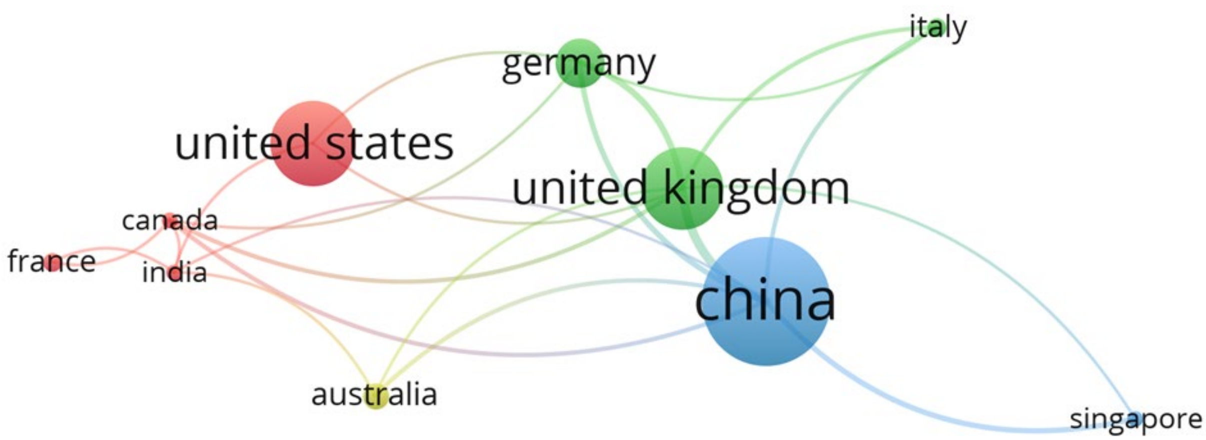


Figure 19: Authorship collaborations across countries

Table 5: Countries with at Least 5 Publications

Country	Pubs	Pubs %	Cites	Cites %	TLS
China	39	27.9%	1,724	21.0%	21
United Kingdom	25	17.9%	1,413	17.2%	19
Germany	15	10.7%	736	8.9%	10
Canada	5	3.6%	379	4.6%	7
India	5	3.6%	60	0.7%	5
Italy	6	4.3%	221	2.7%	5
Australia	8	5.7%	361	4.4%	4
Singapore	5	3.6%	172	2.1%	4
USA	26	18.6%	2,974	36.1%	3
France	6	4.3%	187	2.3%	2

2.1.3 Aircraft Innovation Trends and Design Readiness for AAM

This subsection evaluated aircraft innovation readiness for freight-oriented AAM by synthesizing evidence from a systematic patent review (SPR) of VTOL aircraft technologies (Bridgelall 2024). The objective was to assess how recent innovation trajectories in aircraft design, propulsion, control, and energy systems constrained or enabled the technical feasibility of deploying VTOL aircraft for cargo operations intended to divert freight from ground transportation networks.

The study treated issued patents as observable indicators of applied technological maturity. Hence, the study complemented the theoretical emphasis found in the academic literature. By focusing on U.S.-issued patents from 2018 through 2023, the analysis captured innovations that developers deemed sufficiently mature and commercially relevant to warrant intellectual property protection. This focus was methodologically justified because the United States accounted for more than 40% of global VTOL patent activity, and because many non-U.S. inventors filed their most consequential inventions with the United States Patent and Trademark Office (USPTO) while claiming foreign priority dates (Ugwueze, et al. 2023).

The SPR workflow, illustrated in Figure 20, applied a structured three-stage process consisting of preprocessing, patent screening, and objective classification. This figure established methodological rigor by documenting how over 1.9 million patents were systematically filtered to an analytically tractable set of 156 VTOL-relevant patents. Table 6 summarizes the attrition at each filtering stage by year. This demonstrates both the rarity of VTOL-specific inventions and the increasing pace of innovation over time. This table was particularly relevant to the technology assessment because it showed a clear upward trend in annual VTOL patent filings. This indicated accelerating applied research and development activity rather than stagnation.

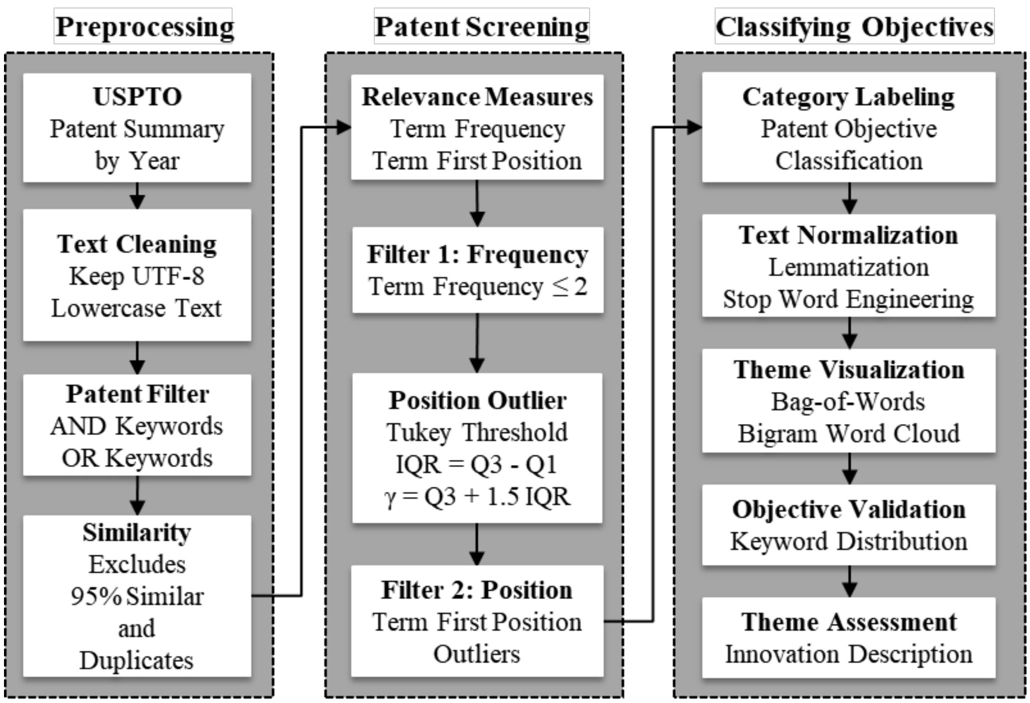


Figure 20: The SPR workflow

Table 6: SPR Workflow Results

SPR Stage	2018	2019	2020	2021	2022	2023
Original	310,568	357,790	355,647	330,645	326,228	314,794
Contains AND/OR Keywords	160	197	215	227	267	406
Remove Duplicates	158	197	213	225	267	403
Remove 95% Similar	152	194	213	217	262	375
Freq (all) ≥ 2	21	36	39	42	48	83
“aircraft” ≤ pos	17 (229)	31 (304)	32 (173)	33 (184)	44 (138)	73 (101)
“vertical” ≤ pos	14 (1058)	28 (1370)	30 (519)	26 (338)	37 (649)	66 (774)
“electric” ≤ pos	12 (3121)	25 (1451)	29 (1828)	25 (1663)	32 (856)	61 (873)
SME Classification	8	22	25	21	32	50

The classified patent objectives provided direct insight into which aircraft design challenges developers prioritized. Figure 21 shows the distribution of patent categories by year. It reveals a pronounced growth in patents addressing transition efficiency beginning in 2020 and continuing through 2023. This trend reflected a sustained effort to improve the energy-intensive transition between vertical and horizontal flight modes, a known bottleneck for VTOL aircraft endurance and payload capacity (Johnson and Silva 2022) (Palaia, et al. 2021). Safety enhancement patents appeared consistently across all years. This pattern aligns with aviation's conservative safety culture and the heightened scrutiny associated with electric and autonomous flight systems (Franciscone and Fernandes 2023).

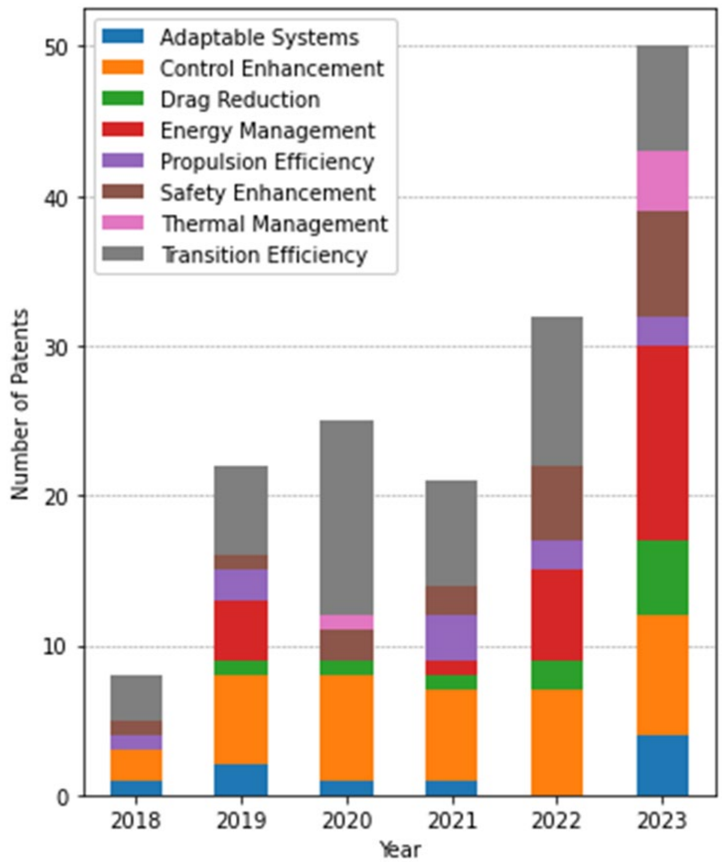


Figure 21: VTOL patent distribution by year, split by category

Figure 22 complements this temporal view by ranking patent categories by total count. Transition efficiency and control enhancement dominated. This confirmed that innovation activity concentrated on improving aircraft stability, controllability, and efficiency during the most demanding flight phases. From a freight perspective, these categories directly affected mission feasibility because transition losses and control margins strongly influenced usable payload and operational reliability in short- and medium-range cargo missions.

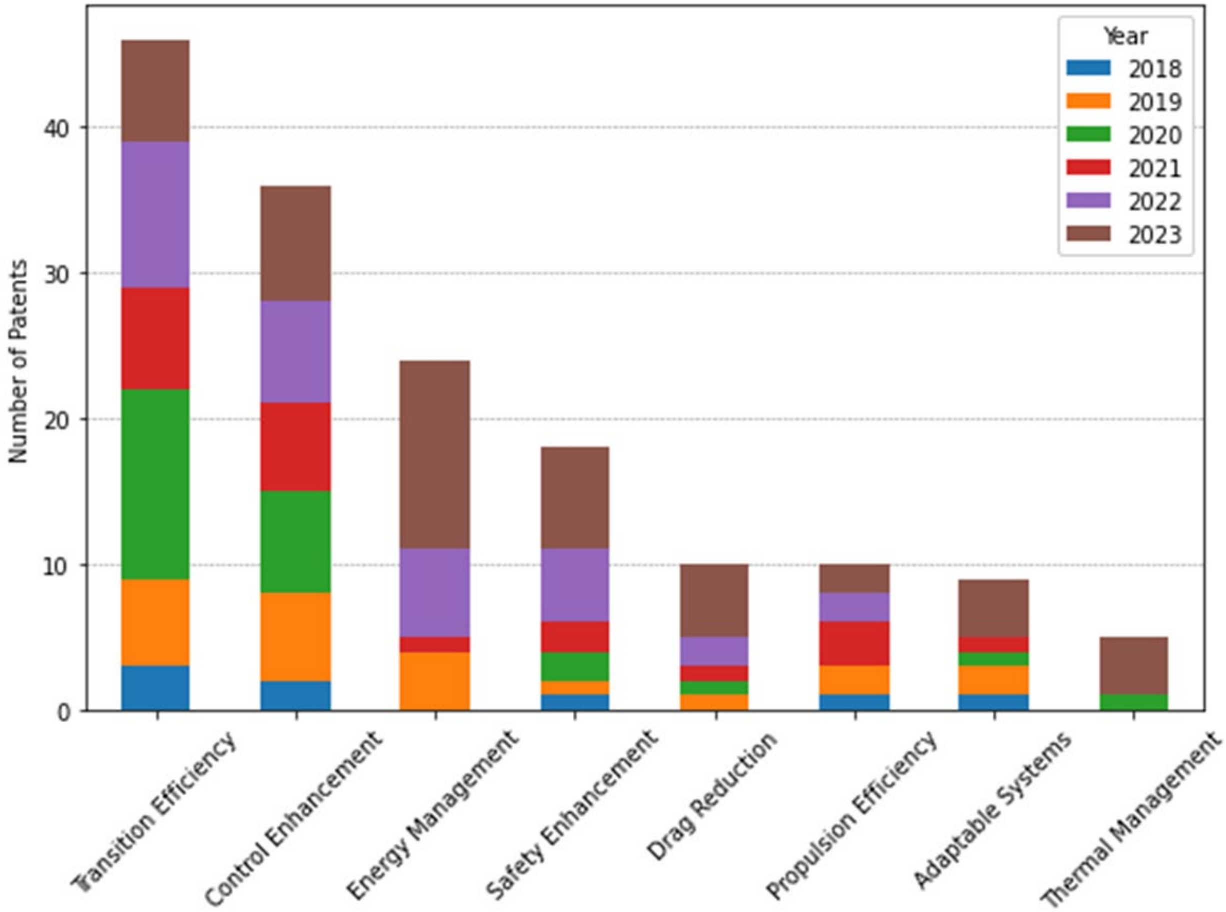


Figure 22: VTOL patent distribution by category, split by year

Textual analysis of patent content further clarified the nature of these innovations. Figure 23 presents word clouds of frequent bigrams for each patent category. In the transition efficiency category, prominent terms such as wing**,** rotor**,** and thrust producing reflect ongoing efforts to optimize lift generation and propulsion integration during mode transitions (Shahjahan, et al. 2024) (Zhang, Barakos and Foster 2023). The thermal management category emphasized battery cell and heat transfer. This highlights the central role of battery safety and heat dissipation in electric VTOL designs (Yang, et al. 2021) (Li, et al. 2023). These visualizations are valuable because they reveal design priorities that quantitative patent counts alone could not capture.

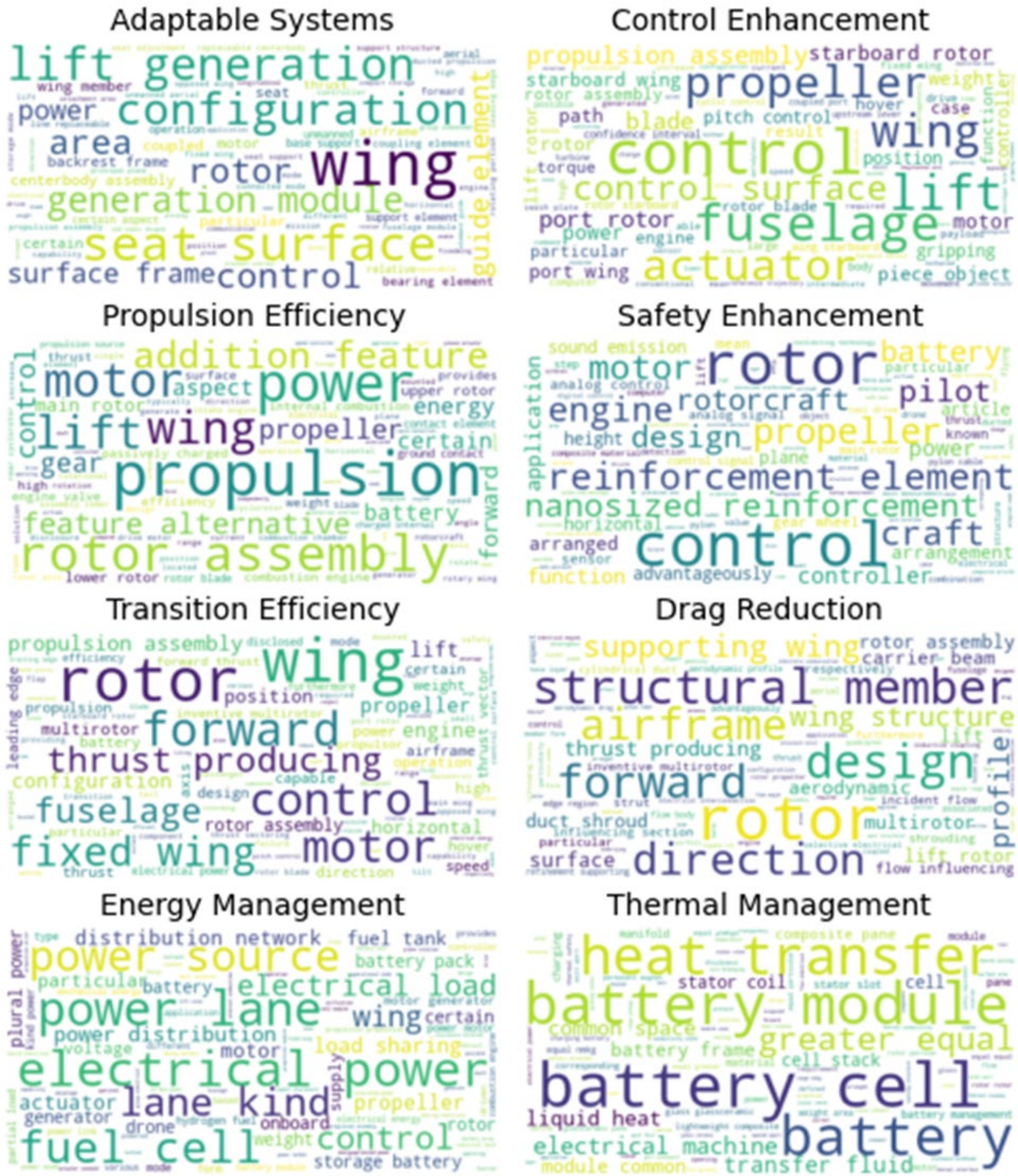


Figure 23: Word cloud depicting categorical bigram frequency distribution

Figure 24 extended this analysis by quantifying the top keywords within each category. The dominance of rotor and propulsion in the propulsion efficiency category highlights continued refinement of electric drive systems, while the prevalence of power and electrical in the energy management category confirmed that energy routing and utilization remained active areas of innovation (Swaminathan, et al. 2022) (Brown and Harris 2020). For freight AAM, these findings reinforce that performance gains were being pursued primarily through efficiency improvements rather than radical increases in energy density.

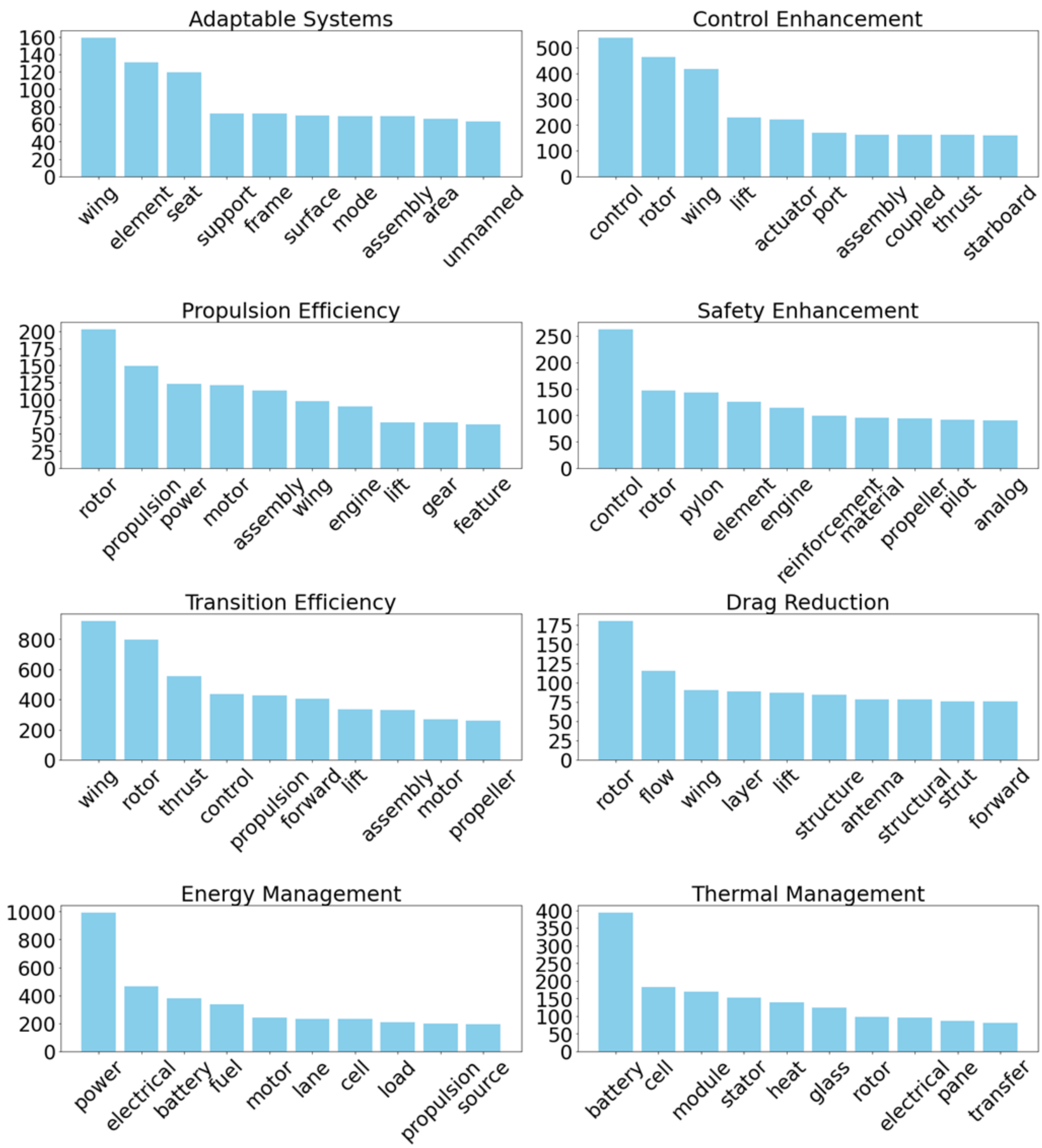


Figure 24: Keyword distribution by patent category

The categorical analysis also revealed strong interdependencies across innovation domains. Energy management patents frequently overlapped with thermal management objectives. This reflects the necessity of dissipating heat generated by high-power batteries and motors in compact airframes (Li, et al. 2023). Similarly, drag reduction innovations influenced propulsion efficiency and transition performance by lowering cruise power requirements and smoothing mode changes (Ugwueze, et al. 2023) (Palaia, et al. 2021). These intertwined trends demonstrated that VTOL innovation progressed through integrated system design rather than isolated component advances.

Collectively, the patent evidence indicated a clear evolution from mechanically focused innovations toward electrically driven, software-intensive, and system-integrated solutions. Earlier patents emphasized structural configurations and rotor arrangements, whereas more recent filings increasingly incorporated advanced control algorithms, adaptive systems, and sophisticated energy management architectures (Wei, et al. 2024) (Xiang, et al. 2023). This shift is aligned with broader trends in aerospace and intelligent transportation systems. It suggested growing readiness for controlled and limited-scale deployment rather than speculative experimentation.

Within the broader technology assessment, this subsection established that aircraft innovation readiness for AAM freight operations depends less on revolutionary breakthroughs and more on incremental, tightly integrated improvements across propulsion, control, energy, and thermal systems. The patent trends supported conservative assumptions regarding near-term payload and range while confirming sustained innovation momentum. These findings provided a defensible technical foundation for subsequent market, regulatory, and infrastructure analyses aimed at quantifying the potential for shifting freight from roads to air while preserving ground transportation infrastructure.

2.1.4 Solid-State Battery Readiness and Energy Storage Constraints

This subsection assessed the readiness of solid-state battery (SSB) technologies as enabling energy storage systems for freight-oriented AAM. The synthesis drew exclusively from two complementary studies: a claims-based patent analysis of solid-state battery innovations (Bridgelall 2024) and a scientometric and thematic analysis of peer-reviewed SSB research (Bridgelall 2024). The objective was to evaluate whether observed innovation trajectories and research priorities supported near-term or mid-term deployment of SSBs in high-power, weight-constrained aviation applications. The assessment treated patents as indicators of applied, commercially motivated innovation and peer-reviewed publications as indicators of scientific maturity and unresolved constraints. Together, these lenses provided a robust basis for bounding expectations regarding SSB performance, scalability, and suitability for AAM cargo aircraft.

Patent-Based Evidence of Innovation Direction

The patent analysis classified invention claims by problem–solution focus. These include ionic conductivity, interfacial resistance, cycling stability, energy density, and manufacturability. Figure 25 illustrates the objective-classification workflow, demonstrating how patent claims were systematically decomposed and mapped to technical bottlenecks. This workflow is essential for establishing traceability between individual inventions and the performance constraints most relevant to aviation energy storage. The distribution of patent activity (Figure 26) showed that innovation clustered heavily around interfacial engineering and cycling stability, rather than radical increases in intrinsic energy density. The frequency of patent objectives by category revealed that a majority of claims addressed interface stabilization, dendrite suppression, and material compatibility. This pattern indicated that developers focused on mitigating failure modes rather than unlocking step-change performance improvements, a critical distinction when evaluating readiness for aviation deployment.

Textual analysis of patent claims further clarified innovation priorities. Figure 27 shows keyword distributions within each objective category, where terms relating to surface coating, composite electrolyte, and interfacial impedance dominate.

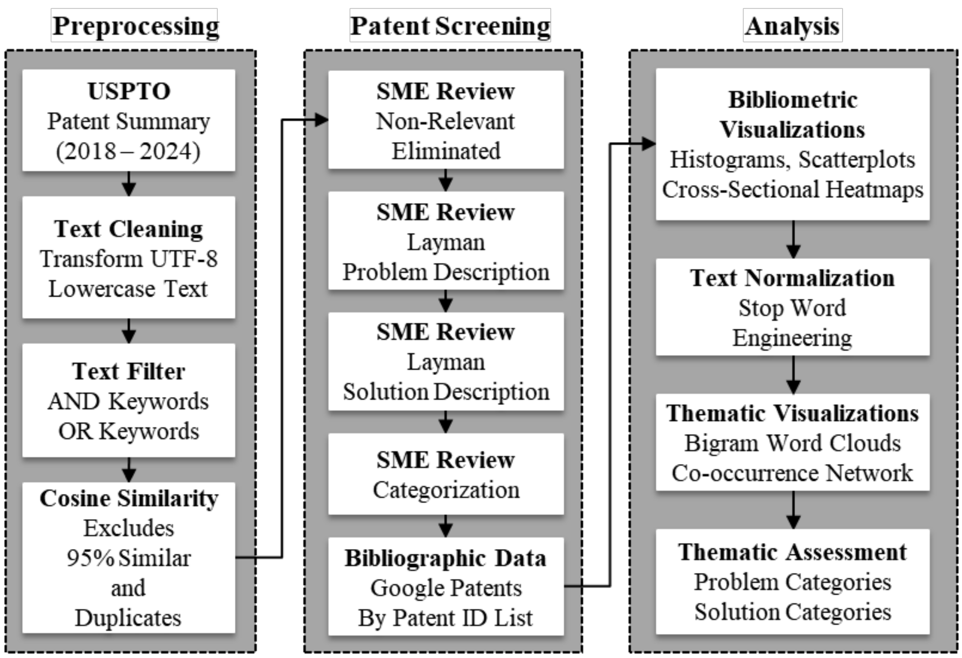


Figure 25: Workflow for the systematic patent review and cross-sectional bibliometric and thematic analysis

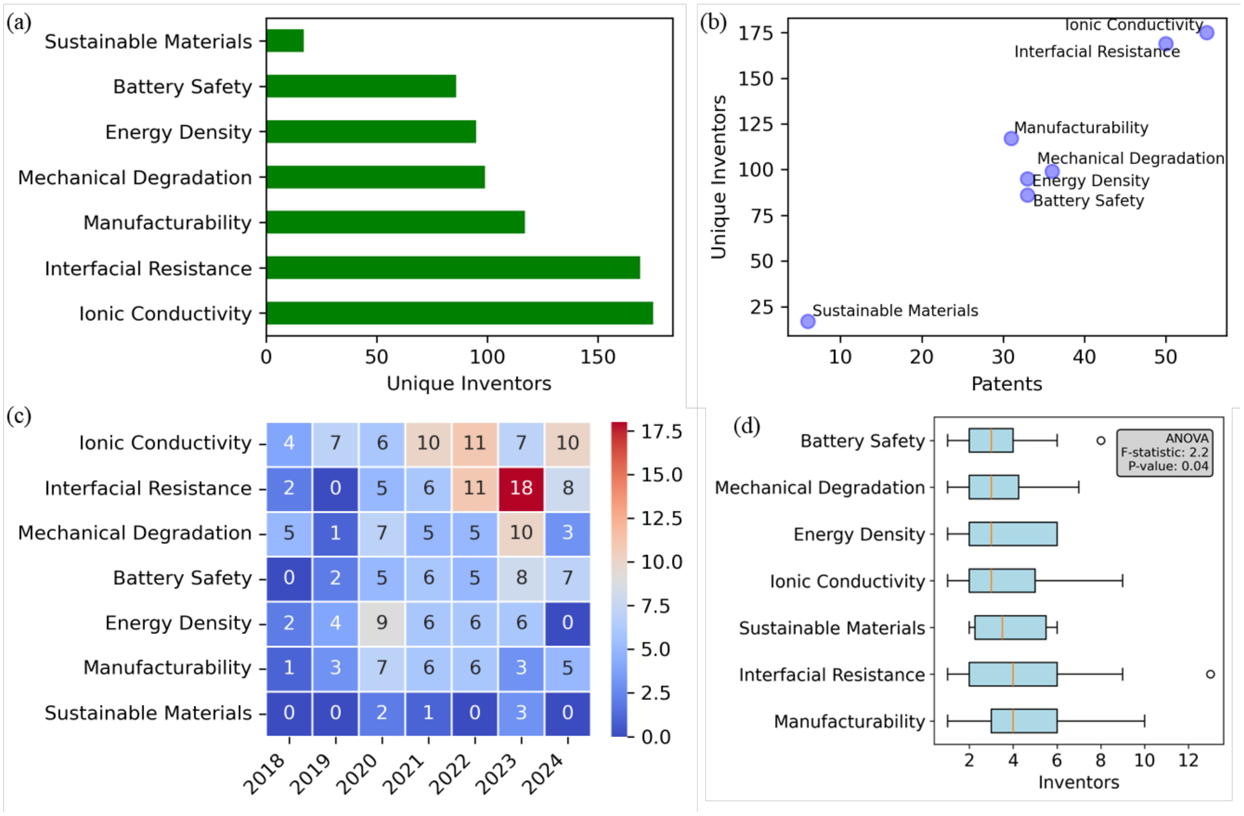


Figure 26: Categorical metrics reflected by a) unique inventors, b) unique inventors by patent volume, c) category by award year, and d) inventors per patent within a category

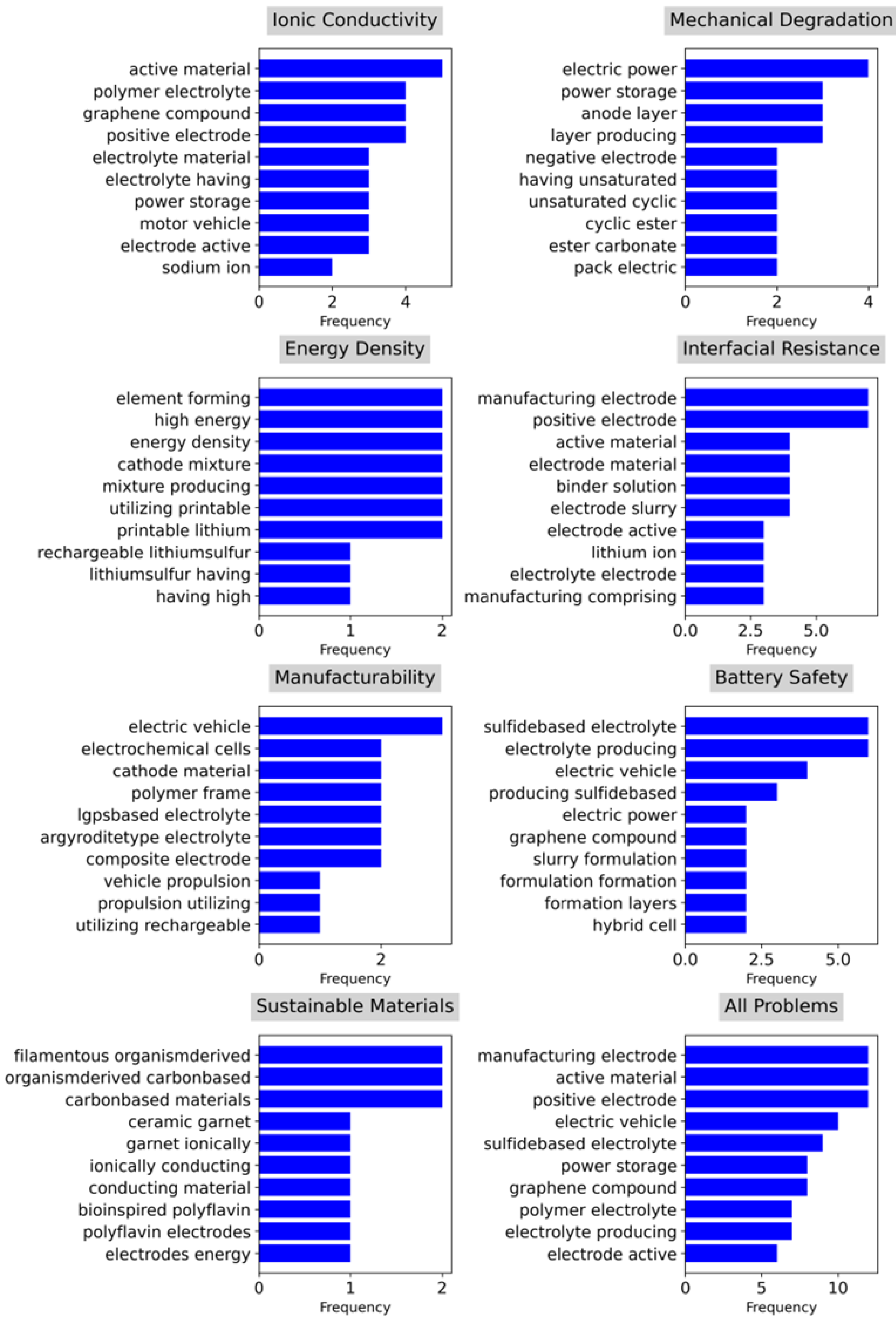


Figure 27: Distribution of top 10 bigrams within each problem category

These areas reflect persistent challenges at electrode–electrolyte interfaces, which directly affected power delivery, safety, and cycle life under high-current operation (Chen, et al. 2019) (Razali, et al. 2023) (Singh, et al. 2023). For AAM cargo aircraft, such interface-driven limitations constrained sustained discharge rates and thermal stability during repeated missions. The patent evidence, therefore, suggested that SSB innovation remained largely constraint-driven, with limited evidence of near-term breakthroughs sufficient to displace lithium-ion systems in aviation-grade applications.

Scientometric Evidence of Research Maturity

The scientometric study reinforced these conclusions by analyzing 131 peer-reviewed SSB articles published between 2018 and 2024. Figure 28 shows the end-to-end methodological workflow. It includes database querying, expert screening, thematic classification, and bibliometric enrichment. This figure anchors the validity of using publication patterns to infer technology readiness.

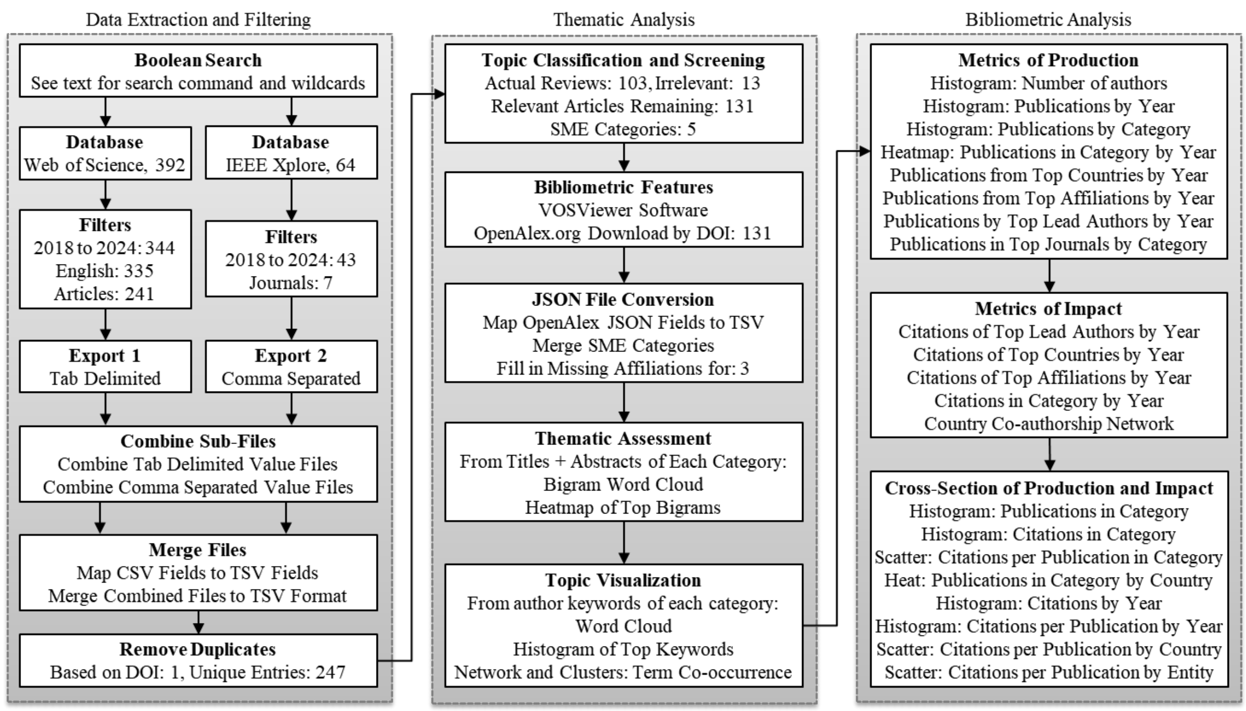


Figure 28: The workflow developed for applied thematic and bibliometric analysis

Subject-matter expert categorization identified the five dominant research areas summarized in Figure 29. These are ionic conductivity, interfacial resistance, cycling stability, energy density, and manufacturability. This categorization explicitly linked electrochemical performance metrics to practical deployment barriers such as supply-chain scalability and thermal robustness. The framework showed that improvements in one dimension often introduced trade-offs in others. This reinforces the need for integrated assessment.

Thematic analysis using NLP revealed persistent research emphasis on electrolyte behavior. Figure 30 presents bigram word clouds by category, where *ionic conductivity*, *composite electrolyte*, and *interfacial resistance* appeared prominently across multiple themes.

Figure 31 quantifies these patterns, showing that ionic conductivity and interface-related terms dominate the frequency distributions.

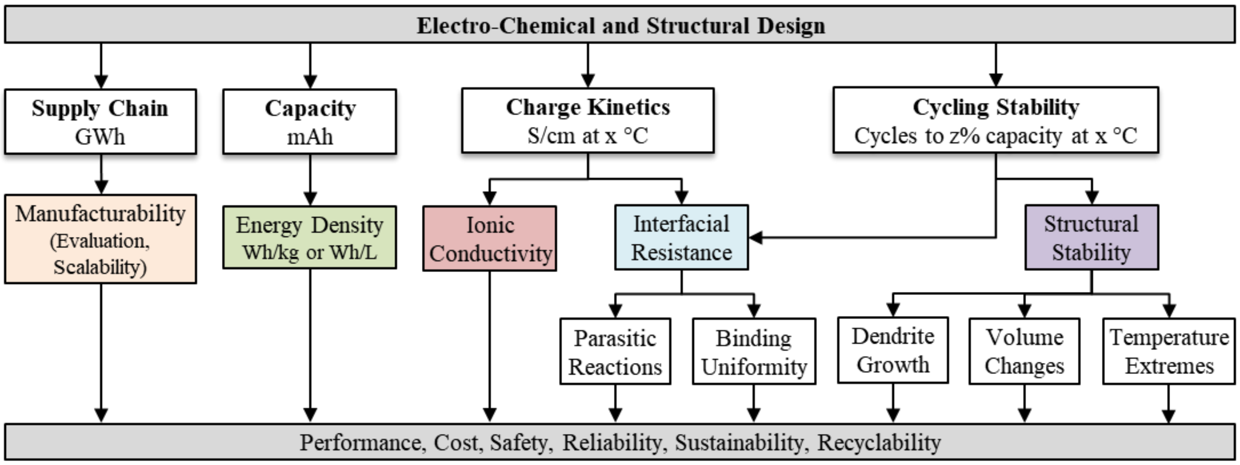


Figure 29: SME categorization of research thrusts

These figures support the conclusion that fundamental materials challenges continue to shape the research agenda (Yang and Wu 2022) (Shen, et al. 2019). Author-provided keywords further confirmed this focus. Figure 32 shows categorical keyword clouds in which *electrolyte* and *fast conductor* appeared consistently across all categories. The cross-sectional heatmap in Figure 33 demonstrates that electrolyte-related terms exhibited the highest frequency across cycling stability, interfacial resistance, and ionic conductivity. This cross-cutting dominance underscored the central role of electrolyte design in determining SSB feasibility for high-power applications.

The term co-occurrence network provided a systems-level view of SSB research structure. Figure 34 showed that "electrolyte" occupied a central position linking clusters associated with energy density, interface stability, and cycling behavior. The clustering pattern indicated that research progress depended on coordinated advances across materials science, electrochemistry, and mechanical integrity rather than isolated improvements.

Bibliometric trends further contextualized maturity. Figure 35 shows steady growth in publications after 2018, with cycling stability and interfacial resistance accounting for the largest share of output. Citation analysis in Figure 36 and Figure 37 reveals that high-impact work concentrated in these same categories. However, manufacturability papers exhibited high citations per publication despite lower volume. This pattern suggested that scalability remained a recognized bottleneck with limited but influential contributions (Chen, et al. 2019) (Lee, et al. 2024). International collaboration analysis reinforced this interpretation. Figure 38 and Table 7 show that China, the United States, and South Korea dominated publication and citation activity, with strong but uneven collaboration networks. Such concentration implied that industrial supply chains and standardization pathways would heavily influence eventual commercialization timelines.

Taken together, the patent and scientometric evidence showed that SSB technologies had not yet achieved the combination of energy density, power capability, cycling robustness, and manufacturability required for near-term AAM freight deployment. Research and innovation activity remained focused on overcoming foundational electrochemical and interface challenges rather than delivering aviation-ready systems. This subsection, therefore, established that SSBs represented a medium- to long-term enabling technology rather than a near-term solution. The findings justify conservative assumptions regarding aircraft range and payload in subsequent analyses. They reinforce the need to rely on existing lithium-ion and hybrid energy architectures when evaluating the potential of AAM to divert freight from ground infrastructure.

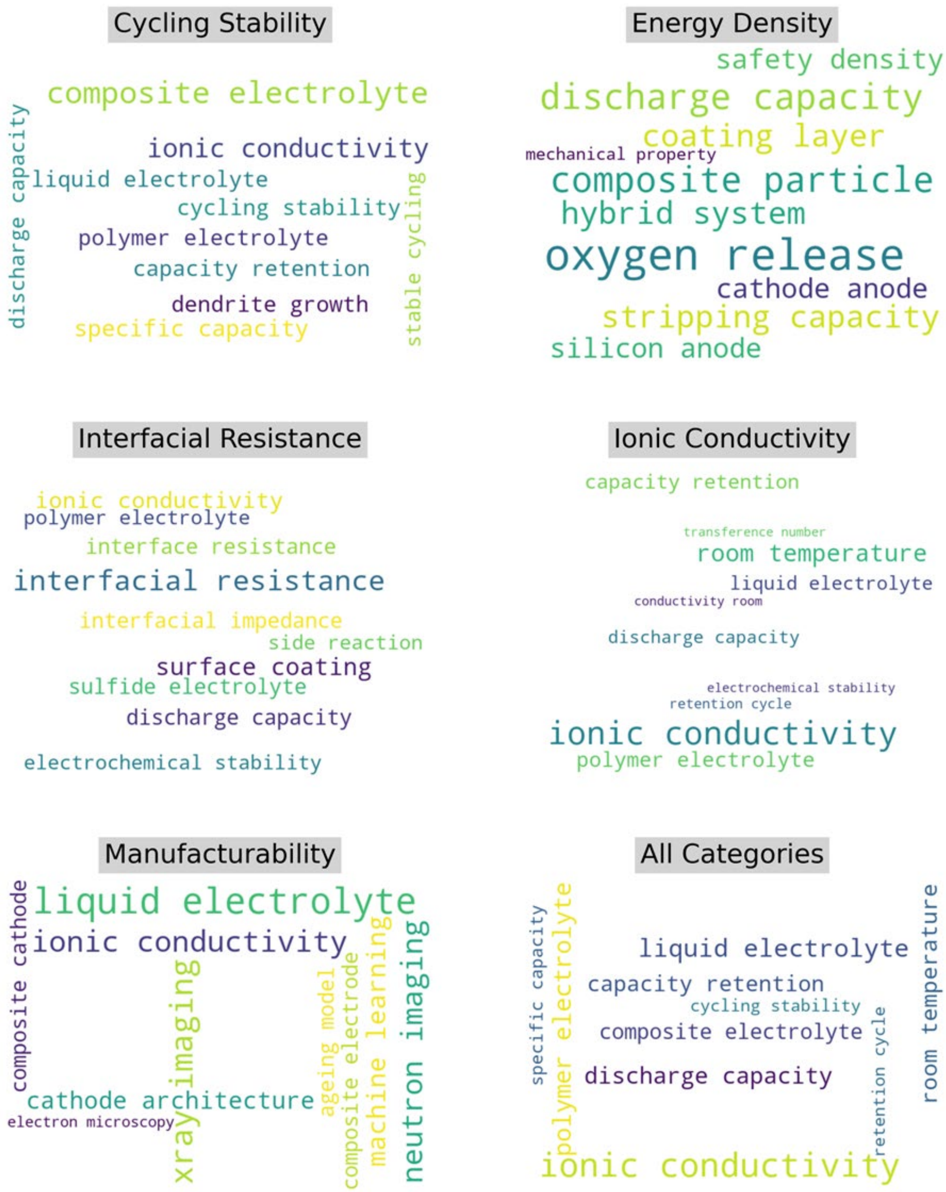


Figure 30: Bigram word cloud of titles and abstracts within each category

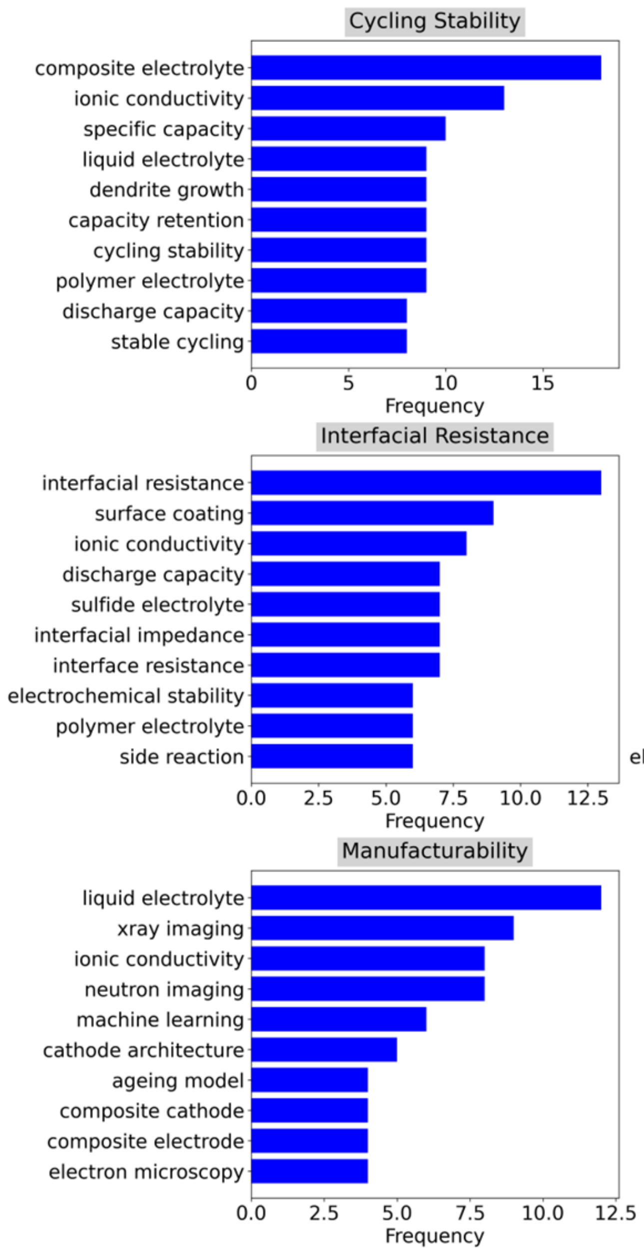


Figure 31: Bigram distribution of titles and abstracts within each category

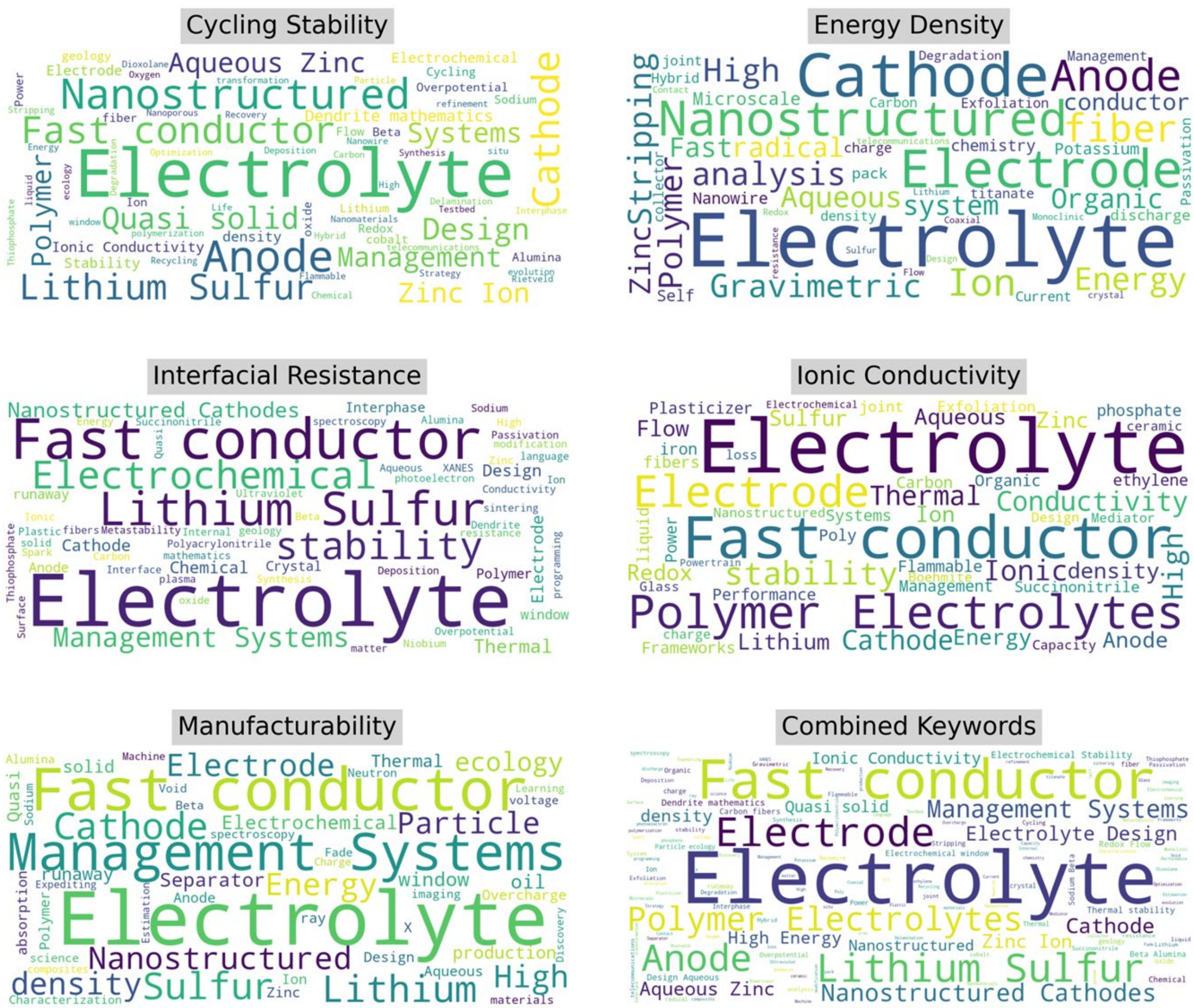


Figure 32: Categorical word clouds of author keywords

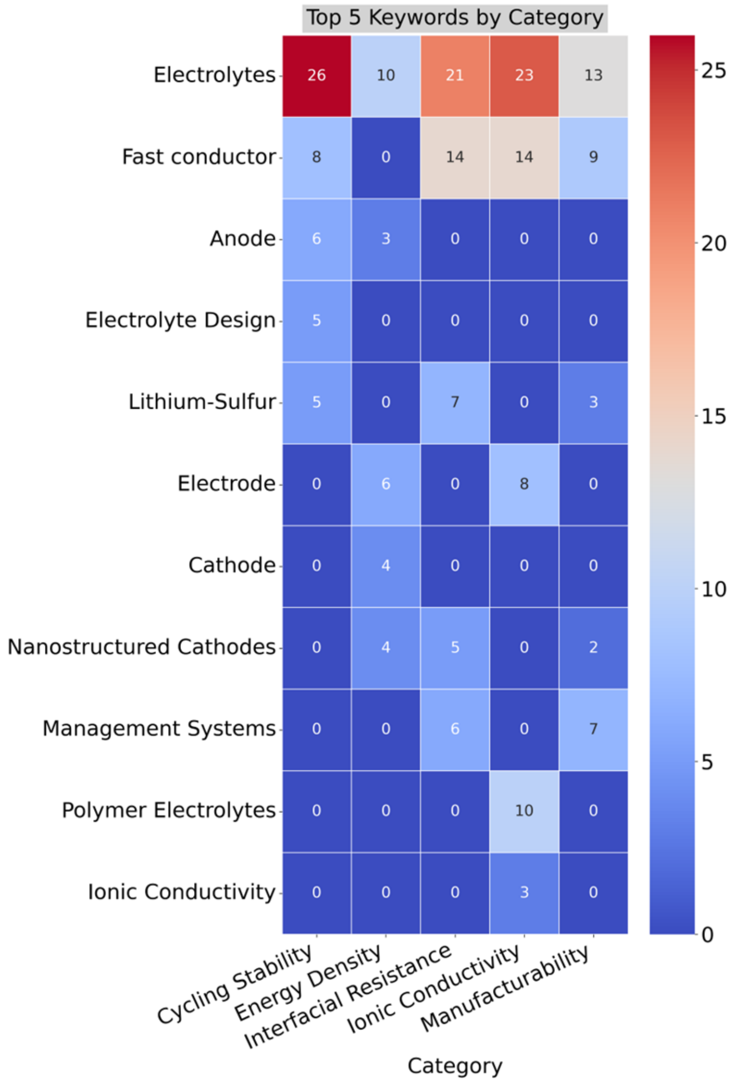


Figure 33: Cross sectional analysis of author keywords and research categories

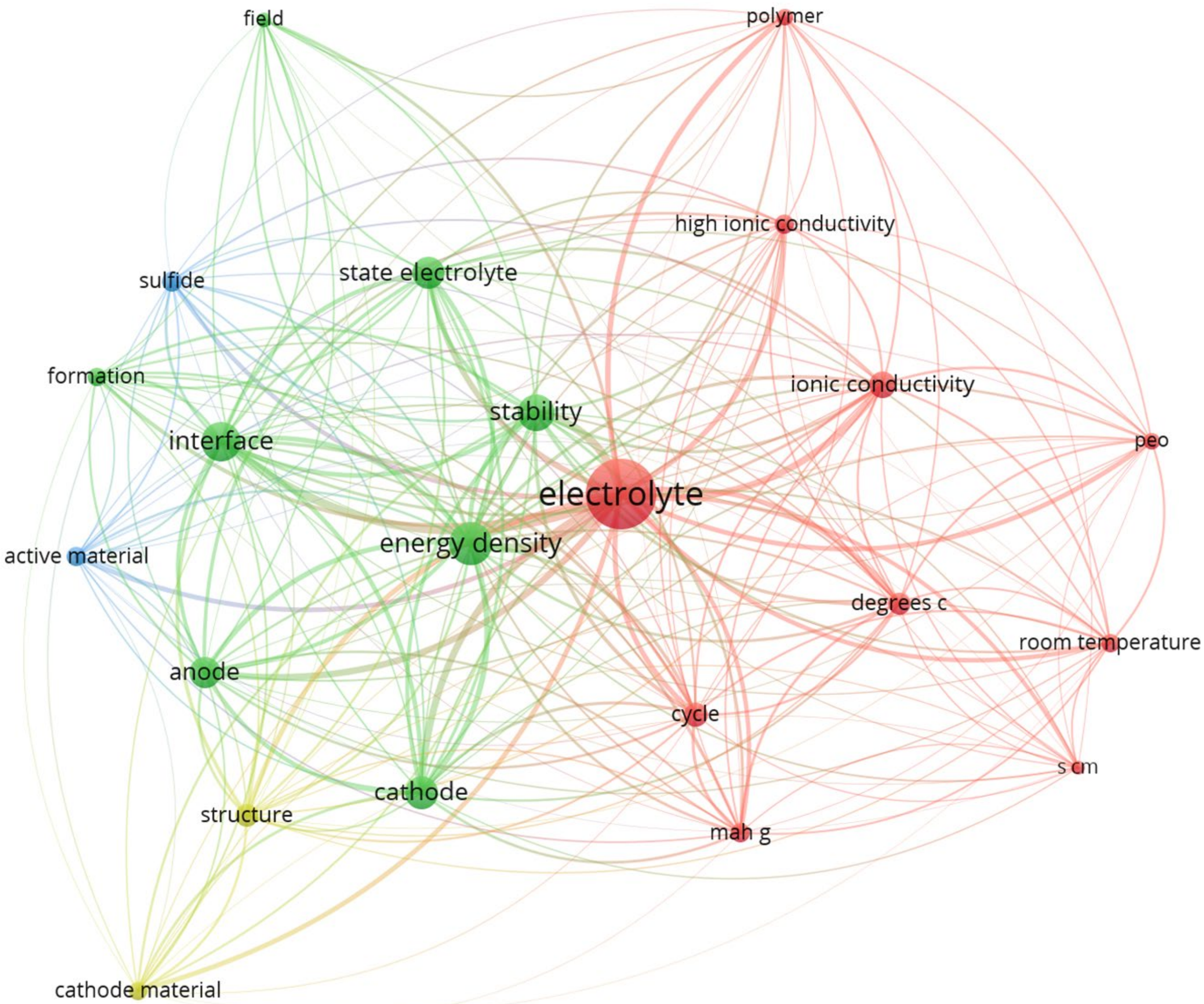


Figure 34: Keyword co-occurrence and cluster analysis

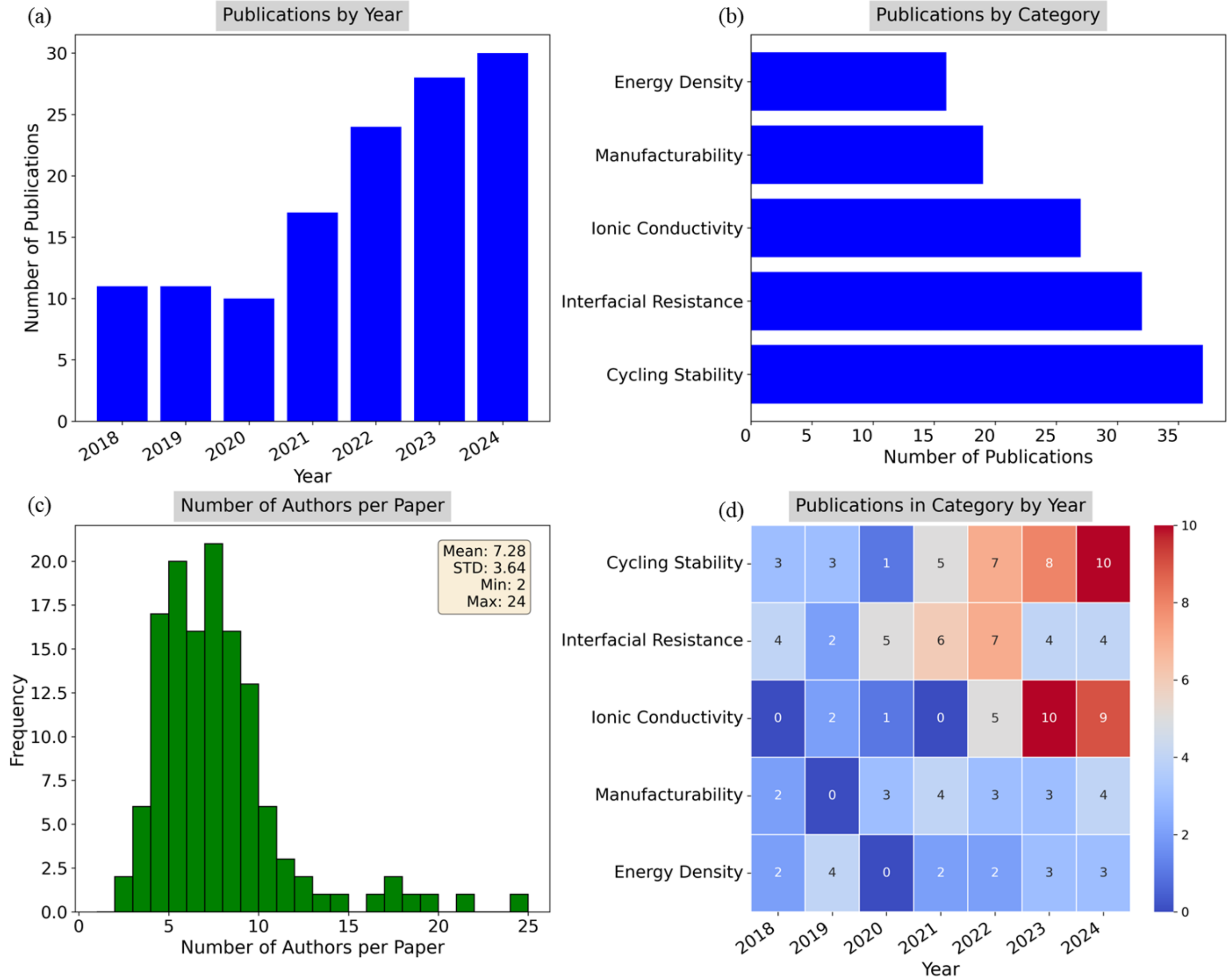


Figure 35: Publications by a) year, b) category, c) author distribution, d) category and year

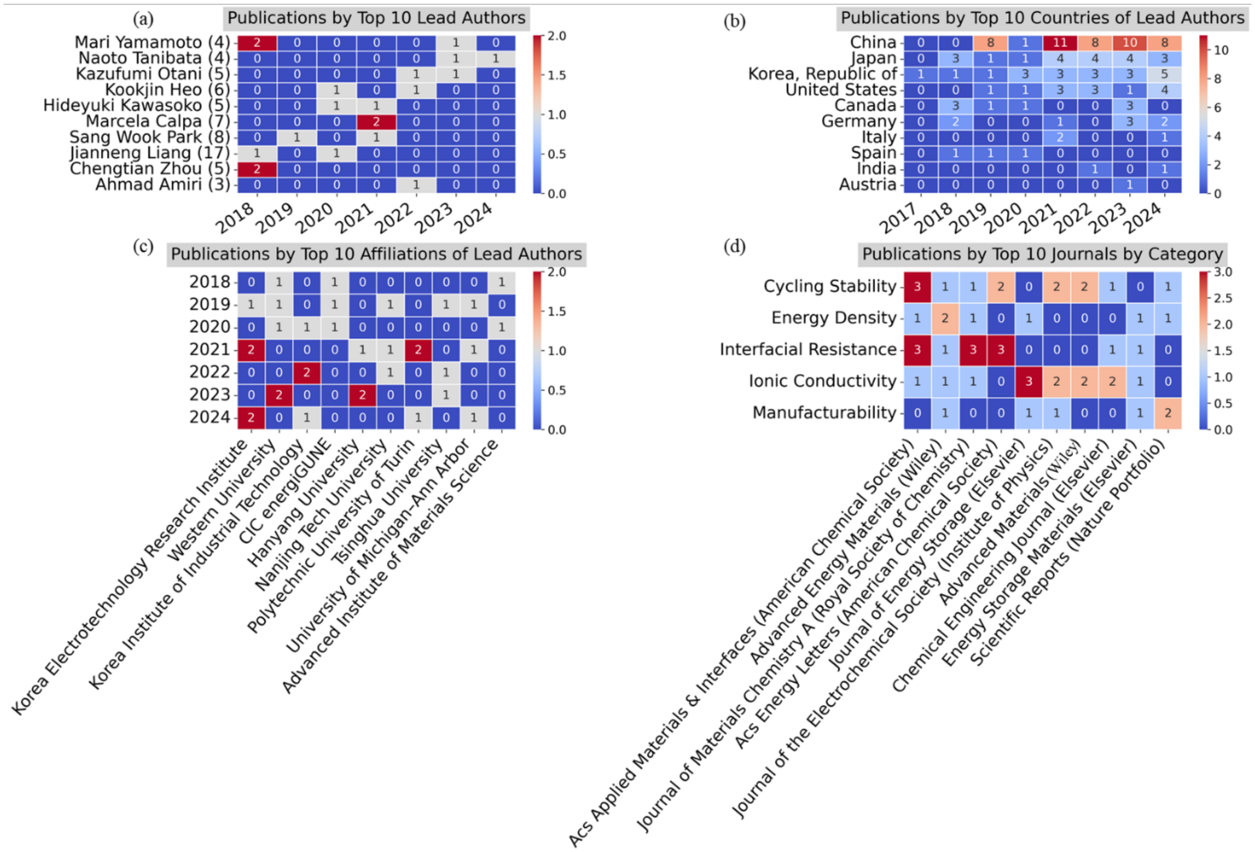


Figure 36: Publications by a) lead authors, b) countries, c) affiliations, and d) category and journal

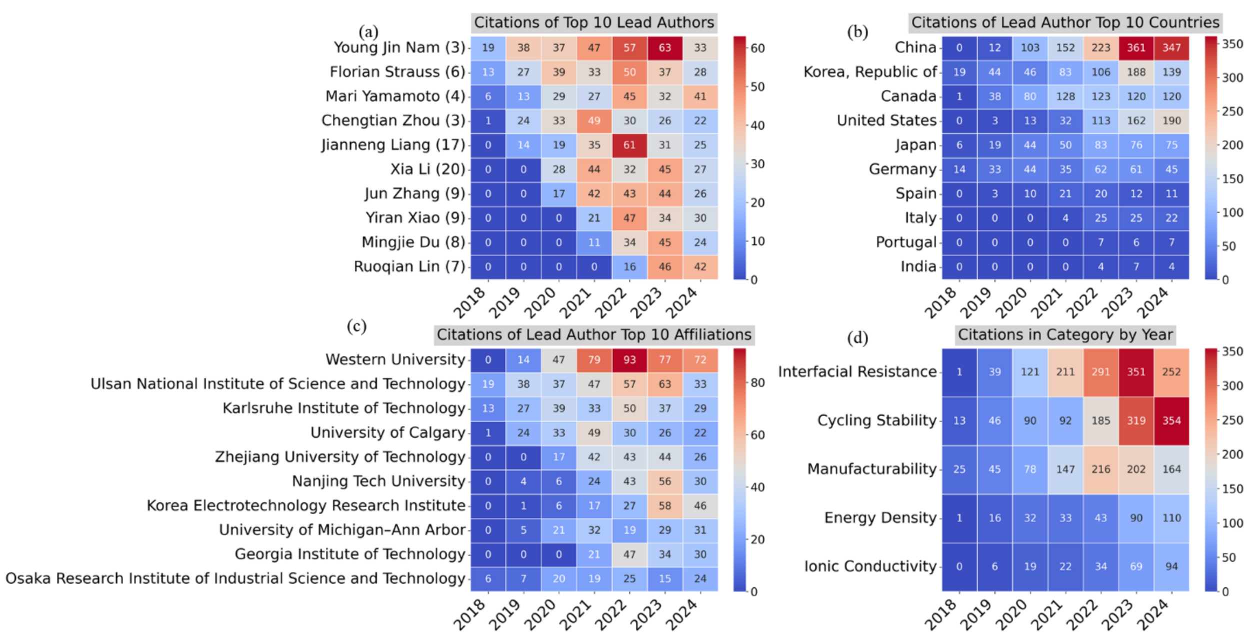


Figure 37: Citations by a) lead authors, b) countries, c) affiliations, and d) category and journal

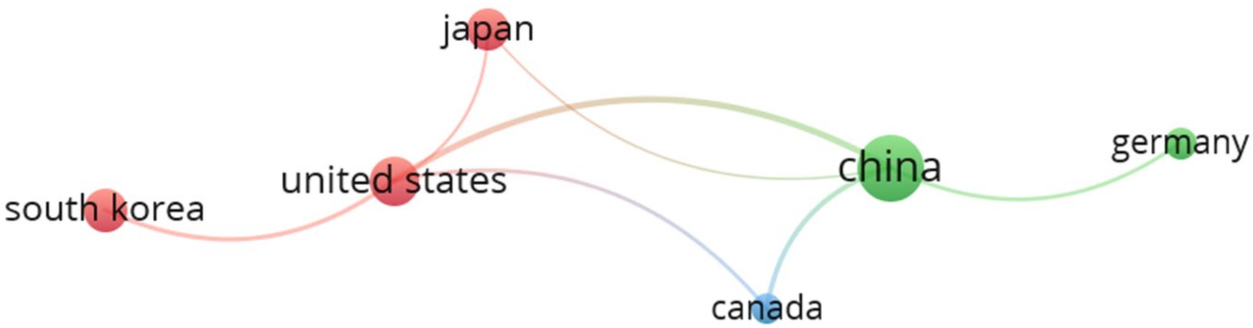


Figure 38: Country co-authorship network

Table 7: Co-authored Publications by Countries

Country	Documents	Citations	TLS
China	51	1,602	17
United States	27	881	17
South Korea	21	637	4
Japan	20	378	3
Germany	12	408	3
Canada	11	632	8

2.1.5 Hydrogen Propulsion Readiness as a Complementary Pathway

This subsection evaluated the readiness of hydrogen-powered aviation technologies as an alternative energy pathway for freight-oriented AAM. The assessment synthesized evidence from a claims-based patent and scientometric analysis (Bridgelall 2025). The objective was to determine whether observed innovation trajectories in hydrogen aviation addressed the fundamental energy-density limitations of battery-electric systems while remaining compatible with the performance, safety, and scalability requirements of freight operations.

The study treated patent claims as direct indicators of commercially protected innovation. This provided a view of practical technology development that complements academic feasibility studies. By focusing on the claims section of patents rather than titles or abstracts, the analysis captured the specific technical solutions that organizations actively pursued toward commercialization. This distinction was critical for technology assessment because claims reflect design choices that developers considered sufficiently mature, valuable, and defensible (Higashide, et al. 2024).

The methodological workflow, shown in Figure 39, illustrates a systematic process of data mining, cleaning, relevance screening, thematic analysis, and scientometric evaluation. The workflow began with Boolean keyword searches across Google Patents, WIPO, and the USPTO claims database. It then converged on the USPTO dataset as a representative proxy for global hydrogen aviation innovation. This figure was central to the methodology because it established transparency and repeatability in tracking innovation readiness. Temporal and geographic analyses revealed rapid growth in hydrogen aviation patenting. Figure 40 shows both country-level distribution and annual growth trends from the Google Patents dataset. This trend indicates a strong linear increase in patent activity after 2021.

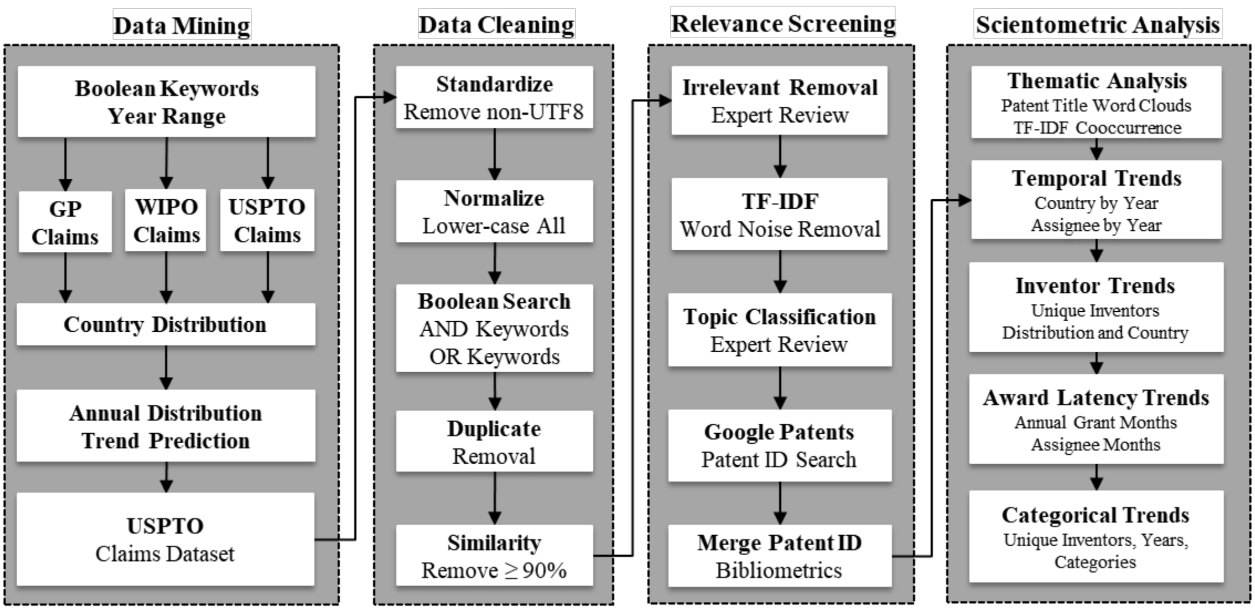


Figure 39: The methodological workflow for hydrogen aviation readiness

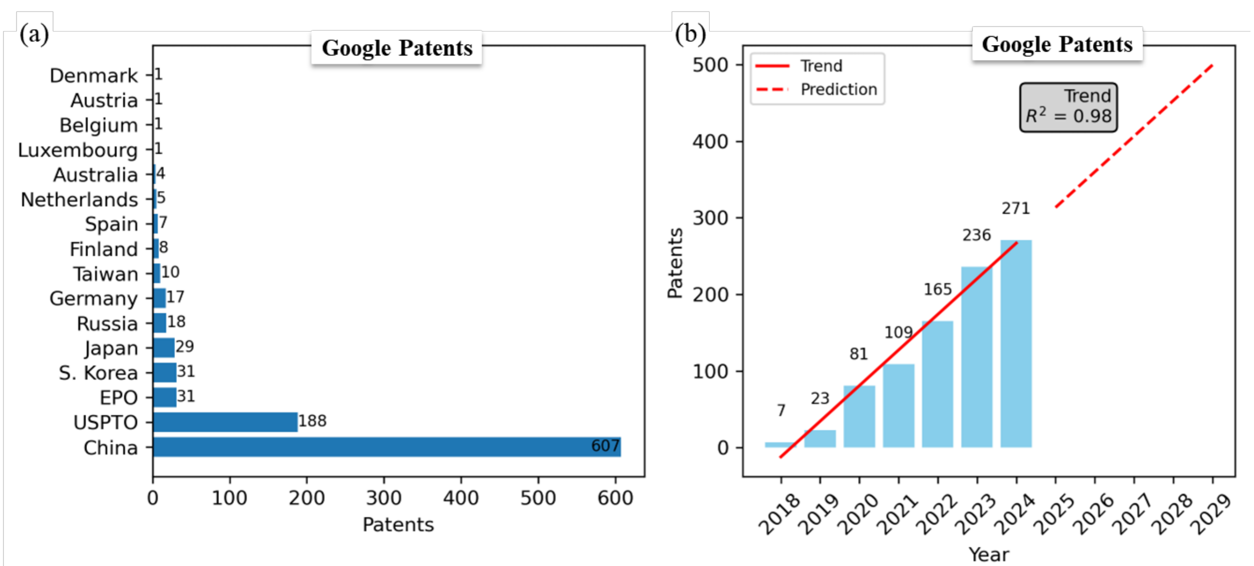


Figure 40: Google Patents results by a) patent office country, and b) year with regression forecast

China and the United States dominated filings, while Europe and South Korea also showed sustained participation. Figure 41 further demonstrates that more than 38% of USPTO-issued hydrogen aviation patents were assigned to non-U.S. entities. This confirmed that foreign applicants prioritized protecting high-value hydrogen aviation innovations in the U.S. market. These figures support the observation that hydrogen aviation is a globally competitive and strategically significant technology domain (Bagarello, Campagna and Benedetti 2024).

After data cleaning and similarity filtering, the study retained 166 relevant patents for detailed analysis, as summarized in Table 8. This table documented the attrition from millions of raw claims to a focused corpus, reinforcing the rigor of the screening process. The retained patents were classified into seven innovation domains: fuel storage, fuel delivery, fuel management, turbine enhancement, fuel cell integration, hybrid propulsion, and safety enhancement. This classification structured the subsequent technology readiness evaluation.

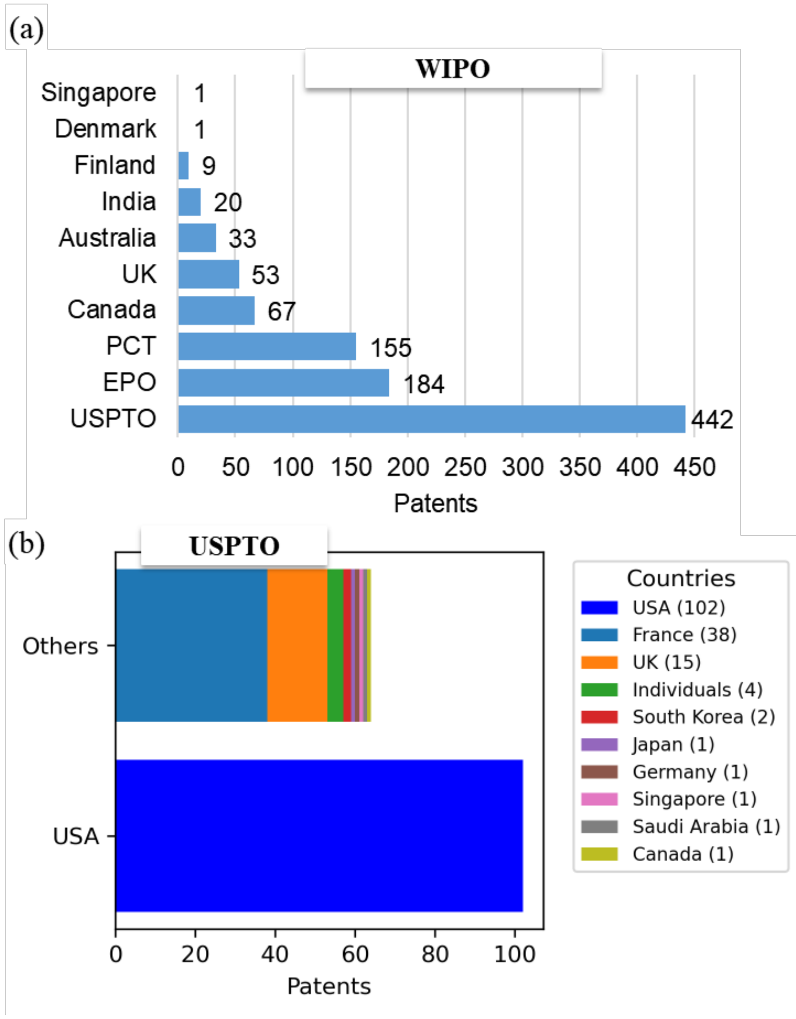


Figure 41: Results from the search engines of a) WIPO, and b) USPTO assignee countries

Table 8: Outcome of the Data Extraction, Data Cleaning, and Relevance Screening.

Procedure	2024	2023	2022	2021	2020	2019	2018	Total
Claims	5,465,182	5,324,681	5,408,479	5,238,192	5,940,592	5,841,994	5,036,914	38,256,034
Patents	373,858	350,097	360,419	348,470	435,901	392,750	341,384	2,602,879
AND kw	778	712	530	496	537	572	534	4,159
OR kw	91	62	24	19	21	22	18	257
- Duplicate	91	62	24	19	21	22	18	257
- Similar	91	60	23	19	20	22	18	253
Relevant	68	43	16	9	11	10	9	166

The invention classification results showed that innovation activity was concentrated in fuel cell integration, hybrid propulsion, and fuel storage. Figure 42a ranked patent volume and unique inventor participation by category. It reveals that fuel cell integration led both measures. This dominance indicated a sustained effort to embed hydrogen fuel cells into aircraft architecture despite known power-density and thermal constraints. Figure 42b tracked category diffusion over time and showed consistent growth in fuel cell integration, hybrid propulsion, and fuel storage. Turbine enhancement exhibited a pronounced spike in 2024. These trends suggest both maturing and emerging focus areas within hydrogen propulsion.

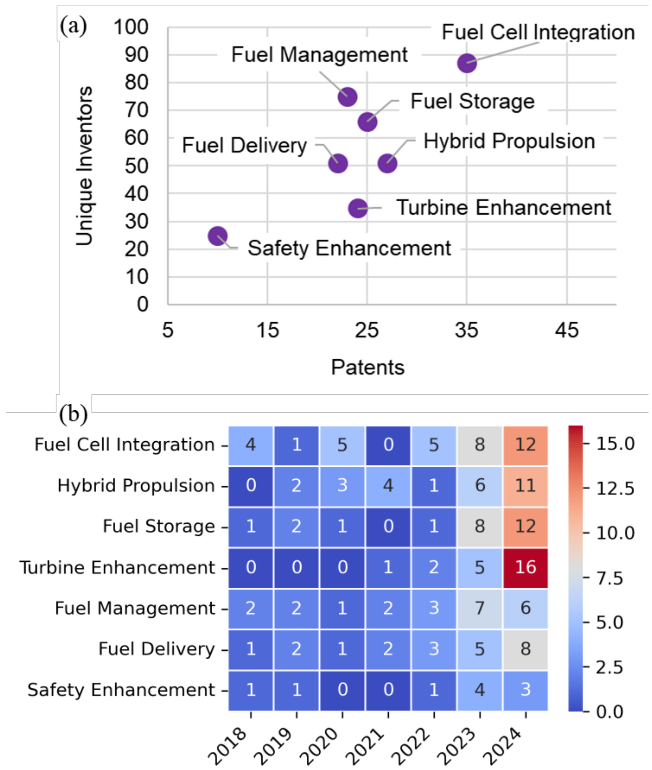


Figure 42: Innovation thrust measures by a) patent category, and b) annual category diffusion

Thematic analysis of patent titles and claims provided insight into the technical nature of these innovations. Figure 43 presents word clouds by invention category. It reveals category-specific design priorities. Fuel storage patents emphasized “cryogenic,” “blended wing,” and “cell device.” This reflects structural integration of hydrogen tanks into airframes to mitigate volumetric energy-density penalties. Fuel delivery patents highlighted “solid storage” and “intercooled turbine.” This indicates efforts to manage hydrogen phase change and thermal conditioning. Hybrid propulsion and fuel cell integration categories emphasized “hybrid electric,” “power density,” and “cell assembly.” This highlight attempts to balance efficiency with thrust and power requirements. These visualizations confirmed that hydrogen aviation innovation addressed multiple interdependent constraints rather than a single dominant bottleneck.

The term co-occurrence network further validated the robustness of the classification. Figure 44 shows three interconnected clusters centered on control and power systems, turbine and engine components, tanks, and fluid handling. Central linking terms such as “heat,” “flow,” and “supply” demonstrated that hydrogen aviation innovations were inherently cross-functional. For freight AAM, this clustering implied that hydrogen propulsion readiness depended on integrated solutions spanning storage, conversion, thermal management, and safety systems. Scientometric analysis provided additional signals of readiness and momentum.

Figure 45 shows USPTO patent awards by country and year. It reveals a sharp increase in issued patents after 2021. This trend indicates accelerating examination and commercialization activity. Organization mapping in Figure 46 identified Airbus, RTX Corporation, Rolls-Royce, Boeing, ZeroAvia, and Alakai Technologies as leading assignees. The coexistence of legacy aerospace firms and emerging startups demonstrated both institutional commitment and entrepreneurial experimentation within hydrogen aviation.

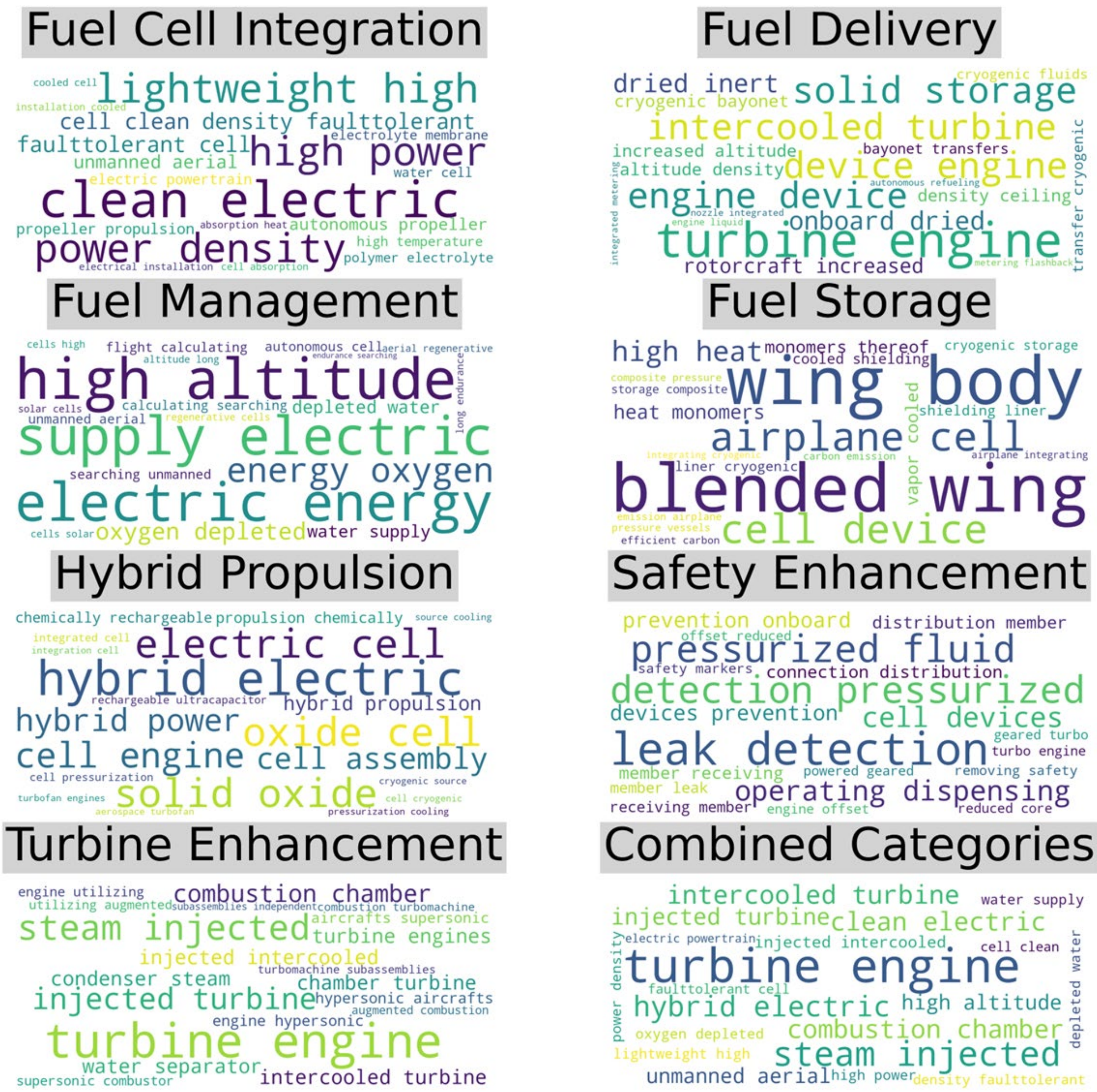


Figure 43: Word cloud of patent titles across invention categories

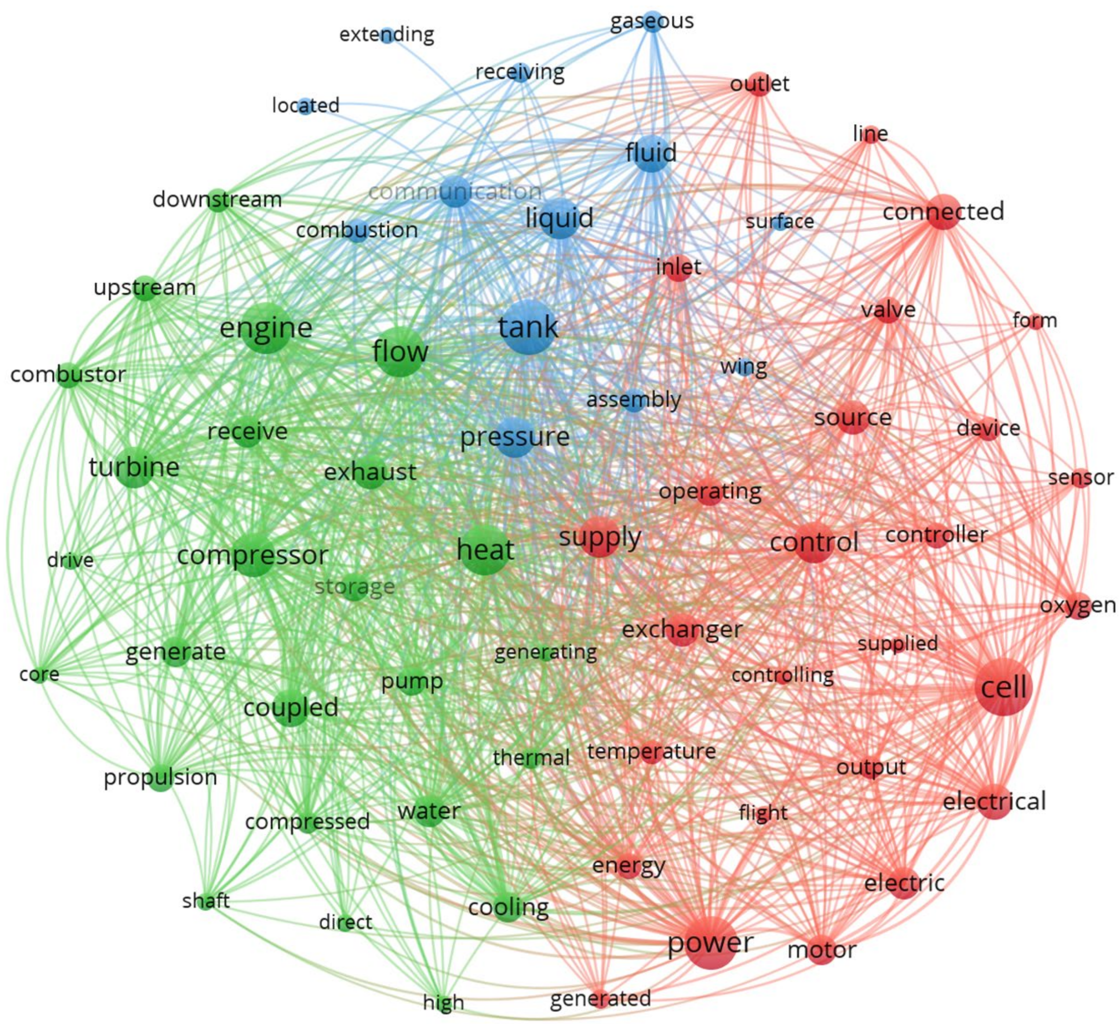


Figure 44: Term co-occurrence network

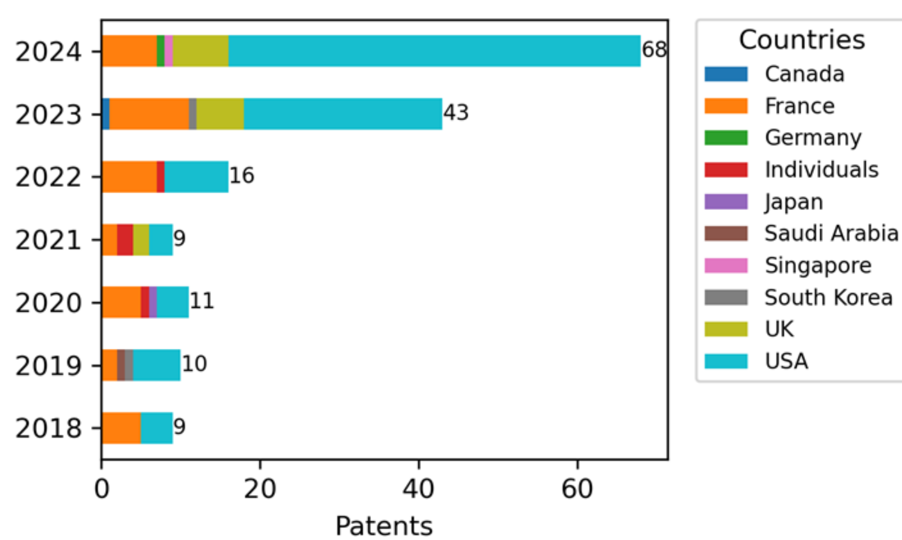


Figure 45: USPTO annual awards by country

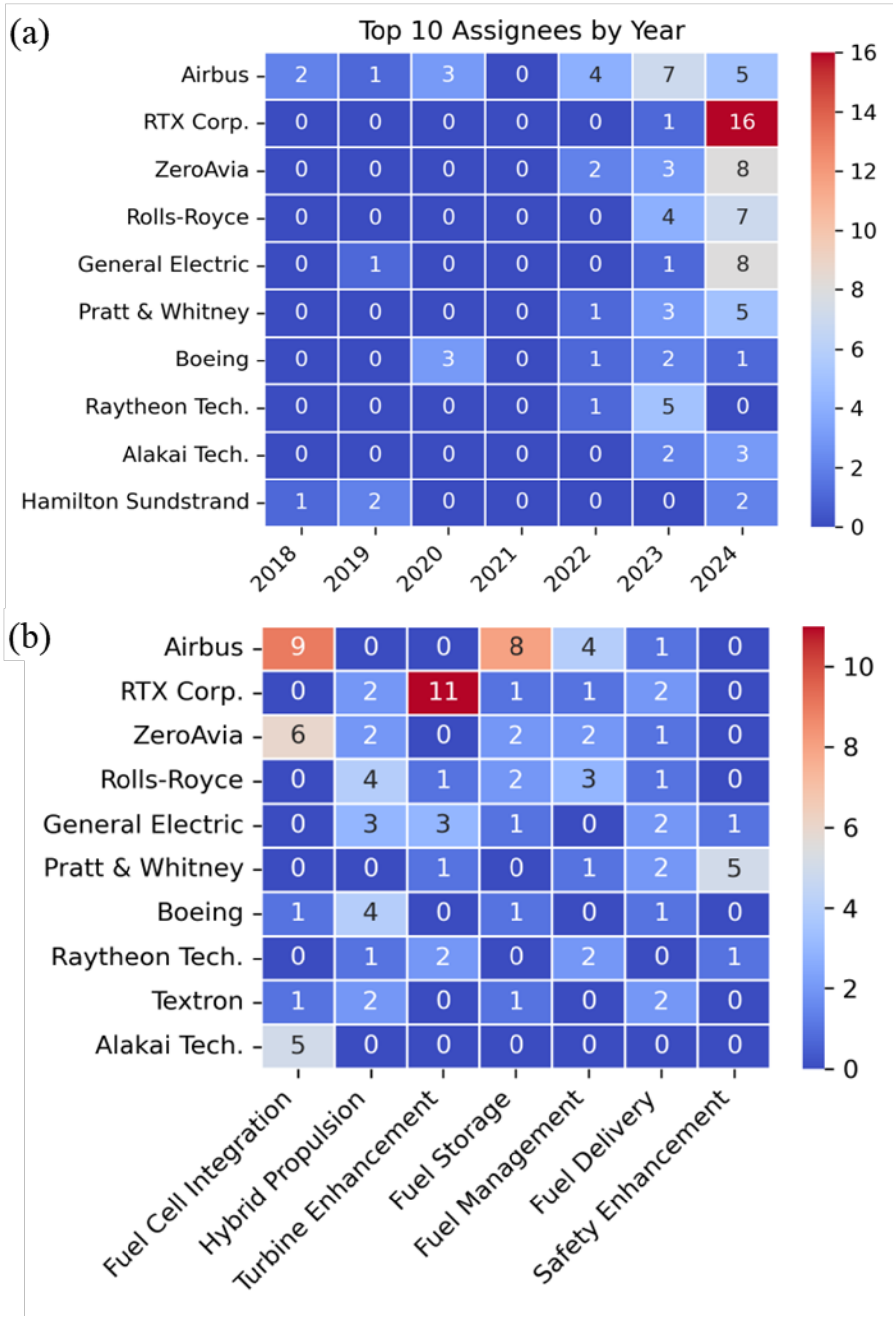


Figure 46: Top 10 key players by a) year, and b) category

Inventor participation patterns reinforced this interpretation. Figure 47 shows increasing inventor counts and expanding international participation. It shows statistically significant differences in team size by country. These patterns indicated growing technical complexity and collaboration intensity.

Latency analysis in Figure 48 and Figure 49 reveal declining time from filing to grant since 2020. This suggests that patent offices increasingly recognized hydrogen aviation technologies and that applicants articulated clearer, more examination-ready claims. Category-level latency comparisons in Figure 50 showed longer grant times for fuel cell integration patents, consistent with higher technical complexity and scrutiny.

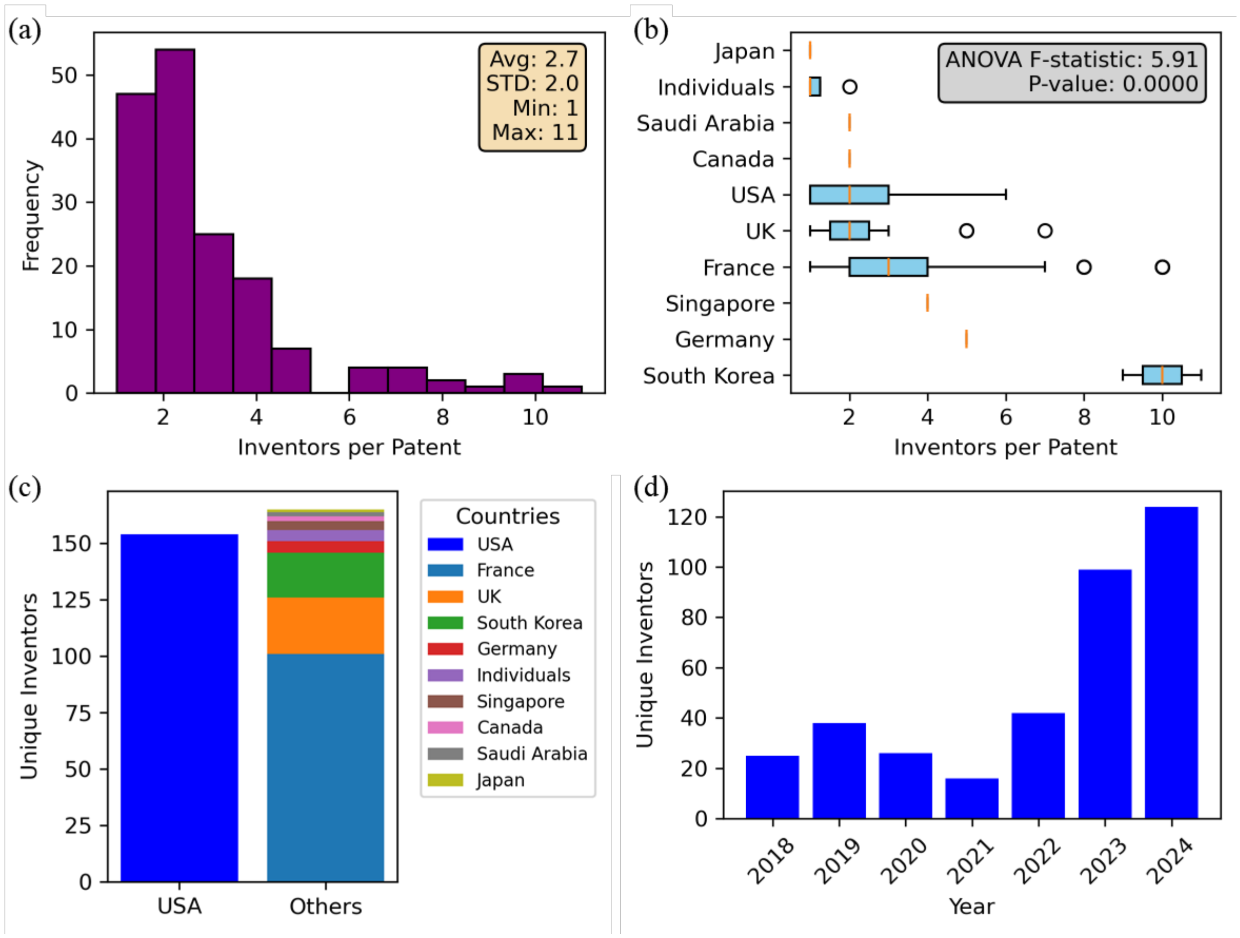


Figure 47: Effort thrust measures by a) distribution of inventors per patent, b) inventors spread by country, c) number of unique inventors by country, and c) number of unique inventors by year

Collectively, the patent and scientometric evidence indicated that hydrogen propulsion had progressed beyond speculative concepts toward structured, commercially oriented innovation. However, the distribution of patent activity also showed that most innovations focused on overcoming integration, storage, thermal, and safety constraints rather than delivering fully aviation-ready systems. For the broader technology assessment, this subsection, therefore, established that hydrogen-powered aircraft represented a promising medium- to long-term pathway for freight-oriented AAM. Hydrogen propulsion offered a credible solution to the gravimetric energy-density limitations of batteries, but it introduced new challenges in volumetric storage, infrastructure, certification, and system complexity. These findings justified treating hydrogen aviation as a complementary pathway in subsequent analyses rather than a near-term substitute for battery-electric AAM. Hence, this subsection provided a defensible, evidence-based foundation for bounding assumptions on range, payload, and deployment timelines when evaluating the potential of AAM to divert freight from ground transportation infrastructure.

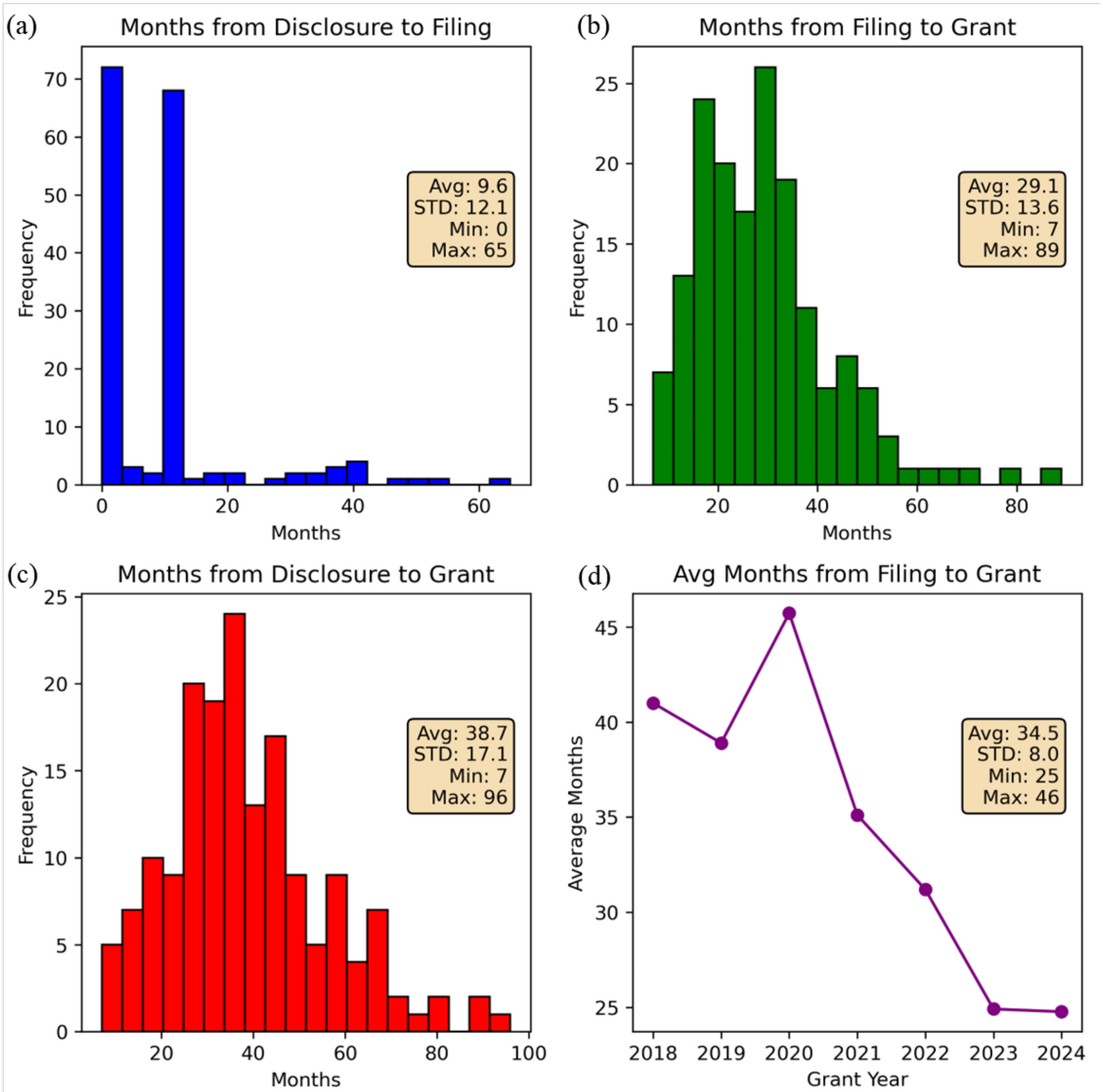


Figure 48: Latency measures a) from disclosure to filing, b) from filing to award, c) disclosure to grant distribution, and c) average latency from filing to grant by award year

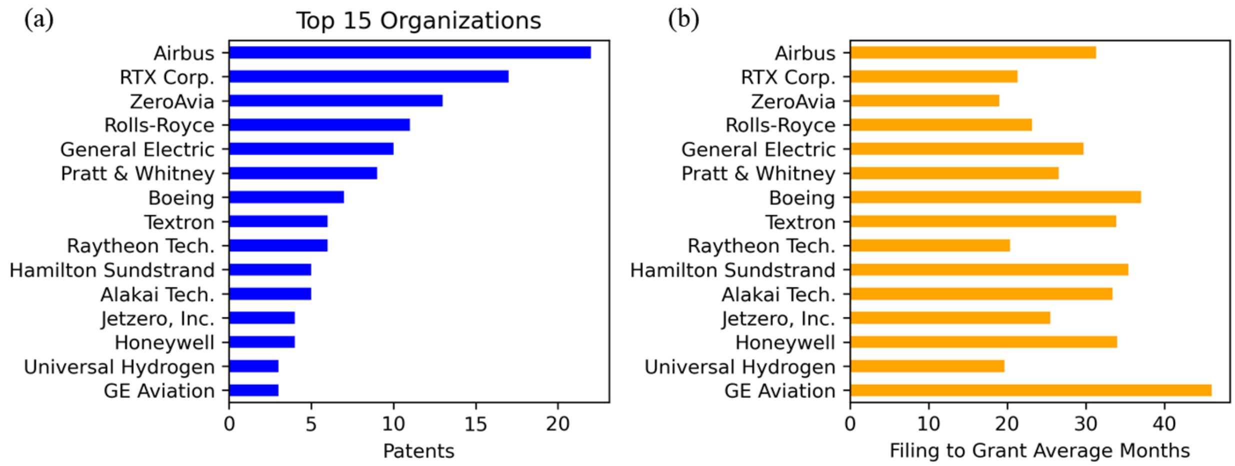


Figure 49: Top 15 organizations by a) production level, and b) latency from filing to grant

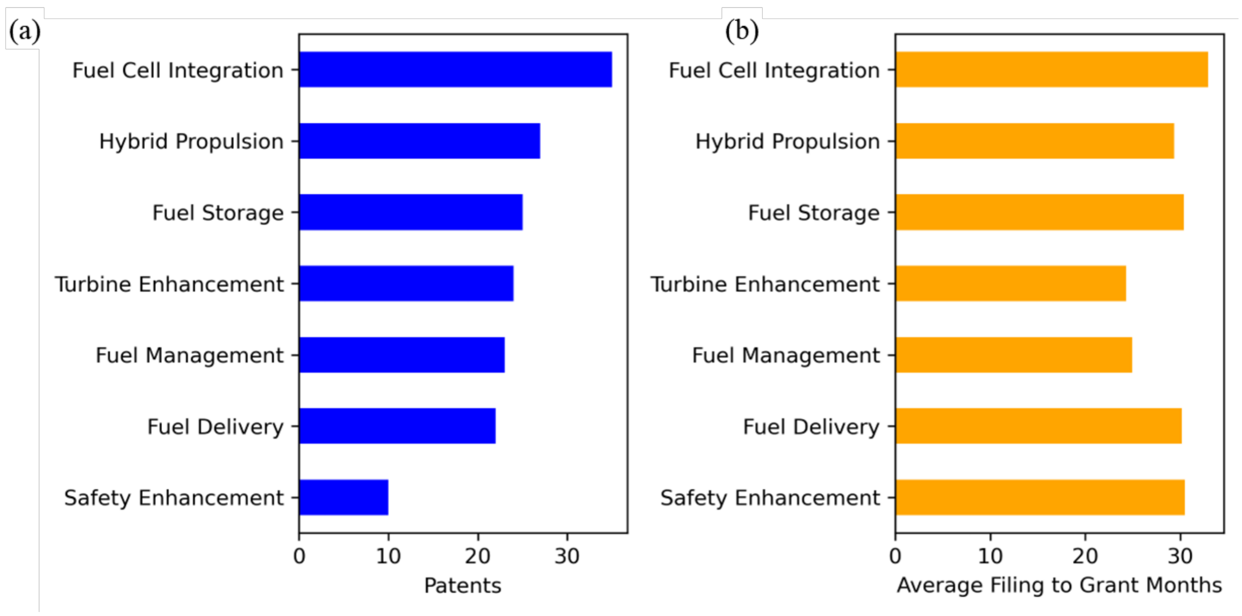


Figure 50: Measures of a) category production level, and b) category latency

2.1.6 Integrated Technology Readiness for Freight Diversion

Synthesizing findings across electrification studies, patent analyses, battery research, hydrogen propulsion, and efficiency modeling yield a coherent technology readiness narrative. Current AAM technologies can support meaningful freight diversion when planners align aircraft capabilities with carefully selected missions and commodities. The literature consistently favors incremental, efficiency-driven deployment over speculative breakthroughs. This technology assessment establishes conservative yet actionable performance bounds that inform subsequent market analysis, infrastructure evaluation, and regulatory review. By grounding the broader study in empirically observed innovation trajectories and validated performance relationships, this research maintains that infrastructure preservation goals remain achievable within realistic technological constraints.

2.2 Market Analysis

2.2.1 Identifying High-Value, Freight-Ready AAM Opportunities

This subsection evaluates the market potential for freight-oriented AAM by synthesizing results from a publication of this research (Bridgelall 2023). The analysis established where, what, and how much freight could realistically shift from trucks to air, with the explicit objective of reducing highway truck miles and preserving surface transportation infrastructure. The study framed market identification as a data-driven problem under uncertainty, rather than a speculative forecasting exercise. It used observed commodity flows to determine which freight segments already exhibited air-compatible characteristics and, therefore, represented low-friction entry points for AAM adoption. This framing aligned directly with infrastructure preservation goals because it prioritized substitution of truck movements that were both frequent and energy intensive.

Commodity Market Identification: What Freight Is Suitable for AAM?

The first stage of the market analysis identified commodity categories with the strongest propensity for air transport based on value–weight characteristics. Using the Freight Analysis Framework (FAF5.5) (FHWA 2021), the study evaluated 2.4 million multimodal freight records and applied three mature unsupervised machine-learning algorithms to cluster commodities in value–weight space. The clustering algorithms were k-means, Louvain, and DBSCAN. The clustering workflow, summarized in Figure 51, structured the analysis around three sequential questions: *what* commodities to target, *where* to deploy services, and *how* to select feasible origin–destination (OD) pairs. This figure provided a clear conceptual bridge between raw freight data and actionable market insights.

Comparative clustering results in Figure 52 showed that k-means produced the most interpretable separation between high-value/low-weight and low-value/high-weight commodities for both truck and air modes. Based on these results, the study selected four commodity categories that consistently appeared in high-value clusters: mixed goods, electronics, machinery, and pharmaceuticals. The distribution of these categories across modes is illustrated in Figure 53, while their relative value proportions appear in Figure 54.

Table-based analysis reinforced the magnitude of this opportunity. Table 9 shows that the four selected commodity categories accounted for 30.7% of total freight value but only 5% of total freight weight in the contiguous United States. In 2017 alone, these commodities required the equivalent of 28.3 million semi-trailer truckloads. This highlights a substantial opportunity for modal substitution. Because these commodities are time-sensitive, high-value, and frequently shipped, they represent the most economically defensible early markets for cargo drones (ACI 2019) (IATA 2022) (Pak 2022).

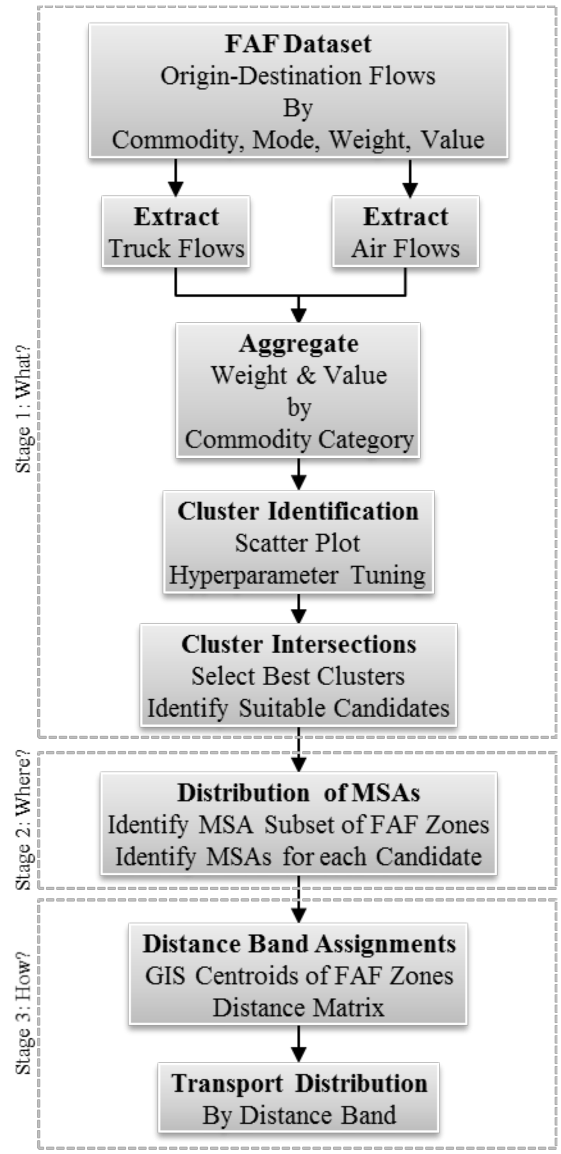


Figure 51: Three-stage data mining workflow

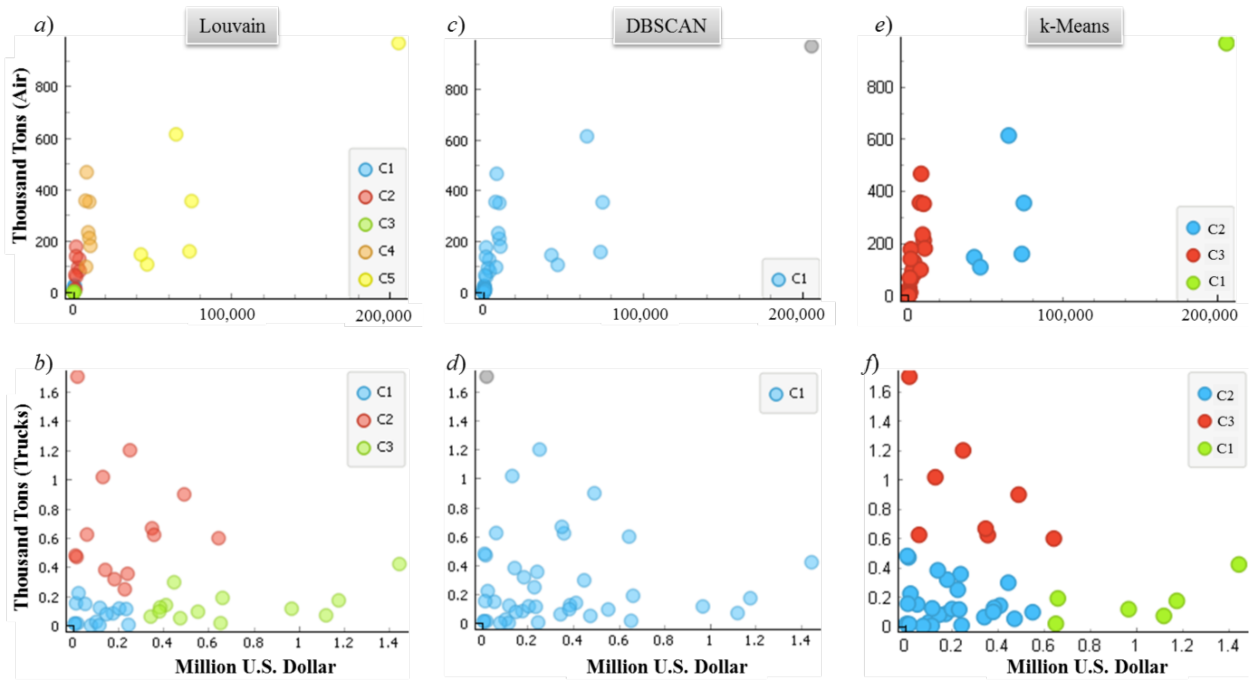


Figure 52: Comparison of clustering results for Louvain (a-b), DBSCAN (c-d), and k-means (e-f)

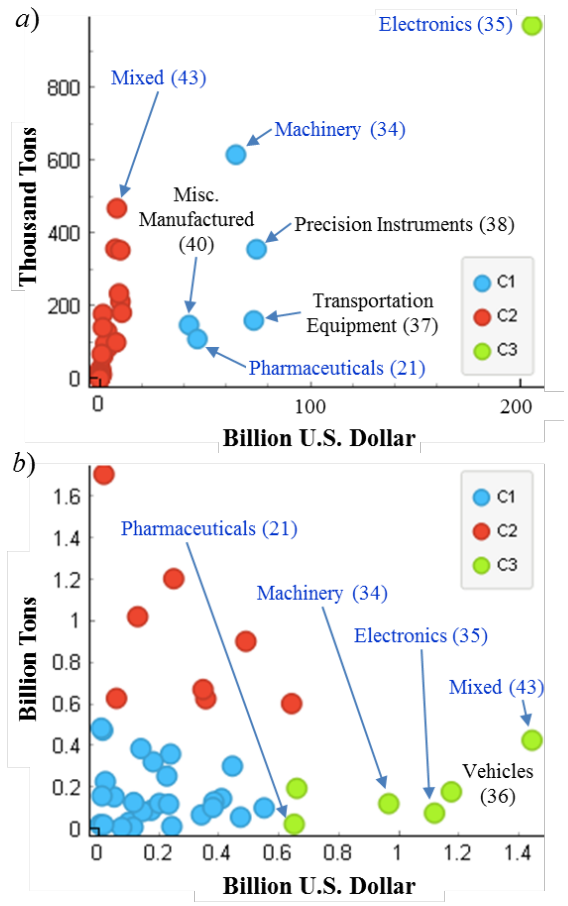


Figure 53: k-means clustered high-value, low-weight commodity categories transported via a) air, and b) trucks

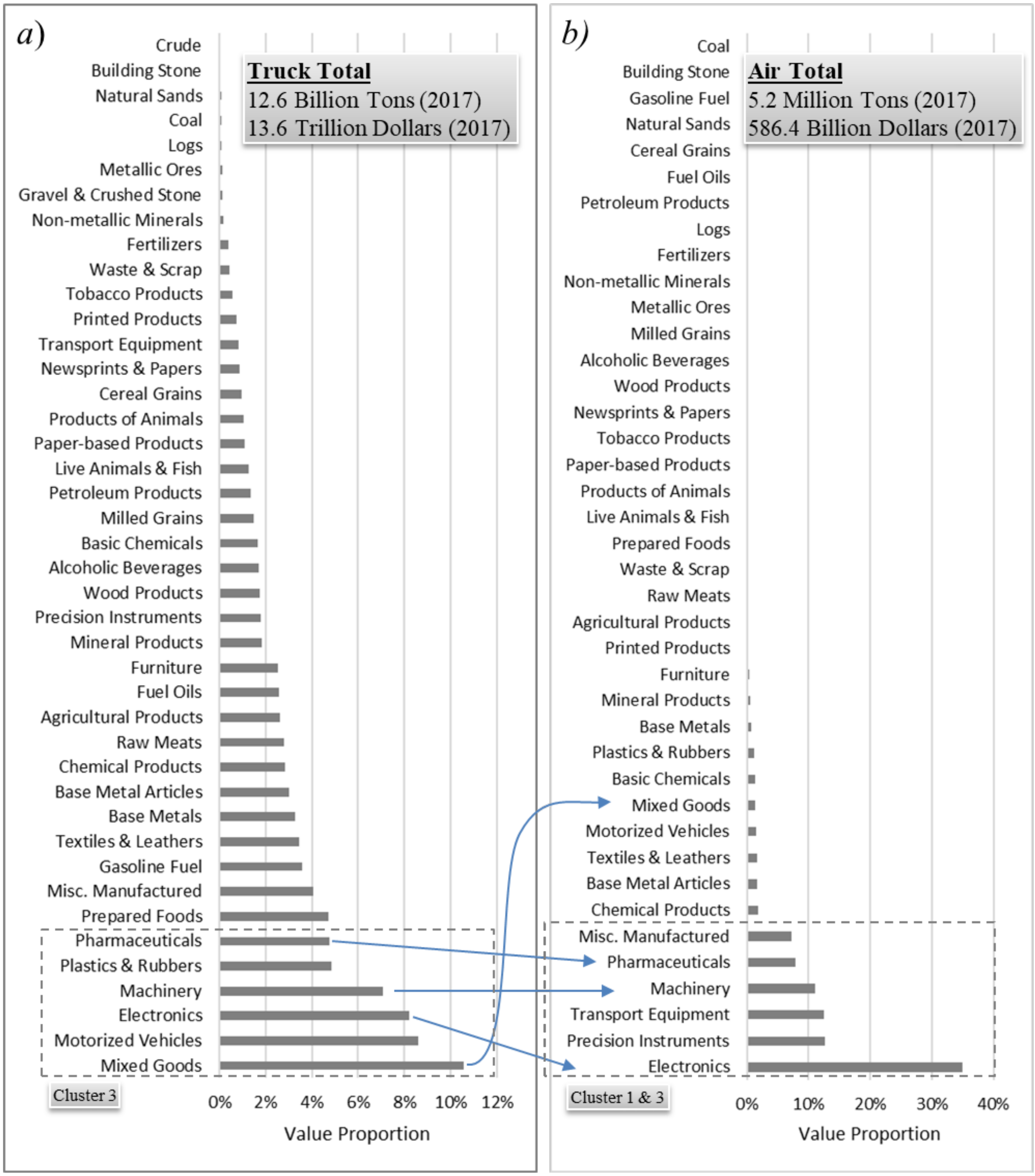


Figure 54: Commodity category distribution by value proportion carried by a) trucks, and b) air

Table 9: Commodity Categories Selected for Spatial Demand Analysis

Commodity	Million Tons	Trillion Dollars	% KTons	% $M	Rank Truck	Rank Air	Truckload Equivalent
Mixed Goods	424.2	1.44	3.3%	10.6%	1	11	18,851,782
Electronics	73.2	1.12	0.6%	8.2%	3	1	3,253,678
Machinery	118.8	0.97	0.9%	7.1%	4	4	5,280,730
Pharmaceuticals	19.8	0.65	0.2%	4.8%	6	5	882,067
Total	636.0	4.2	5.0%	30.7%			28,268,257
All Commodities	12,669.0	13.6					563,065,851

Spatial Market Concentration: Where Demand Is Highest?

The second stage of the analysis examined spatial concentration of demand to identify where AAM deployment would yield the greatest immediate impact. The study focused on metropolitan statistical areas (MSAs) as candidate service nodes because of their high freight density, trade significance, and logistical centrality. Using FAF zone metadata, the workflow identified 83 MSAs among 129 FAF zones. The geographic distribution of these MSAs—and their centroids—is shown in Figure 55, which also documented necessary corrections to FAF zone codes summarized in Table 10. These preprocessing steps were critical to ensuring spatial accuracy in subsequent distance and flow calculations.

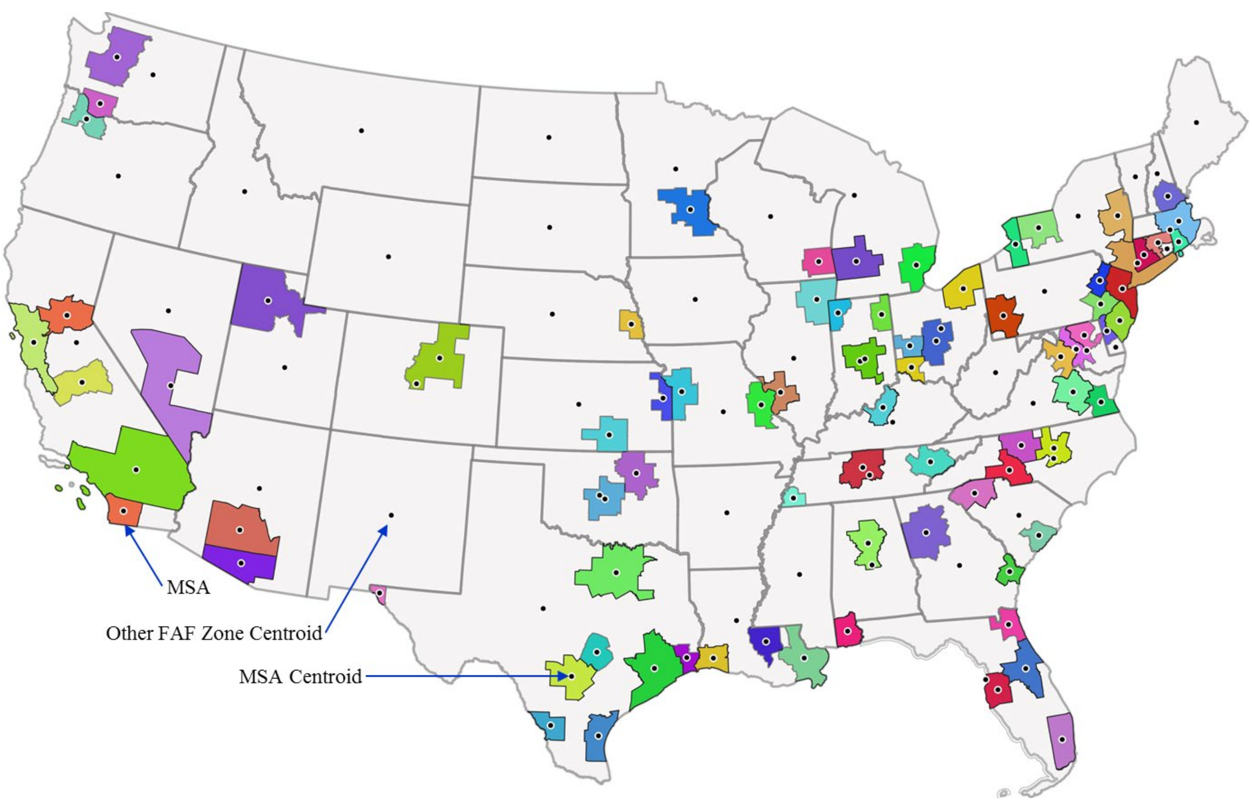


Figure 55: MSAs, other FAF Zones, and their centroids

Table 10: Mismatched FAF Zone Codes in the CFSG Database

CFS Area Name	CFS Code Replaced	FAF Code Substituted
Fresno-Madera, CA CFS Area	69	65
Philadelphia-Reading-Camden, PA-NJ-DE-MD (DE Part)	100	101
Philadelphia-Reading-Camden, PA-NJ-DE-MD (NJ Part)	349	342
Remainder of Delaware	100	109
Fort Wayne-Huntington-Auburn, IN	189	183
Wichita-Arkansas City-Winfield, KS	209	202
Louisville/Jefferson County-Elizabethtown-Madison, KY-IN (KY Part)	211	212
Cincinnati-Wilmington-Maysville, OH-KY-IN CFS Area (KY Part)	219	211
Omaha-Council Bluffs-Fremont, NE-IA (NE Part)	310	311
Remainder of Nebraska	310	319
Boston-Worcester-Providence, MA-RI-NH-CT (NH Part)	330	331
Remainder of New Hampshire	330	339
New York-Newark, NY-NJ-CT-PA (PA Part)	429	423
New York-Newark, NY-NJ-CT-PA (NJ Part)	349	341
Knoxville-Morristown-Sevierville, TN	479	473
Portland-Vancouver-Salem, OR-WA (WA Part)	539	532

Weight distributions by commodity and MSA, presented in Figure 56, revealed pronounced concentration in a small number of regions. Trucks serving the Los Angeles, Dallas-Fort Worth, Houston, Chicago, New York, Atlanta, San Francisco, and Tampa MSAs moved disproportionately large volumes of the four selected commodities. Table 11 quantified this concentration, showing that these eight MSAs alone accounted for 20.1% of the national weight of the selected commodities. This spatial concentration matters for infrastructure preservation because it implies that targeted AAM deployment at a limited number of high-impact nodes could displace a large share of long-haul and regional truck traffic, rather than requiring ubiquitous national coverage (USDOT 2020) (FHWA 2021).

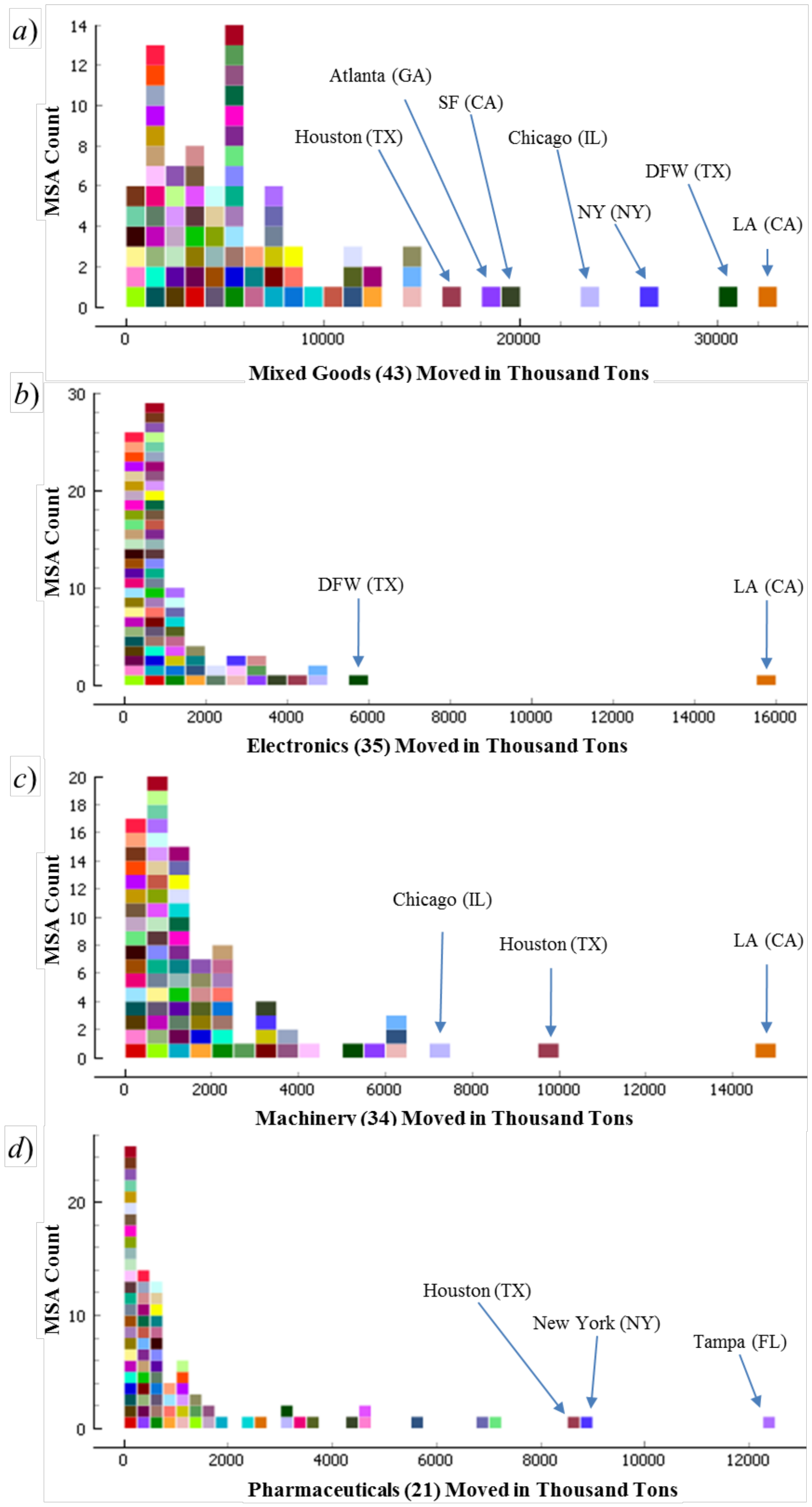


Figure 56: MSA weight distribution of a) mixed goods, b) electronics, c) machinery, and d) pharmaceuticals

Table 11: Commodity Weight Moved in the Top MSAs

MSA	Pharmaceuticals	Machinery	Electronics	Mixed Goods	Total KTons
Los Angeles, CA	2,725.7	14,866.3	15,523.6	32,170.3	65,286.0
San Francisco, CA	4,441.2	3,331.6	3,707.0	19,142.1	30,622.0
Tampa, FL	12,360.8	759.9	1,040.1	7,532.0	21,692.8
Atlanta, GA	411.1	5,975.9	3,195.6	18,506.3	28,088.8
Chicago, IL	3,026.0	7,069.2	4,867.2	23,411.6	38,374.0
New York, NY	8,794.0	3,132.8	2,646.3	26,132.2	40,705.3
Dallas-Fort Worth, TX	3,061.4	5,071.5	5,716.2	30,506.5	44,355.6
Houston, TX	8,724.7	9,928.9	4,367.9	16,874.2	39,895.7
Total	43,545.0	50,136.1	41,064.0	174,275.2	309,020.2
CONUS	302,783.0	237,632.8	146,415.5	848,330.2	1,535,162
Top MSA %	14.4%	21.1%	28.0%	20.5%	20.1%

Distance Feasibility: How Much Freight Falls Within AAM Range?

The third stage of the market analysis evaluated distance feasibility, which directly constrained the fraction of truck freight that AAM could realistically replace. Using GIS-based centroid-to-centroid distances between FAF zones, the study constructed a complete OD distance matrix and truncated flows into discrete distance bands. Truckload-equivalent flows across distance bands appear in Table 12, while the cumulative distribution is visualized in Figure 57. The results showed that 80.5% of truckload equivalents among the top eight MSAs occurred within 400 miles, with nearly 40% occurring within 100 miles. This finding was central to the market assessment because it aligned observed freight demand with plausible near- to mid-term cargo drone range capabilities, given known energy-density constraints discussed earlier in the technology assessment (Schwab, et al. 2021). The analysis, therefore, avoided speculative assumptions about long-range performance and instead grounded market sizing in achievable operational envelopes.

Table 12: Truckload Equivalent Flows Between the Top MSAs

Miles Band	Mixed Goods	Electronics	Machinery	Pharma	Total	%	% Acc
100	2,583,396	299,612	419,312	80,519	3,382,840	39.3%	39.3%
200	1,357,662	257,587	288,219	44,434	1,947,902	22.6%	61.9%
300	591,588	154,589	236,029	46,440	1,028,646	12.0%	73.9%
400	326,591	122,995	98,965	14,829	563,380	6.5%	80.5%
Totals	4,859,238	834,782	1,042,526	186,222	6,922,768	80.5%	

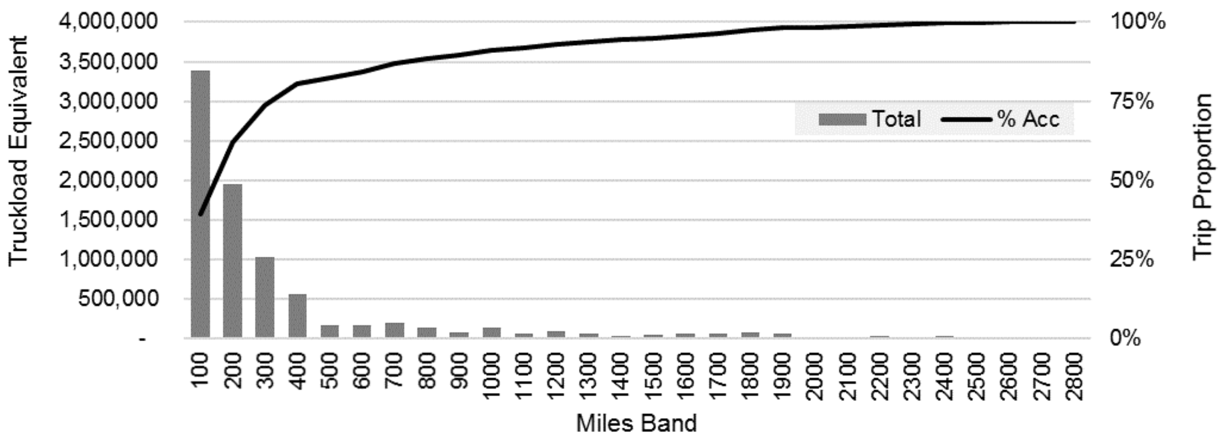


Figure 57: Truckload equivalent and accumulated trip proportion for the selected commodities and MSAs

Market Implications for Infrastructure Preservation

Collectively, the figures and tables in this section demonstrated that the AAM freight market was highly structured rather than diffuse. A small set of commodity categories, a limited number of MSAs, and a bounded distance range accounted for a disproportionate share of truck movements. This structure supported a phased deployment strategy in which cargo drones first target high-value middle-mile corridors before expanding to broader networks.

From an infrastructure perspective, the study established that even partial adoption could yield outsized benefits. The four identified commodity categories alone were projected to experience a 35% increase in truck volumes by 2040 if current trends persisted (USDOT 2020). Diverting even a fraction of these flows to air would reduce pavement loading, congestion, emissions, and exposure to hazardous incidents, particularly in freight-intensive corridors (ATRI 2020). Within the overall report, this subsection provides the empirical foundation for linking technology readiness to deployable demand. It demonstrates that viable AAM freight markets already exist within current performance limits and that targeted deployment can advance the primary objective of preserving ground transportation infrastructure while enabling secondary benefits in reliability, safety, and sustainability.

2.2.2 Dangerous Goods as a High-Impact Early AAM Freight Market

This subsection evaluates dangerous goods (hazardous materials) as a priority market segment for freight-oriented AAM (Bridgelall 2022). The analysis establishes why hazardous materials constitute a uniquely compelling early market for AAM, where safety risk reduction and infrastructure preservation reinforce economic viability. The study frames hazardous materials transport as a systemic risk problem rather than a pure logistics optimization problem. Ground transport of hazardous materials exposes dense populations and critical infrastructure to low-probability but high-consequence events. This is despite extensive regulation under Title 49 of the Code of Federal Regulations (NARA 2022). Historical data cited in the study showed more than 189,000 non-pipeline hazmat incidents in the United States between 2012 and 2021. These resulted in fatalities, injuries, and nearly $827 million in property damage (PHMSA 2022). Roadways accounted for the majority of incidents (Yilmaz, Serpil and Aplak 2016). These risks motivated the market analysis to focus on commodities where removing freight from roads delivered disproportionate societal benefit.

Table 13 summarizes the nine hazmat classes defined by the U.S. Pipeline and Hazardous Materials Safety Administration (PHMSA).

Table 13: Classification of Dangerous Goods

Class	Description & Examples	Typical Uses	Risks
Explosives	Substance, article, or device that can explode. Examples: gunpowder, safety flares, and fireworks.	War, demolition, mining, avalanche control (McCormack 2008).	Explosion triggered by heat, radiation, vibration, or chemical reaction.
Gases	Non-solid and non-liquid matter. Examples: butane, aerosols, oxygen, methane, acetylene, carbon monoxide and hydrogen sulfide.	Industrial uses, cooking grills, household cleaners, cosmetics.	Accidental release from pressurized containers, and possible contact with ignition sources.
Flammable Liquids	Liquids with flash points between 100°F and 140°F. Examples include gasoline, acetone, toluene, diethyl ether, and alcohols.	Fuels, cleaning solutions, paints, polishes, varnishes, adhesives, paint thinners.	Exposure to heat can bring a liquid to its flash point (release of vapor) when ignition can occur.
Flammable Solids	Ignitable solids. Examples: alkali, coal, carbon, magnesium, metallic hydrides, sulfur, cellulose nitrate, matches.	Battery manufacturing, cooking, composting.	Ignitable by heat, friction, contact with other substances such as oxidants or acids.
Oxidizing Substances & Organic Peroxides	Chemicals that oxidize other substances and/or provide fuel to burn. Examples: ammonium nitrate, potassium nitrate, nitric acid, halogens, and potassium bromate.	Manufacturing of plastics and rubbers and agricultural uses such as fertilizers.	Unstable—prone to exothermic decomposition (Oxley, et al. 2002).
Toxic and Infectious Substances	Poisons, infectious, and irritating materials. Examples: bacteria, blood samples, cyanide, methyl bromide, tear gases, medical waste, and forensic materials.	War, pesticides, medicines, fuel additives, disinfectants.	Accidental releases can harm humans.
Radioactive Material	Materials with specific activity greater than 0.002 microcuries per gram. Examples: Cobalt-60, Americium-241, Cesium-137, Iridium-192, and Plutonium-239.	Weapons manufacturing, power production, smoke alarms, and medical imaging (Galatas 2020).	Accidental releases can harm humans.
Corrosive Substances	Chemicals that destroy materials or cause irreversible alterations of living tissue. Examples: sulfuric acid, sodium hydroxide, hydrofluoric acid, and some battery fluids.	Cleaning solutions, drain unclogging, paint stripping.	Accidental release can cause severe burning and irritation of human skin.
Other	Examples: batteries (lithium-ion, lithium metal), magnetized material, asbestos, dry ice.	Batteries for electric vehicles, electronics, electric scooters, drones.	Known to be combustible under certain circumstances.

The table includes examples, typical uses, and associated risks. The table links abstract commodity codes in freight datasets to real-world safety consequences, including explosion, toxicity, environmental contamination, and long-term public health impacts (Saccomanno and Shortreed 1993) (Bondžić, et al. 2021) (Jacqz 2022).

For market quantification, the study focused on basic chemical materials (BCMs) within the FAF. This commodity category captured a large share of non-pipeline hazardous goods such as acids, hydrocarbons, peroxides, rare gases, and radioactive elements. This choice was methodologically justified because BCMs represented dangerous goods that currently rely heavily on truck and rail transport rather than pipelines. Hence, this presents immediate opportunities for modal substitution.

The market analysis employed a hybrid data mining (HDM) workflow that combined unsupervised machine learning and geospatial processing. The workflow, documented in Figure 58, transformed raw FAF commodity flow records into spatially explicit demand clusters.

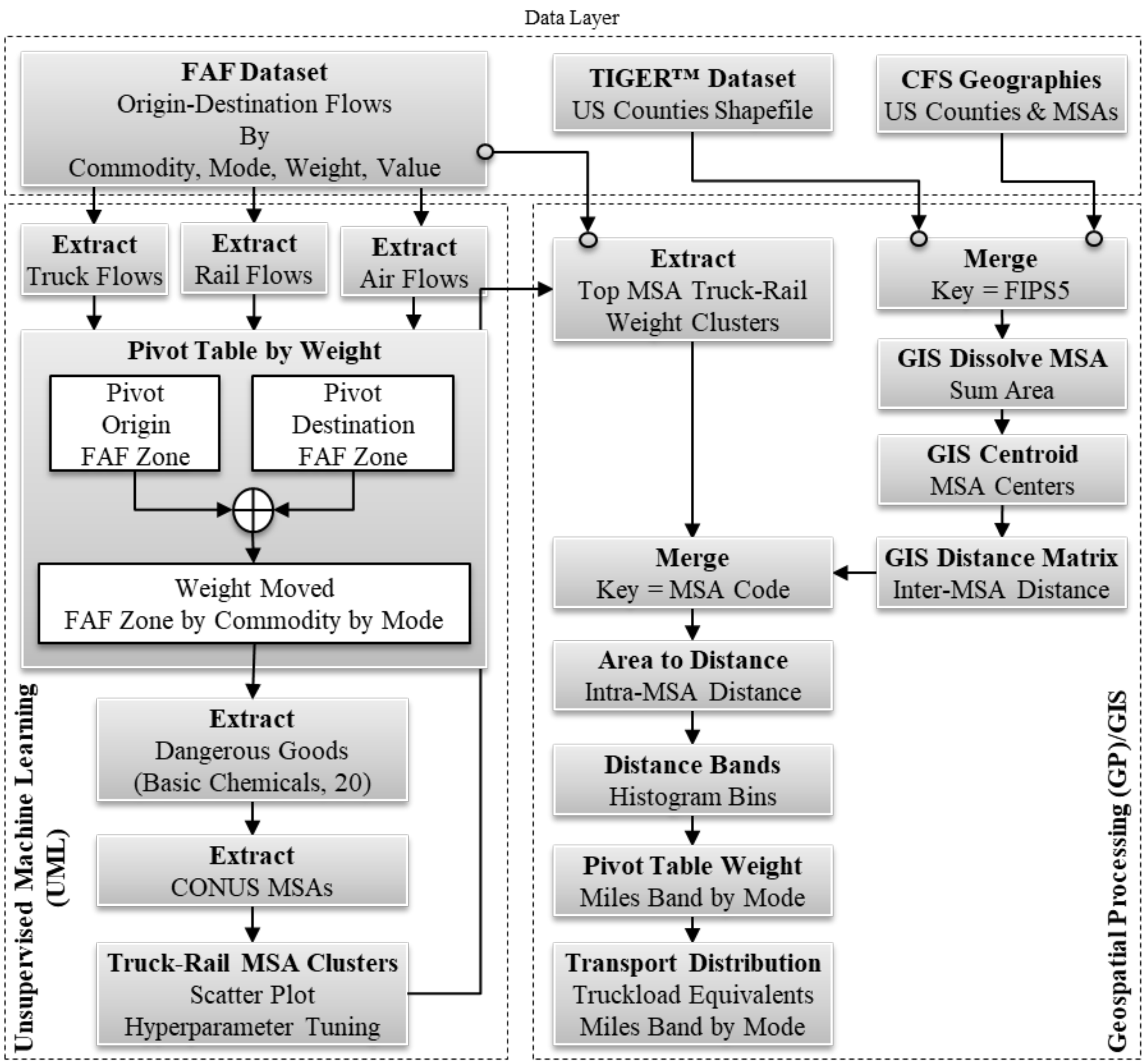


Figure 58: The HDM workflow to analyze hazardous material flows

This workflow demonstrates how market identification progressed from national-scale freight data to a small, actionable set of deployment locations using a reproducible method (Burkov 2019) (Kelleher, Namee and D'Arcy 2020). The study focused on MSAs (Figure 55) because accidents involving hazardous materials in dense urban regions amplified potential harm, economic disruption, and infrastructure impacts (Grieco, et al. 2018) (Amundsen, Hansen and Whitta-Jacobsen 2022).

To identify priority markets, the study applied DBSCAN, Louvain, and k-means clustering to MSA-level BCM flows across truck, rail, and air modes. Visual comparison in Figure 59 shows that DBSCAN most effectively isolated outlier MSAs with exceptionally high BCM movements.

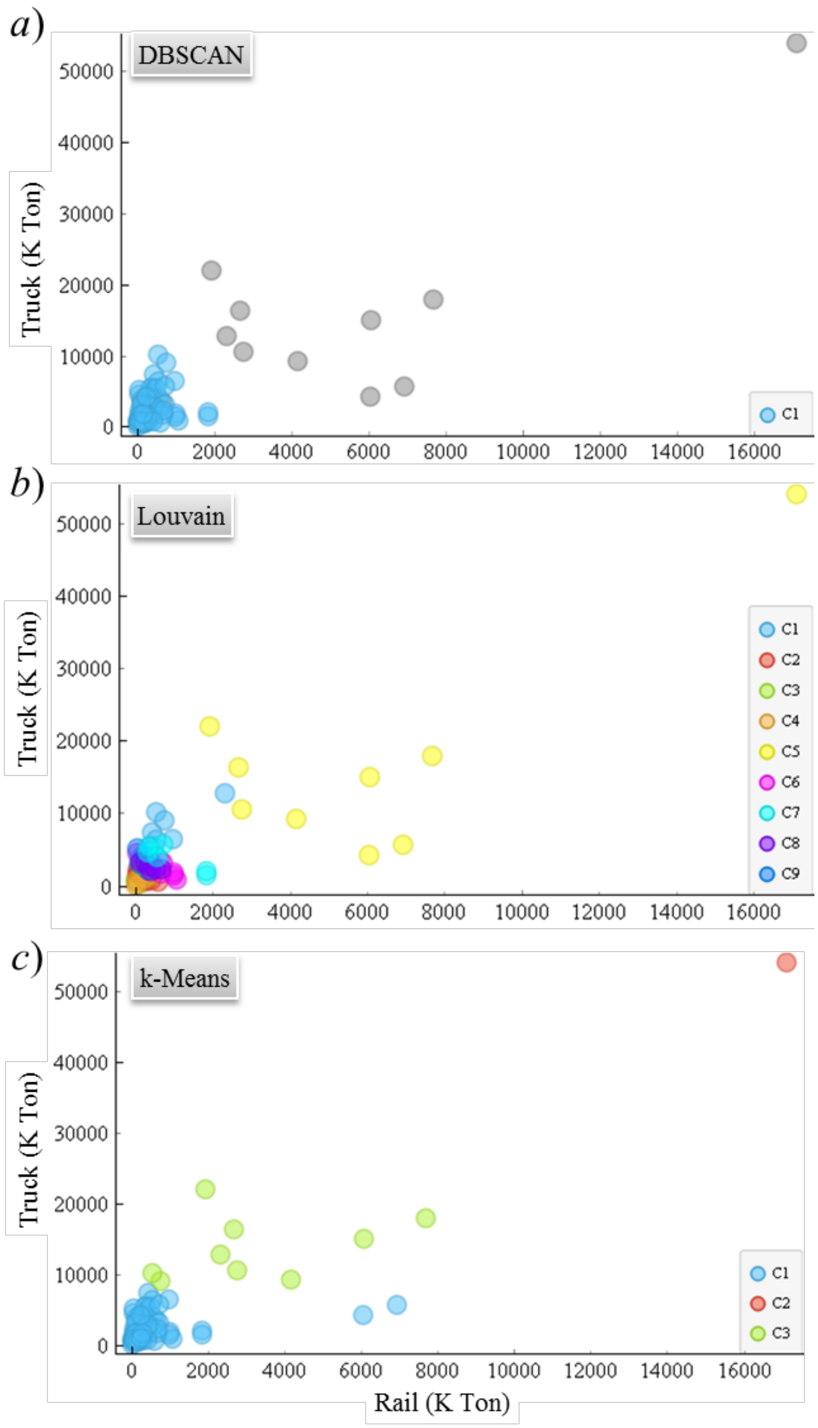


Figure 59: Comparison of clustering results for a) DBSCAN, b) Louvain, and c) k-means

This result demonstrated that hazardous material demand was highly concentrated rather than diffuse.

The clustering results revealed that only nine MSAs in four states (California, Texas, Louisiana, and Illinois) accounted for 49.3% of all BCM weight moved in the continental United States. Figure 60 ranks MSAs by BCM volume. It shows that truck transport dominated hazardous material movements even in regions with rail and air alternatives. From a market perspective, this concentration implied that early AAM deployments could focus on a small number of jurisdictions. This would reduce regulatory complexity while maximizing demonstrable safety benefits.

Distance feasibility analysis further strengthened the market case. Using GIS-derived centroid-to-centroid distances, the study binned BCM flows into 100-mile distance bands. Table 14 and Figure 61 show that 84.7% of truck-moved BCMs in the outlier MSAs traveled within 400 miles, with clear diminishing returns beyond that threshold. This finding aligned with plausible near-term cargo drone range capabilities discussed earlier in the technology assessment (Schwab, et al. 2021) (Sahoo, Zhao and Kyprianidis 2020).

Combining spatial concentration and distance feasibility, this study demonstrated that deploying cargo drones in only nine MSAs could carry approximately 38% of all BCM movements nationwide within a 400-mile range. This is equivalent to 4.7 million truckloads displaced in 2017 alone. This result positioned hazardous materials as one of the highest-impact early markets for AAM, not because of volume alone, but because of the compounded benefits of risk reduction, congestion relief, and infrastructure preservation.

Within the broader market analysis, this subsection established hazardous goods as a strategic anchor market for AAM freight. The findings showed that targeted deployment could rapidly demonstrate safety, environmental, and infrastructure benefits. This outcome would support regulatory confidence and accelerate adoption. Unlike generalized freight markets, hazardous material logistics offers a clear societal justification for moving freight from roads to air. This aligns directly with the primary objective of preserving ground transportation infrastructure while realizing secondary benefits in safety, resilience, and sustainability.

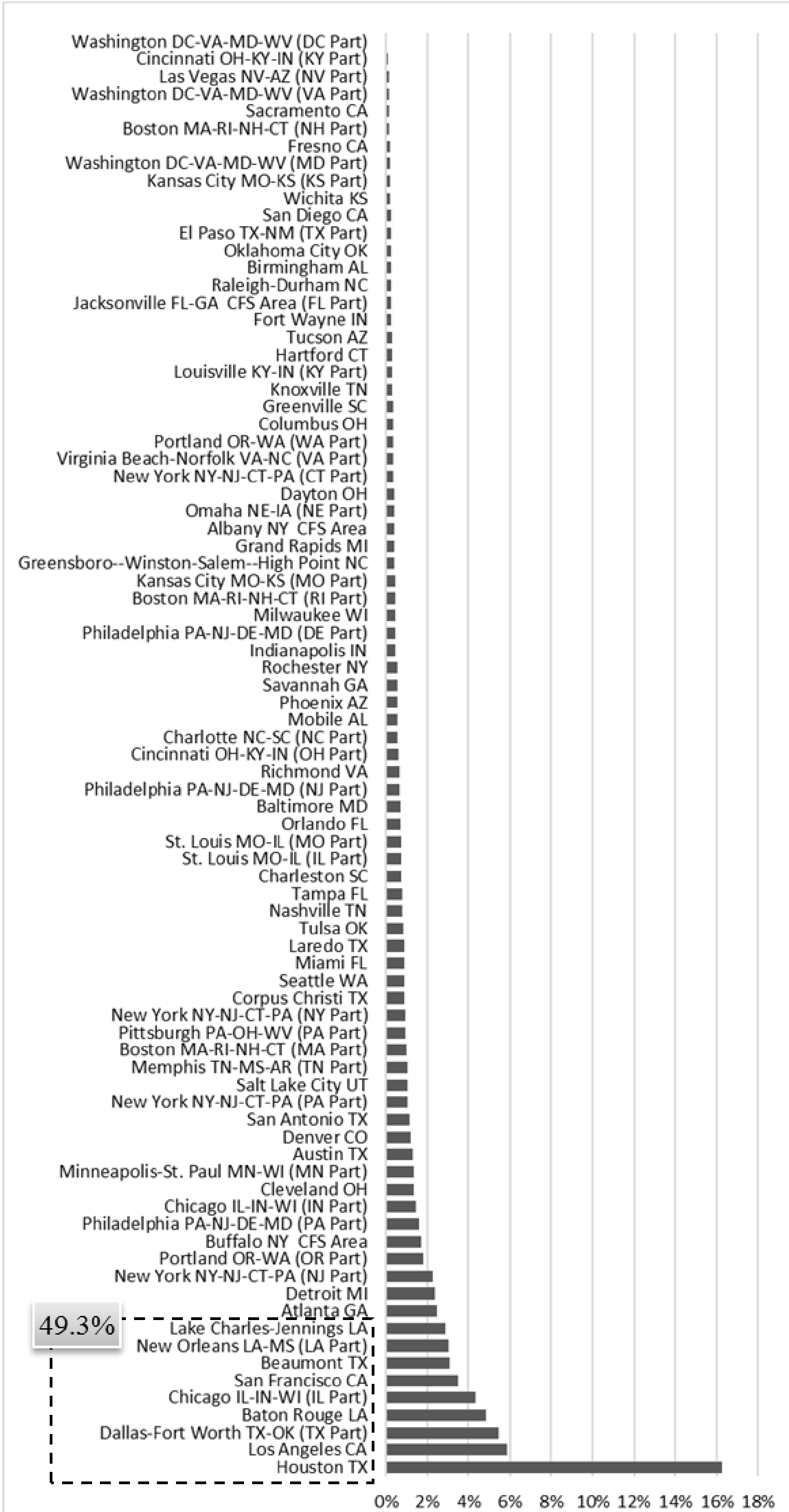


Figure 60: MSA rank of BCMs moved by truck, rail, and air

Table 14: Truckload Equivalent and Proportion Moved by Miles Band and Mode in the Outlier MSAs

Band	Air	Air Acc.	Rail	Rail Acc.	Truck	Truck Acc.	3-Modes	3-Modes Acc.
100	11.4	0.5%	239,468.1	14.5%	1,858,411.2	40.8%	2,097,890.7	33.8%
200	8.8	1.0%	217,816.7	27.7%	892,520.1	60.4%	1,110,345.6	51.7%
300	555.1	27.7%	291,106.7	45.4%	892,206.9	80.0%	1,183,868.7	70.8%
400	440.1	48.9%	130,613.3	53.3%	213,958.3	84.7%	345,011.7	76.3%
500	151.9	56.3%	29,614.7	55.1%	102,053.0	86.9%	131,819.5	78.5%
600	107.8	61.5%	54,879.4	58.4%	75,802.3	88.6%	130,789.5	80.6%
700	137.3	68.1%	65,460.3	62.4%	88,755.7	90.6%	154,353.3	83.1%
800	99.1	72.9%	71,947.0	66.8%	79,644.7	92.3%	151,690.7	85.5%
900	53.4	75.4%	63,921.1	70.6%	38,083.4	93.1%	102,057.9	87.2%
1000	99.9	80.2%	123,533.8	78.1%	66,995.1	94.6%	190,628.7	90.2%
1100	21.6	81.3%	41,494.4	80.6%	36,211.3	95.4%	77,727.3	91.5%
1200	22.1	82.4%	191,184.6	92.2%	79,192.4	97.2%	270,399.1	95.8%
1300	17.5	83.2%	69,207.6	96.4%	19,629.7	97.6%	88,854.8	97.3%
1400	9.3	83.6%	27,812.5	98.1%	33,419.6	98.3%	61,241.3	98.3%
1500	22.2	84.7%	5,078.4	98.4%	12,496.8	98.6%	17,597.4	98.5%
1600	40.2	86.7%	8,511.9	98.9%	15,235.8	98.9%	23,787.9	98.9%
1700	21.1	87.7%	5,197.4	99.3%	10,123.7	99.1%	15,342.2	99.2%
1800	41.3	89.7%	2,393.1	99.4%	10,285.0	99.4%	12,719.3	99.4%
1900	59.6	92.5%	1,328.6	99.5%	11,822.8	99.6%	13,211.0	99.6%
2000	30.6	94.0%	278.9	99.5%	4,089.5	99.7%	4,399.0	99.7%
2100	6.1	94.3%	3,991.5	99.7%	2,650.4	99.8%	6,647.9	99.8%
2200	18.9	95.2%	347.0	99.8%	966.8	99.8%	1,332.7	99.8%
2300	16.6	96.0%	2,785.5	99.9%	2,669.3	99.9%	5,471.4	99.9%
2400	34.7	97.7%	447.3	100.0%	4,383.5	100.0%	4,865.5	100.0%
2500	15.2	98.4%	431.6	100.0%	473.2	100.0%	920.0	100.0%
2600	22.5	99.5%	141.5	100.0%	1,335.7	100.0%	1,499.7	100.0%
2700	7.6	99.9%	39.5	100.0%	32.1	100.0%	79.2	100.0%
2800	2.7	100.0%	1.2	100.0%	2.7	100.0%	6.5	100.0%

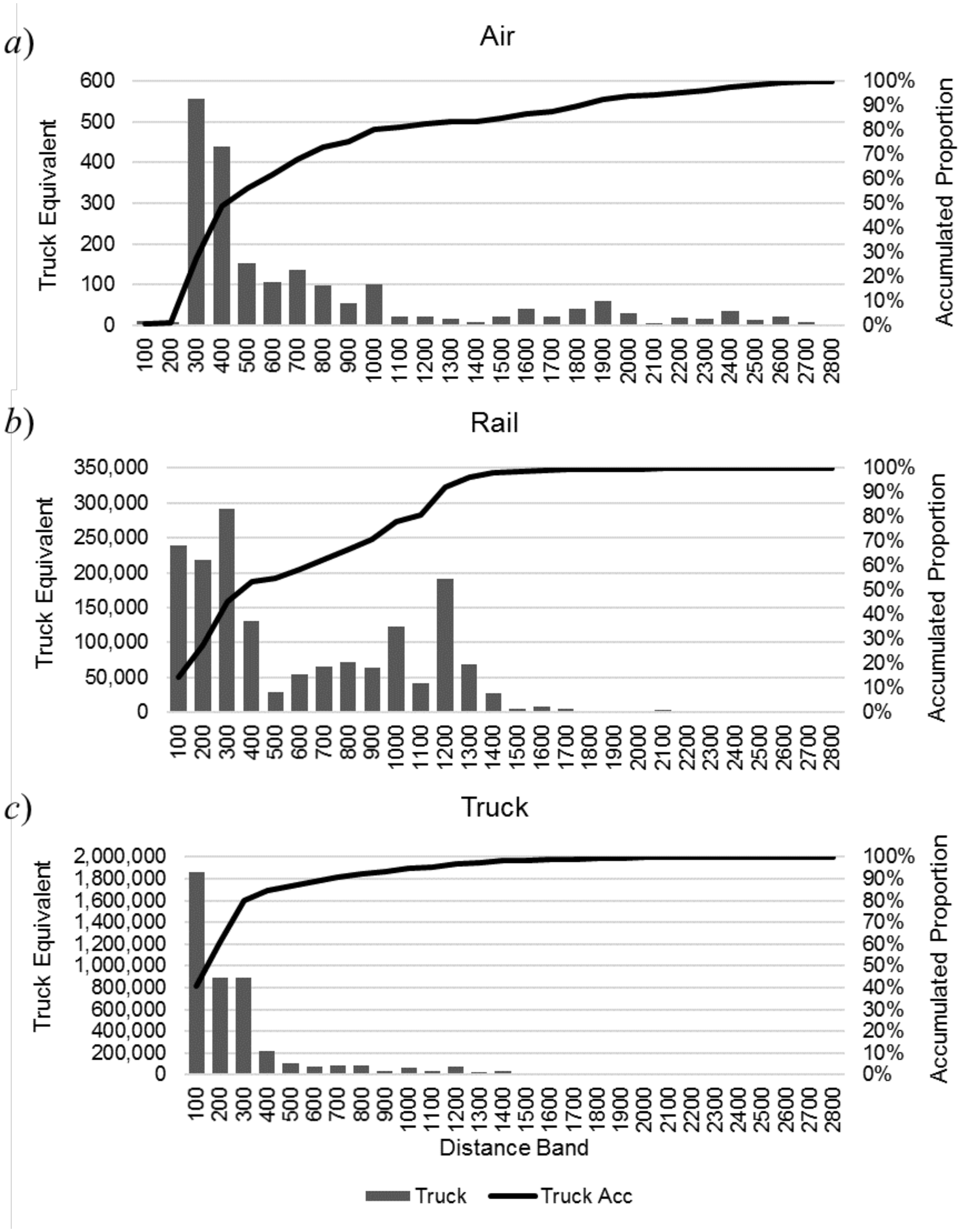


Figure 61: Truckload equivalent by distance band for a) air, b) rail, and d) truck modes

2.2.3 Pharmaceutical Middle-Mile Transport as an AAM Opportunity

This subsection evaluates pharmaceutical middle-mile logistics as a priority market for freight-oriented AAM (Bridgelall 2023). The analysis complements the hazardous materials market assessment by focusing on time-sensitive, high-value, disruption-prone commodities whose transport reliability directly affects public health. Similar to hazardous materials, this study found regional concentration for pharmaceutical flows. The study frames pharmaceutical logistics as a reliability-critical middle-mile problem rather than a last-mile delivery challenge. Ground transport congestion, weather disruptions, and infrastructure constraints increasingly threaten consistent access to medical products, even in well-served urban regions (ACI 2019) (GAO 2022). The study evaluated cargo drones as an intermediate-range mode that preserves the speed and security advantages of air transport while improving accessibility and cost relative to conventional air cargo. This framing aligns with the infrastructure-preservation objective by prioritizing mode shift where truck dependence is highest and societal consequences of delay are severe.

The methodological foundation rested on a hybrid data mining (HDM) workflow that integrated unsupervised machine learning (UML) with geospatial processing (GP) to identify the fewest locations where initial AAM deployments could deliver the largest benefits. The workflow architecture is documented in Figure 62.

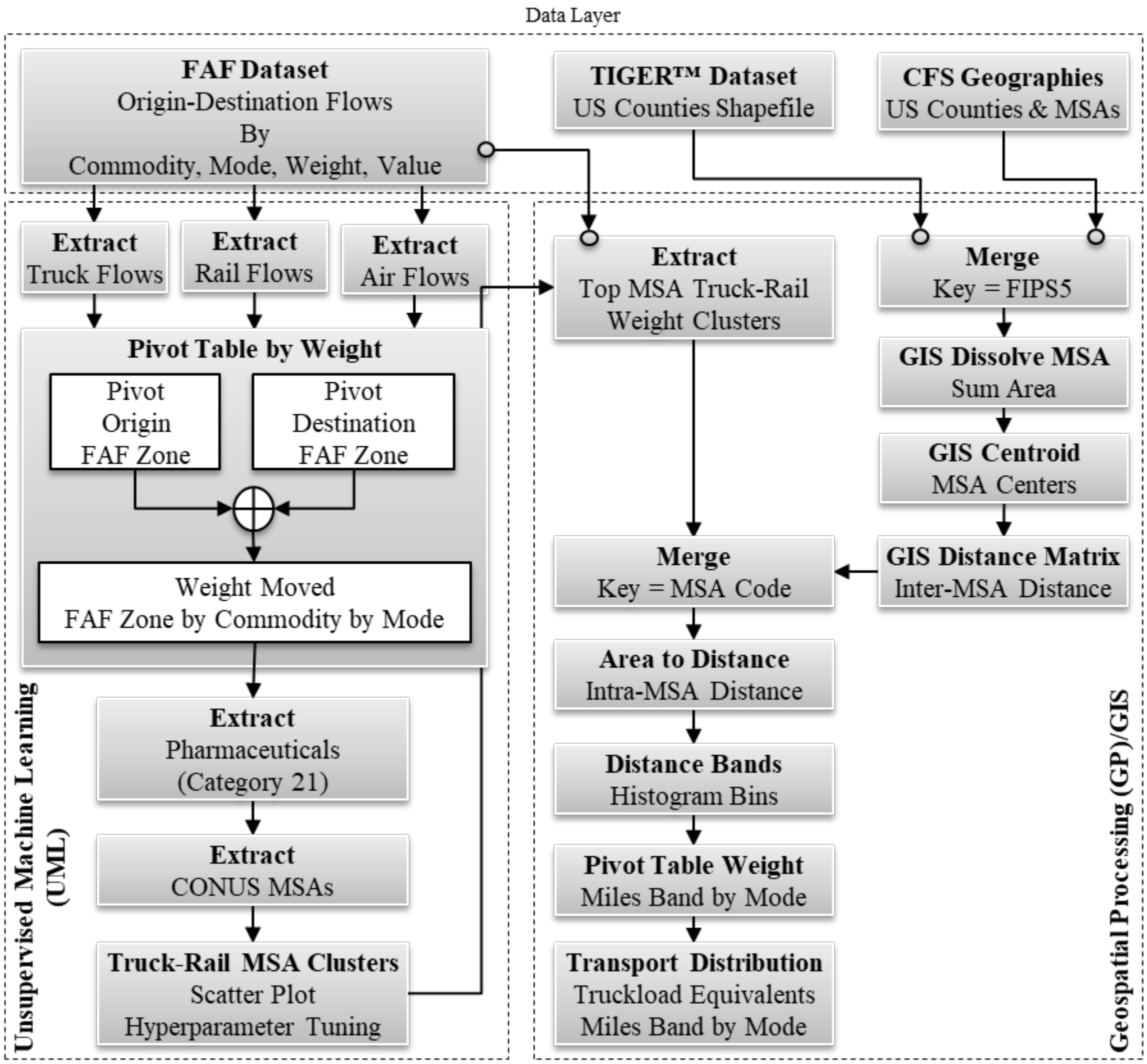


Figure 62: The HDM workflow to analyze pharmaceutical flows

It shows how national freight data were transformed into actionable market insights through sequential extraction, clustering, spatial aggregation, and distance banding. Hence, this figure demonstrates a reproducible approach for translating freight datasets into deployment decisions.

Using the FAF dataset, the study extracted pharmaceutical commodity flows across truck, rail, and air modes and filtered them to MSAs in the contiguous United States. The pharmaceutical category was narrowly defined by FAF metadata to include chemical mixtures for medical use, biological products, bandages, sutures, and related items. This definition ensured consistency with national freight accounting while capturing products that demand secure, reliable transport (FHWA 2021). Similar to the hazardous material analysis, the study identified priority markets by applying DBSCAN, Louvain, and k-means clustering to MSA-level pharmaceutical weights. The selected clustering methods justified algorithm selection based on their ability to isolate extreme outliers.

Visualization of the clustering results in Figure 63 showed strong agreement across methods.

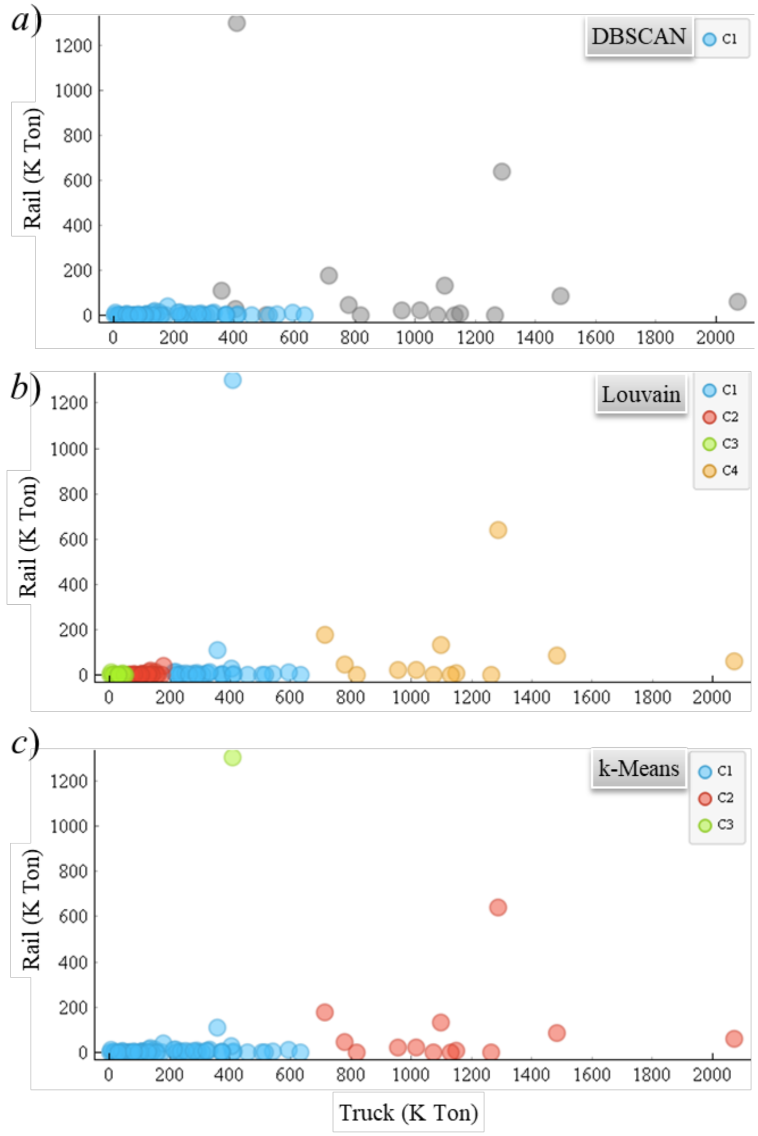


Figure 63: Outlier MSA identification by a) DBSCAN, b) Louvain, and c) k-means clustering methods

This confirmed that pharmaceutical flows were highly concentrated rather than evenly distributed.

The ranked distribution of MSAs in Figure 65 demonstrated that nine MSAs across four regions accounted for 41.6% of all pharmaceutical weight moved in the contiguous United States.

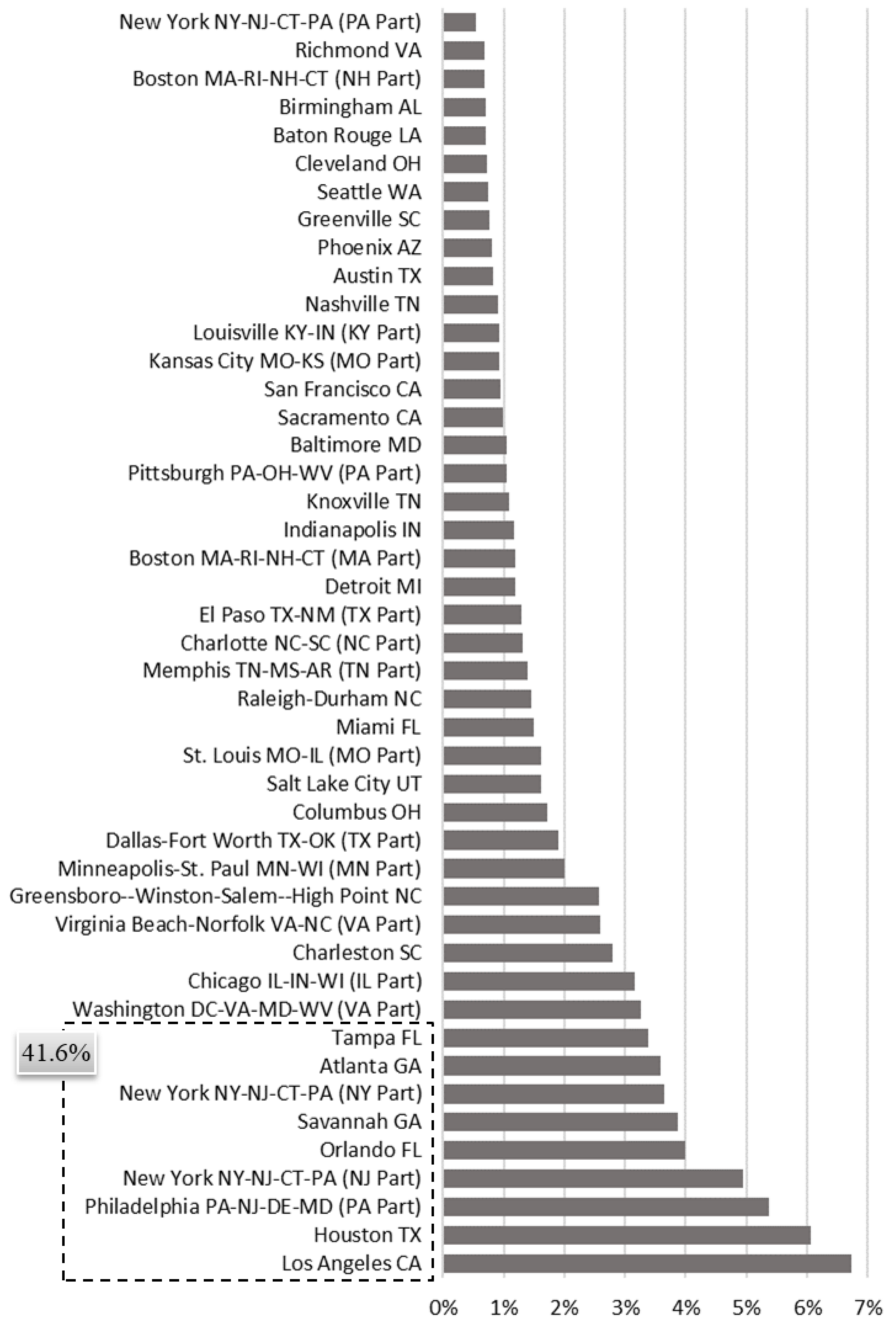


Figure 64: The top 9 MSAs among those moving more than 90% of the weight of pharmaceuticals by air, truck, and rail

These regions overlapped substantially with those identified in the hazardous materials analysis. This reinforced the conclusion that early AAM deployment can focus on a small, common set of freight-intensive markets to serve multiple high-value commodity classes. Adding additional MSAs beyond this set yielded diminishing returns, a finding that supports phased deployment strategies.

Distance feasibility analysis further refined market size estimates. Because the FAF does not report OD distances, the GP component of the workflow estimated inter-MSA distances using centroid-based geodesic calculations in the same manner discussed for the hazardous material flows. The resulting distance band distributions are shown in Figure 65.

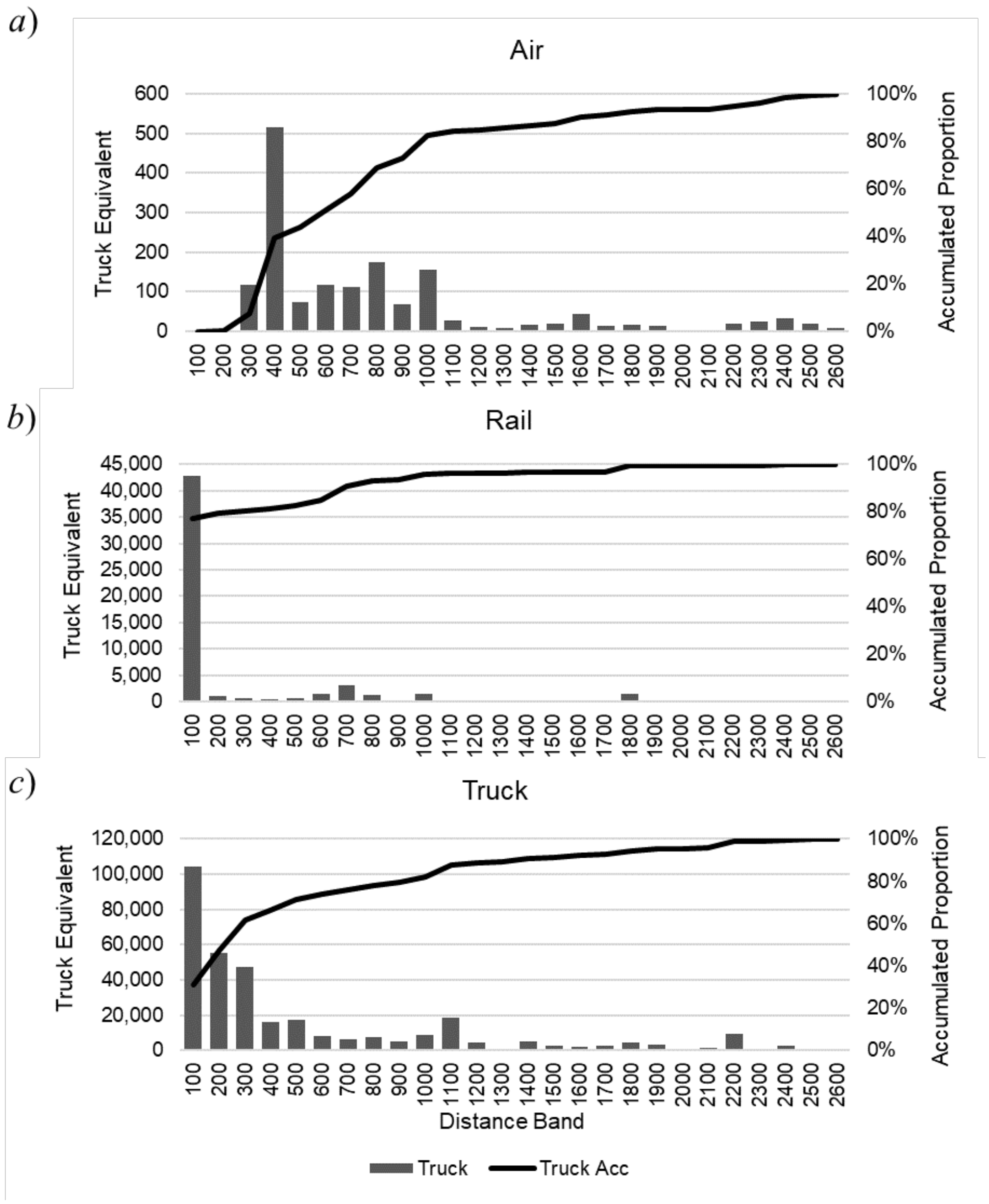


Figure 65: Distance band distribution for the top 9 MSAs moving pharmaceuticals by a) air, b) rail, and c) truck

It reports truckload-equivalent pharmaceutical movements within consecutive 100-mile bands for air, rail, and truck modes. The analysis shows that 68.2% of pharmaceutical truckload equivalents among the target MSAs moved within 400 miles, and a substantial share moved within the first 100 miles.

Combining spatial concentration with distance feasibility, the study demonstrated that cargo drones with a robust 400-mile range could transport 28.4% of all pharmaceutical truckload equivalents nationwide by initiating service in only four regions. This estimate is grounded in observed freight behavior rather than aspirational performance assumptions. It aligns with near-term heavy-lift cargo drone capabilities discussed earlier in the report.

The pharmaceutical market analysis reinforced and extended insights from the hazardous materials subsection. Both markets exhibited strong regional concentration, dominance of truck transport, and distance distributions well matched to plausible AAM operating envelopes. However, pharmaceuticals added a distinct reliability and resilience dimension. Unlike hazardous materials, where risk reduction drives the value proposition, pharmaceutical transport emphasized continuity of care, inventory freshness, and protection against cascading disruptions (Nisingizwe, et al. 2022) (Rejeb, et al. 2021).

Within the broader market analysis, this subsection established pharmaceuticals as a synergistic anchor market for AAM freight. Targeting the same MSAs and regions identified for hazardous goods allows operators and policymakers to aggregate demand across safety-critical and healthcare-critical commodities. This would accelerate utilization while maximizing infrastructure preservation benefits. The findings demonstrate that AAM can displace a meaningful share of truck traffic in markets where reliability matters most. Hence, the findings support both public health outcomes and long-term sustainability of the surface transportation network.

2.2.4 Rural Last-Mile Pharmaceutical Delivery in AAM

This subsection evaluates rural last-mile pharmaceutical logistics as a complementary market to the previously assessed middle-mile AAM applications (Bridgelall and Tolliver 2024). The analysis demonstrates how last-mile AAM deployments extend the value of middle-mile air freight networks by reaching low-density populations where truck transport is structurally inefficient, unreliable, and costly.

Where the earlier market analysis subsections established that middle-mile freight demand concentrates in a small number of MSAs and regional corridors, this rural case study shows that last-mile demand fragments spatially but remains socially critical. Pharmaceutical logistics in rural regions do not benefit from economies of scale. Yet they directly influence healthcare access, treatment continuity, and patient outcomes. AAM therefore serves a different, but synergistic, role in the last mile; that is, not facilitating volume displacement alone, but time, reliability, and access optimization.

Rural Demand Structure and Market Rationale

The study framed North Dakota as a representative rural market characterized by dispersed population centers, long travel distances, frequent weather disruptions, and underutilized aviation infrastructure. These characteristics amplified the shortcomings of truck-based last-mile delivery, particularly for pharmaceuticals that require frequent replenishment, cold-chain integrity, and predictable arrival times (Abedi, Kwon and Yoon 2023) (Naor, et al. 2024).

Unlike middle-mile flows, which concentrate in MSAs already discussed, last-mile demand originates at hospitals and healthcare facilities serving geographically diffuse populations. This study, therefore, anchored demand at hospitals and treated surrounding populated places as dependent catchments. This structure aligns with healthcare delivery realities and avoids redundancy with MSA-based market definitions developed earlier.

GIS-Based Market Identification and Route Feasibility

The market analysis relied on a GIS and optimization framework that integrated road networks, airports, hospitals, and populated places to identify feasible last-mile AAM routes. The complete workflow appears in Figure 66. It documents how raw spatial datasets were transformed into optimized truck and drone routes. This workflow shows that market identification was constrained by real network connectivity rather than abstract distance assumptions.

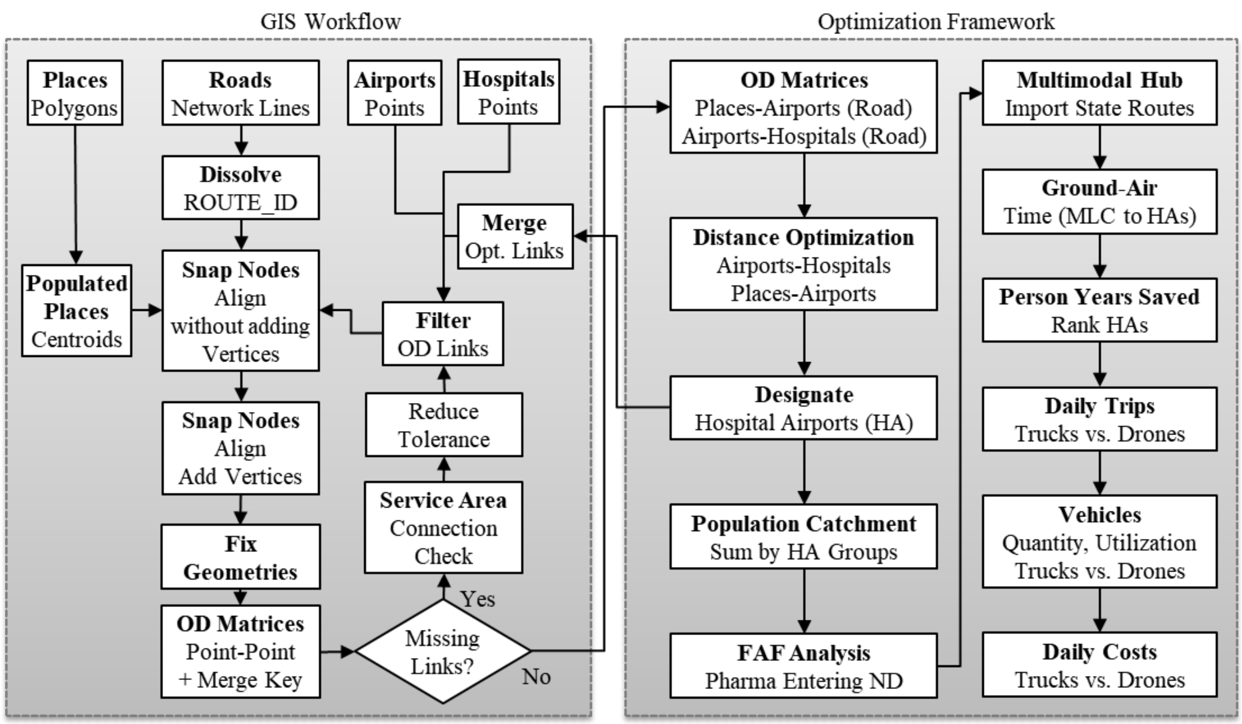


Figure 66: The GIS workflow and optimization framework

The optimized assignment of hospitals to their nearest airports defined a set of hospital airports (HAs) that function as last-mile aerial gateways. Table 15 summarizes the hospitals served by each HA, average airport to hospital miles (AHM), number of hospitals (H), population catchment (PC), and number of populated places served (P). The results showed that a small subset of HAs served the majority of the state population, while many others served very small, isolated communities.

Distance distributions reinforced the feasibility of last-mile drone operations. Figure 67 and Figure 68 show that the mean road distance between population centroids and their assigned HAs was approximately 23 miles. Nearly all routes were within the round-trip range of large package-delivery drones currently under development (Purtell, Hong and Hiatt 2024). These distances were substantially shorter than middle-mile routes. This highlights how last-mile AAM operates within a fundamentally different performance envelope.

Person-Years-Saved as a Market Prioritization Metric

To quantify market impact beyond tonnage, the study introduced person-years-saved (PYS) as a demand-weighted performance metric. PYS combined population catchment with time savings achieved by replacing truck routes with air routes. This metric linked logistics performance to healthcare outcomes, making it especially suitable for rural market evaluation.

Table 15: Hospitals Served by the Airports, Drive Distances, and Population Catchment

City	Hospital Airport	Hospital	AHM	H	PC	P
Bismarck	Bismarck Muni	CHI St Alexius & Sanford Children's	3.8	2	105598	15
Minot	Minot Intl	Trinity Health	1.7	1	59995	20
Williston	Williston Basin Intl	CHI St Alexius	12.2	1	30228	8
Dickinson	Theodore Roosevelt Rgnl	CHI St Alexius	7.6	1	32115	14
Grand Forks	Grand Forks Intl	Altru & Specialty Hospitals	7.5	2	64869	8
Fargo	Hector Intl	Essentia Health Fargo	7.7	1	135608	12
Tioga	Tioga Muni	Tioga Medical Center	2.8	1	8654	8
Watford City	Watford City Muni	McKenzie County Healthcare	2.4	1	7999	5
Fargo	West Fargo Muni	Sanford Medical Center	6.3	1	50706	18
Jamestown	Jamestown Rgnl	Jamestown Regional Medical Center	5.2	1	18022	16
Hazen	Mercer County Rgnl	Sakakawea Medical Center	2.5	1	7892	10
Devils Lake	Devils Lake Rgnl	CHI St Alexius Health	3.0	1	8884	8
Rolla	Rolla Muni	Presentation & QNB Hospitals	8.6	2	5442	11
Harvey	Harvey Muni	St Aloisius Medical Center	1.9	1	6097	18
Bottineau	Bottineau Muni	St Andrews Health Center	1.9	1	4736	16
Grafton	Hutson Field	Unity Medical Center	2.9	1	8251	16
Garrison	Garrison Muni	CHI St. Alexius & Memorial Hospitals	6.0	2	3736	9
Hettinger	Hettinger Muni	West River Regional Medical Center	2.4	1	2816	8
Valley City	Barnes County Muni	CHI Mercy Health	1.8	1	7852	12
Turtle Lake	Turtle Lake Muni	CHI St Alexius Health	1.2	1	3188	9
Kenmare	Kenmare Muni	Kenmare Community Hospital	2.3	1	2613	11
Carrington	Carrington Muni	Carrington Health & CHI St. Alexius	1.5	2	4228	11
Bowman	Bowman Rgnl	Southwest Healthcare Services	5.4	1	2116	7
Crosby	Crosby Muni	St Luke's Hospital	1.4	1	1838	10
Cavalier	Cavalier Muni	Pembina County Memorial Hospital	0.9	1	3562	10
Langdon	Robertson Field	Cavalier County Memorial Hospital	2.3	1	2562	14
Fort Yates	Standing Rock	Fort Yates & Standing Rock Hospitals	4.2	2	1745	9
Cando	Cando Muni	Towner County Medical Center	2.0	1	1900	10
Mayville	Mayville Muni	Sanford Medical Center	2.1	1	4518	8
Oakes	Oakes Muni	CHI Oakes & Community Hospitals	1.7	2	5336	14
Lisbon	Lisbon Muni	CHI Lisbon Health	2.6	1	5579	15
Cooperstown	Cooperstown Muni	Cooperstown Medical Center	1.9	1	2372	14
McVille	McVille Muni	Nelson County Health System	0.5	1	2008	9
Wishek	Wishek Muni	Wishek Community Hospital	1.6	1	2249	6
Linton	Linton Muni	Linton Hospital	3.9	1	1761	5
Hillsboro	Hillsboro Muni	Sanford Medical Center	4.6	1	3025	8
Ashley	Ashley Muni	Ashley Medical Center	1.9	1	752	4

Figure 69 visualizes PYS by hospital airport. It reveals that a small number of HAs accounted for a large share of total potential benefit. Table 16 and Table 17 provide the detailed logistical indicators underlying this result. They include truck and drone travel times, charging and refueling adjustments, and daily trip requirements. The aggregate PYS exceeded 5,090 person-years. This finding quantifies the scale of potential healthcare access improvement achievable through targeted last-mile AAM deployment.

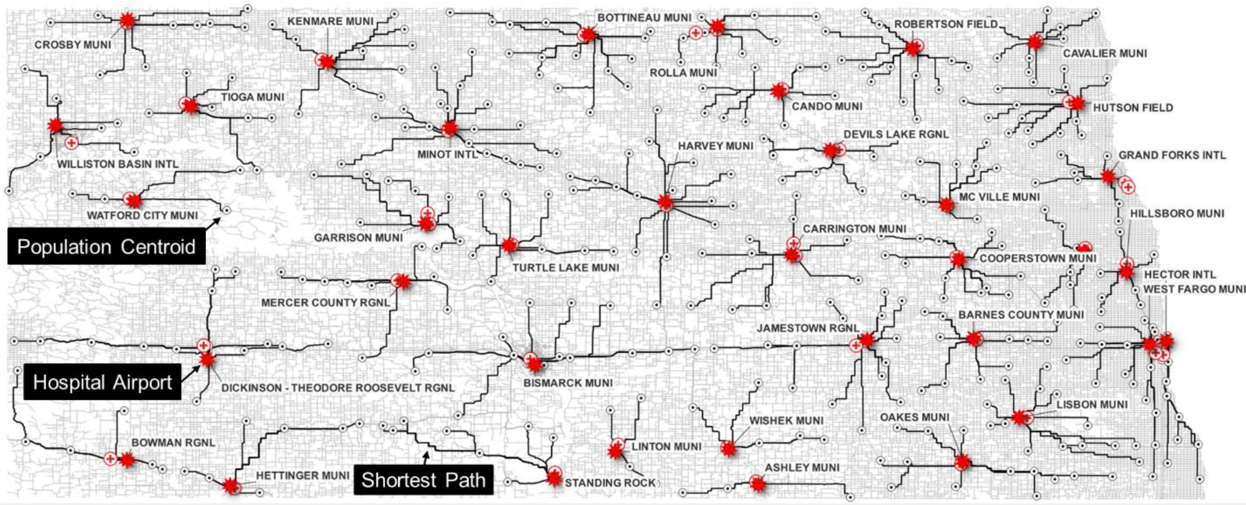


Figure 67: Shortest paths between population centroids and hospital airports

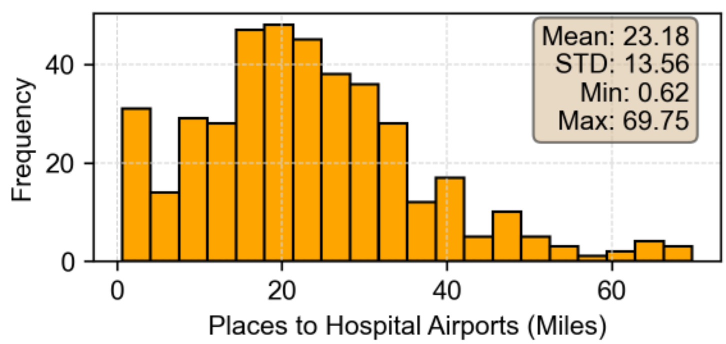


Figure 68: Distribution shortest path road distances between population centroids and HAs

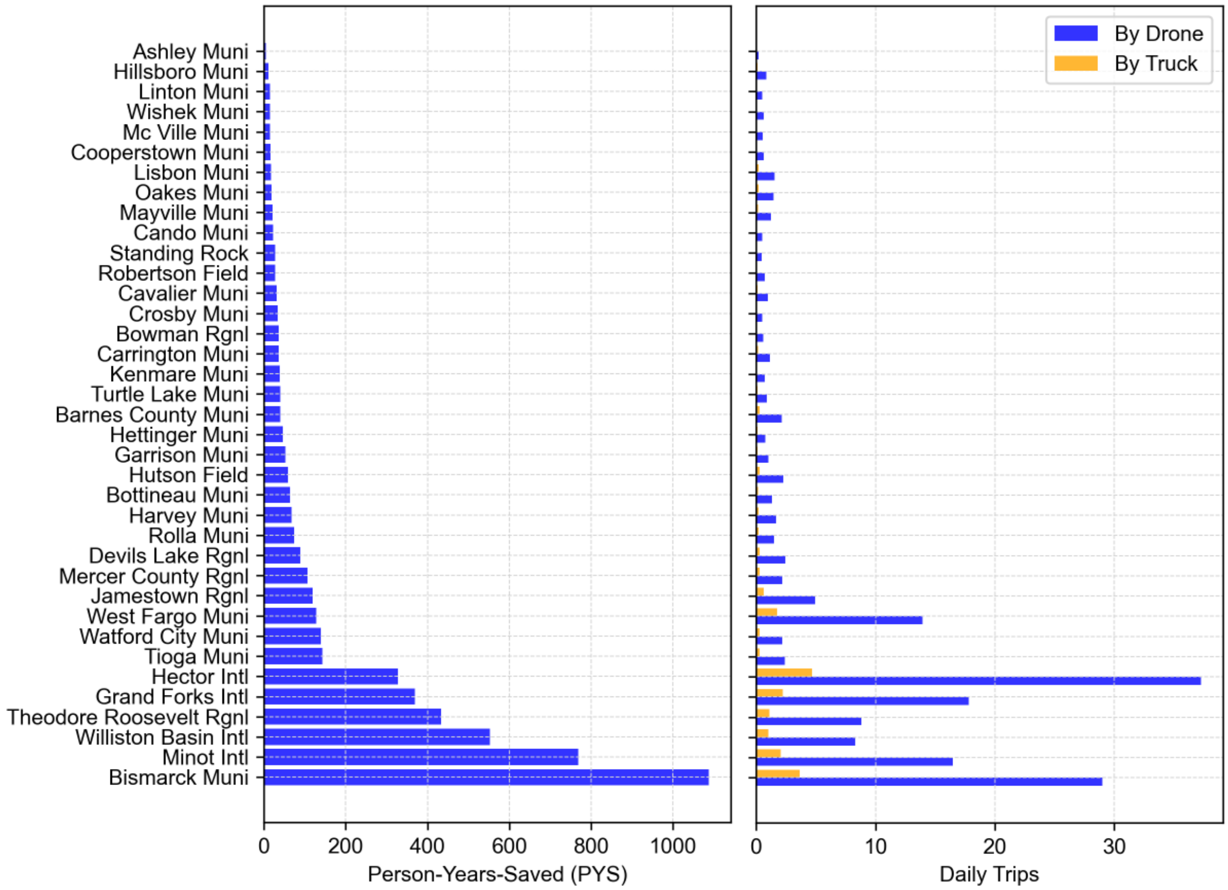


Figure 69: PYS by AAM deployments at each HA and their daily vehicle trips required

Table 16: Logistical Indicators of the Analysis

Parameter	Description
City	The city served by the hospital.
HA	Hospital airport (HA) defined as the nearest airport to a hospital.
Hospital	The specific hospital referenced.
AHM	Airport to hospital miles.
H	The number of hospitals covered by the airport.
PC	Population catchment, based on minimizing the total drive time to all HAs.
P	Number of populated places served by the airport/hospitals.
DS	Drone speed (average) based on the typical specification for heavy-lift cargo drones.
TS	Truck speed (average) based on the average speed limit of expected truck routes.
DC	Drone payload capacity (0.5 tons) based on leading heavy-lift cargo drones.
TC	TC = truck capacity (4 tons) based on the mean industry figures for refrigerated box trucks (Leslie and Murray 2023).
HARM	Hub (logistical center) to airport (hospital) road miles.
HAFM	Hub (logistical center) to airport (hospital) flight (geodesic) miles.
NDH	Nominal drive hours from the MLH to the hospital airport. NDH = HARM / TS.
NFH	Nominal flight hours from the MLH to the hospital airport. NFH = HAFM / DS.
CT	Aircraft charge time based on the typical specification (30 minutes) for heavy-lift cargo drones.
RT	Truck refueling time of 15 minutes.
CS	Charge/refuel stops required using 250 miles for both heavy-lift cargo drones and refrigerated trucks.
HRS	Hours saved over driving, including adjustment for drone charging. HRS = NDH – NFH – CS
PYS	Person years saved. PYS = PC × HRS / 365
PWD	Population weighted demand in annual tons. PWD = PC/(Total Population) × (FAF Tons Entering)
DTT	Daily truck trips required. DTT = PWD/TC/365
DDT	Daily drone trips required. DDT = PWD/DC/365
TTH	Truck trip hours, based on round trips and refueling. THR = $\lceil DTT \rceil \times 2 \times (NDH + CS \times RT)$
TPR	Trucks per route required daily. Ceil{TTH/24}
DTH	Drone trip hours based on round trips and charging. THR = $\lceil DDT \rceil \times 2 \times (NFH + CS \times CT)$
DPR	Drones per route required daily. DPR = $\lceil DTH/24 \rceil$
TCM	Truck cost per mile (average) for refrigerated loads.
DCM	Drone cost per mile (average) for refrigerated pods.
DTC	Daily truck cost for outbound trip. DTC = TCM × HARM × $\lceil DTT \rceil$
DDC	Daily drone cost for outbound trip. DDC = DCM × HAFM × $\lceil DDT \rceil$
TCPT	Truck cost per ton. TCPT = DTC / PWD
DCPT	Drone cost per ton. DCPT = DDC / PWD
DUR	Drone underutilization rate. DUR = $(\lceil DDT \rceil - DDT) / \lceil DDT \rceil$
TUR	Truck underutilization rate. TUR = $(\lceil DTT \rceil - DTT) / \lceil DTT \rceil$

Table 17: Logistical Indicators for Trips Between the MLC and HAs

Hospital Airport	HARM	HAFM	NDH	NFH	CS	HRS	PYS	PWD	DDT	DTT
Bismarck Muni	230.8	201.1	5.8	2.0	0	3.8	1087.8	5296.3	29.0	3.63
Minot Intl	311.3	260.0	7.8	2.6	1	4.7	769.5	3009.0	16.5	2.06
Williston Basin Intl	432.1	363.6	10.8	3.6	1	6.7	552.1	1516.1	8.3	1.04
Theodore Roosevelt Rgnl	336.0	297.7	8.4	3.0	1	4.9	433.2	1610.7	8.8	1.10
Grand Forks Intl	131.4	121.0	3.3	1.2	0	2.1	368.9	3253.5	17.8	2.23
Hector Intl	54.5	47.9	1.4	0.5	0	0.9	328.2	6801.4	37.3	4.66
Tioga Muni	393.6	330.5	9.8	3.3	1	6.0	143.1	434.0	2.4	0.30
Watford City Muni	407.4	331.7	10.2	3.3	1	6.4	139.5	401.2	2.2	0.28
West Fargo Muni	56.1	47.9	1.4	0.5	0	0.9	128.3	2543.2	13.9	1.74
Jamestown Rgnl	140.0	109.4	3.5	1.1	0	2.4	118.8	903.9	5.0	0.62
Mercer County Rgnl	296.1	246.6	7.4	2.5	0	4.9	106.7	395.8	2.2	0.27
Devils Lake Rgnl	214.5	168.6	5.4	1.7	0	3.7	89.5	445.6	2.4	0.31
Rolla Muni	290.8	230.5	7.3	2.3	0	5.0	74.0	272.9	1.5	0.19
Harvey Muni	238.2	190.5	6.0	1.9	0	4.1	67.7	305.8	1.7	0.21
Bottineau Muni	316.1	252.8	7.9	2.5	1	4.9	63.3	237.5	1.3	0.16
Hutson Field	164.6	153.7	4.1	1.5	0	2.6	58.3	413.8	2.3	0.28
Garrison Muni	302.6	248.4	7.6	2.5	0	5.1	52.0	187.4	1.0	0.13
Hettinger Muni	375.2	290.8	9.4	2.9	1	6.0	46.1	141.2	0.8	0.10
Barnes County Muni	107.6	82.5	2.7	0.8	0	1.9	40.1	393.8	2.2	0.27
Turtle Lake Muni	271.7	222.3	6.8	2.2	0	4.6	39.9	159.9	0.9	0.11
Kenmare Muni	360.4	304.8	9.0	3.0	1	5.5	39.1	131.1	0.7	0.09
Carrington Muni	184.5	147.0	4.6	1.5	0	3.1	36.4	212.1	1.2	0.15
Bowman Rgnl	393.3	320.9	9.8	3.2	1	6.1	35.5	106.1	0.6	0.07
Crosby Muni	431.6	363.3	10.8	3.6	1	6.7	33.5	92.2	0.5	0.07
Cavalier Muni	200.2	182.3	5.0	1.8	0	3.2	31.1	178.7	1.0	0.12
Robertson Field	229.7	192.3	5.7	1.9	0	3.8	26.8	128.5	0.7	0.09
Standing Rock	301.3	193.6	7.5	1.9	0	5.6	26.8	87.5	0.5	0.06
Cando Muni	247.8	197.8	6.2	2.0	0	4.2	22.0	95.3	0.5	0.07
Mayville Muni	106.5	92.0	2.7	0.9	0	1.7	21.6	226.6	1.2	0.16
Oakes Muni	77.8	70.8	1.9	0.7	0	1.2	18.1	267.6	1.5	0.18
Lisbon Muni	66.1	55.4	1.7	0.6	0	1.1	16.8	279.8	1.5	0.19
Cooperstown Muni	138.6	108.5	3.5	1.1	0	2.4	15.5	119.0	0.7	0.08
McVille Muni	162.4	129.3	4.1	1.3	0	2.8	15.2	100.7	0.6	0.07
Wishek Muni	151.8	140.6	3.8	1.4	0	2.4	14.7	112.8	0.6	0.08
Linton Muni	187.2	174.6	4.7	1.7	0	2.9	14.2	88.3	0.5	0.06
Hillsboro Muni	86.5	79.8	2.2	0.8	0	1.4	11.3	151.7	0.8	0.10
Ashley Muni	149.8	132.9	3.7	1.3	0	2.4	5.0	37.7	0.2	0.03

This approach complements earlier middle-mile analyses, which focused on truckload displacement and infrastructure preservation. In the last mile, time savings dominate, and PYS provides a defensible mechanism for ranking markets where AAM delivers the highest societal return.

Cost Structure and Vehicle Utilization in Rural Markets

The study further evaluated economic viability. This recognizes that rural markets often fail under traditional cost-per-mile logic. Using ATRI cost estimates for refrigerated trucks, the analysis compared daily truck and drone costs per ton across all HAs. Table 18 and Figure 70 show that drone delivery became more cost-effective than truck delivery when population-weighted demand dropped below 445 annual tons. This is a condition met by most rural healthcare catchments. On average, truck transport was 2.3 times more expensive (per ton) than drone transport, even before accounting for delay risk and weather exposure (Leslie and Murray 2023).

Table 18: Daily Truck and Drone Costs for Each Destination Airport

Hospital Airport	PWD	DTT	DDT	DTC	DDC	TCPT	DCPT
Hector Intl	6801.4	4.66	37.3	$665.09	$1,592.57	$0.10	$0.23
Bismarck Muni	5296.3	3.63	29.0	$2,252.87	$5,272.27	$0.43	$1.00
Grand Forks Intl	3253.5	2.23	17.8	$961.90	$1,903.07	$0.30	$0.58
Minot Intl	3009.0	2.06	16.5	$2,278.43	$3,863.83	$0.76	$1.28
West Fargo Muni	2543.2	1.74	13.9	$273.76	$586.42	$0.11	$0.23
Theodore Roosevelt Rgnl	1610.7	1.10	8.8	$1,639.85	$2,342.21	$1.02	$1.45
Williston Basin Intl	1516.1	1.04	8.3	$2,108.64	$2,860.41	$1.39	$1.89
Jamestown Rgnl	903.9	0.62	5.0	$341.67	$478.13	$0.38	$0.53
Devils Lake Rgnl	445.6	0.31	2.4	$523.48	$442.15	$1.17	$0.99
Tioga Muni	434.0	0.30	2.4	$960.32	$866.76	$2.21	$2.00
Hutson Field	413.8	0.28	2.3	$401.56	$403.13	$0.97	$0.97
Watford City Muni	401.2	0.28	2.2	$993.98	$869.75	$2.48	$2.17
Mercer County Rgnl	395.8	0.27	2.2	$722.46	$646.72	$1.83	$1.63
Barnes County Muni	393.8	0.27	2.2	$262.62	$216.36	$0.67	$0.55
Harvey Muni	305.8	0.21	1.7	$581.20	$332.94	$1.90	$1.09
Lisbon Muni	279.8	0.19	1.5	$161.21	$96.81	$0.58	$0.35
Rolla Muni	272.9	0.19	1.5	$709.60	$402.91	$2.60	$1.48
Oakes Muni	267.6	0.18	1.5	$189.89	$123.71	$0.71	$0.46
Bottineau Muni	237.5	0.16	1.3	$771.34	$441.85	$3.25	$1.86
Mayville Muni	226.6	0.16	1.2	$259.82	$160.80	$1.15	$0.71
Carrington Muni	212.1	0.15	1.2	$450.11	$256.90	$2.12	$1.21
Garrison Muni	187.4	0.13	1.0	$738.33	$434.26	$3.94	$2.32
Cavalier Muni	178.7	0.12	1.0	$488.58	$159.35	$2.73	$0.89
Turtle Lake Muni	159.9	0.11	0.9	$662.84	$194.29	$4.15	$1.22
Hillsboro Muni	151.7	0.10	0.8	$210.95	$69.79	$1.39	$0.46
Hettinger Muni	141.2	0.10	0.8	$915.58	$254.14	$6.48	$1.80
Kenmare Muni	131.1	0.09	0.7	$879.43	$266.45	$6.71	$2.03
Robertson Field	128.5	0.09	0.7	$560.59	$168.10	$4.36	$1.31
Cooperstown Muni	119.0	0.08	0.7	$338.29	$94.87	$2.84	$0.80
Wishek Muni	112.8	0.08	0.6	$370.29	$122.90	$3.28	$1.09
Bowman Rgnl	106.1	0.07	0.6	$959.64	$280.46	$9.04	$2.64
McVille Muni	100.7	0.07	0.6	$396.22	$113.00	$3.93	$1.12
Cando Muni	95.3	0.07	0.5	$604.64	$172.88	$6.34	$1.81
Crosby Muni	92.2	0.07	0.5	$1,053.07	$317.58	$11.42	$3.45
Linton Muni	88.3	0.06	0.5	$456.84	$152.64	$5.17	$1.73
Standing Rock	87.5	0.06	0.5	$735.20	$169.20	$8.40	$1.93
Ashley Muni	37.7	0.03	0.2	$365.49	$116.16	$9.69	$3.08

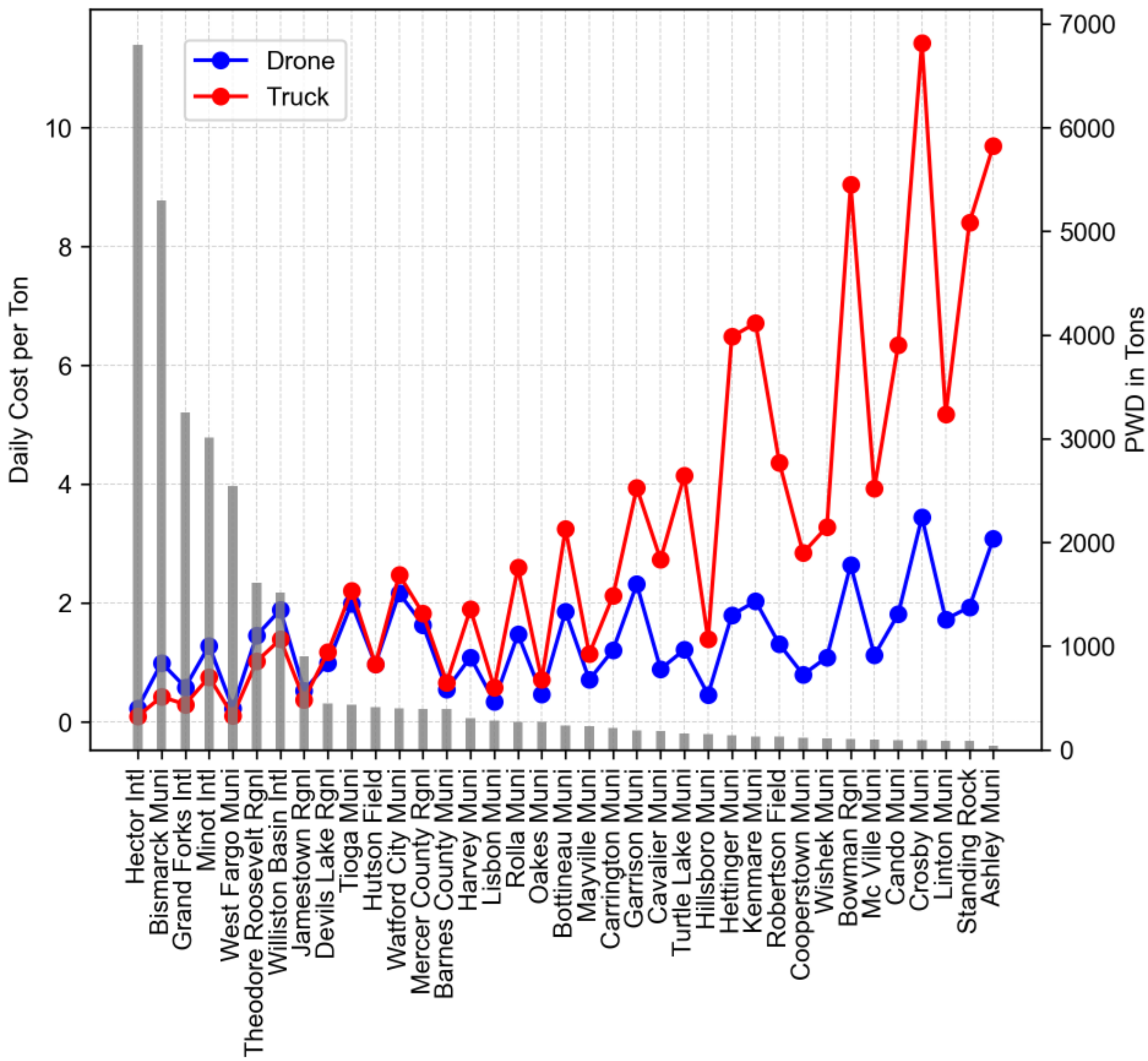


Figure 70: Daily truck and drone cost per ton by destination airport, ranked by weight demand

Vehicle utilization analysis reinforced this result. Figure 71 and Table 19 show that truck capacity underutilization averaged **72.6%**, compared with **26.3% for drones**. The structural mismatch between truck capacity and rural demand made trucks inherently inefficient for last-mile pharmaceutical logistics, whereas drones could scale payloads and trip frequency with more flexibility.

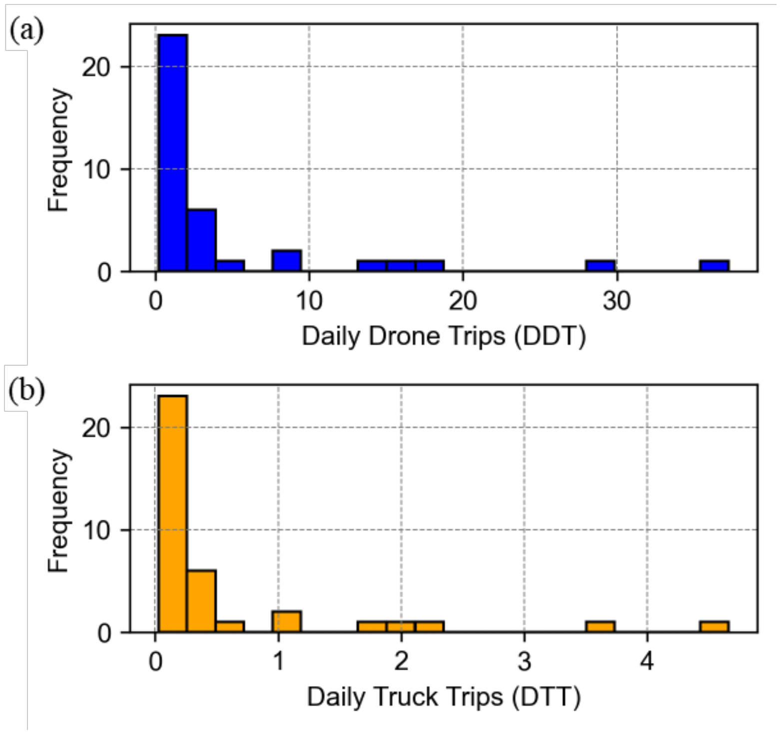


Figure 71: Distribution of a) daily drone trips, and b) daily truck trips required

Table 19: Daily Truck and Drone Underutilization Rate by Destination Airport

Hospital Airport	PWD	DTT	DDT	TTH	TPR	DTH	DPR	TUR	DUR
Hector Intl	6801.4	4.66	37.3	13.6	1	36.4	2	6.8%	1.9%
Bismarck Muni	5296.3	3.63	29.0	46.2	2	120.6	6	9.2%	3.3%
Grand Forks Intl	3253.5	2.23	17.8	19.7	1	43.5	2	25.7%	1.0%
Minot Intl	3009.0	2.06	16.5	48.2	3	105.4	5	31.2%	3.0%
West Fargo Muni	2543.2	1.74	13.9	5.6	1	13.4	1	12.9%	0.5%
Theodore Roosevelt Rgnl	1610.7	1.10	8.8	34.6	2	62.6	3	44.8%	1.9%
Williston Basin Intl	1516.1	1.04	8.3	44.2	2	74.5	4	47.9%	7.7%
Jamestown Rgnl	903.9	0.62	5.0	7.0	1	10.9	1	38.1%	0.9%
Devils Lake Rgnl	445.6	0.31	2.4	10.7	1	10.1	1	69.3%	18.6%
Tioga Muni	434.0	0.30	2.4	20.2	1	22.8	1	70.1%	20.7%
Hutson Field	413.8	0.28	2.3	8.2	1	9.2	1	71.5%	24.4%
Watford City Muni	401.2	0.28	2.2	20.9	1	22.9	1	72.3%	26.7%
Mercer County Rgnl	395.8	0.27	2.2	14.8	1	14.8	1	72.9%	27.7%
Barnes County Muni	393.8	0.27	2.2	5.4	1	5.0	1	72.9%	28.1%
Harvey Muni	305.8	0.21	1.7	11.9	1	7.6	1	78.9%	16.2%
Lisbon Muni	279.8	0.19	1.5	3.3	1	2.2	1	80.8%	23.3%
Rolla Muni	272.9	0.19	1.5	14.5	1	9.2	1	81.1%	25.2%
Oakes Muni	267.6	0.18	1.5	3.9	1	2.8	1	81.6%	26.7%
Bottineau Muni	237.5	0.16	1.3	16.3	1	12.1	1	83.6%	34.9%
Mayville Muni	226.6	0.16	1.2	5.3	1	3.7	1	84.4%	37.9%
Carrington Muni	212.1	0.15	1.2	9.2	1	5.9	1	85.2%	41.9%
Garrison Muni	187.4	0.13	1.0	15.1	1	9.9	1	87.1%	48.7%
Cavalier Muni	178.7	0.12	1.0	10.0	1	3.6	1	87.7%	2.1%
Turtle Lake Muni	159.9	0.11	0.9	13.6	1	4.4	1	89.0%	12.4%
Hillsboro Muni	151.7	0.10	0.8	4.3	1	1.6	1	89.6%	16.9%
Hettinger Muni	141.2	0.10	0.8	19.3	1	6.8	1	90.1%	22.6%
Kenmare Muni	131.1	0.09	0.7	18.5	1	7.1	1	91.0%	28.2%
Robertson Field	128.5	0.09	0.7	11.5	1	3.8	1	91.0%	29.6%
Cooperstown Muni	119.0	0.08	0.7	6.9	1	2.2	1	91.8%	34.8%
Wishek Muni	112.8	0.08	0.6	7.6	1	2.8	1	92.1%	38.2%
Bowman Rgnl	106.1	0.07	0.6	20.2	1	7.4	1	92.6%	41.8%
McVille Muni	100.7	0.07	0.6	8.1	1	2.6	1	92.9%	44.8%
Cando Muni	95.3	0.07	0.5	12.4	1	4.0	1	93.4%	47.8%
Crosby Muni	92.2	0.07	0.5	22.1	1	8.3	1	93.4%	49.5%
Linton Muni	88.3	0.06	0.5	9.4	1	3.5	1	93.7%	51.6%
Standing Rock	87.5	0.06	0.5	15.1	1	3.9	1	94.0%	52.0%
Ashley Muni	37.7	0.03	0.2	7.5	1	2.7	1	97.3%	79.3%

Synergy with Middle-Mile AAM Networks

When viewed alongside the middle-mile market analyses, this rural case study demonstrates a networked AAM market structure. Middle-mile AAM displaces high-value, time-sensitive freight from highways between MSAs and regional hubs. Last-mile AAM then extends those flows from multimodal logistics centers and hospital airports to dispersed population centers where trucks perform poorly.

The use of underutilized regional airports as both middle-mile nodes and last-mile gateways creates economies of scope rather than scale. This synergy allows a single AAM network to serve hazardous materials, pharmaceuticals, and general high-value freight while advancing the primary objective of ground infrastructure preservation and the secondary objective of equitable healthcare access. Hence, within the market analysis, this subsection establishes rural last-mile pharmaceutical delivery as a critical completion layer of the AAM freight market. It shows that the full value of AAM emerges not from isolated use cases, but from integrated middle-mile and last-mile deployments that align technology capability with spatial demand structure and societal need.

2.3 Infrastructure Evaluation

2.3.1 Leveraging Existing Airports and Healthcare Assets for AAM Integration

This subsection evaluates the infrastructure readiness and deployment logic for freight-oriented AAM (Bridgelall 2024). The analysis demonstrates how existing infrastructure, particularly underutilized airports and healthcare-linked facilities, can support scalable AAM operations without requiring extensive new construction. This evaluation directly builds on the prior market analysis sections that relied on hospitals, MSAs, and regional airports as anchor nodes for hazardous materials, pharmaceuticals, and high-value freight. The infrastructure assessment frames readiness as a network design problem, not a greenfield development challenge. Instead of proposing new vertiports or purpose-built facilities, the study shows that repurposing existing public-use airports enables rapid AAM integration while preserving surface transportation infrastructure by reducing truck travel.

Role of Underutilized Airports as Multimodal Freight Hubs

The study identifies public-use, underutilized airports as the primary physical enablers of middle-mile AAM. These facilities already possess key aviation assets. These include runway access, controlled airspace integration, security perimeters, and utilities. Yes, they remain lightly trafficked, particularly in rural states. Prior literature cited in the study documented that many small U.S. airports operate well below capacity, making them suitable candidates for AAM repurposing (Cox, et al. 2023) (Wheeler, Esselman and Organ 2024). The proposed infrastructure model introduced two functional airport roles:

- Multimodal freight hubs (MFHs) for distributing freight to population centers and healthcare facilities
- Truck transfer hubs (TTHs) for intercepting long-haul truck freight near interstate corridors and transferring it to air

The conceptual architecture of this system appears in Figure 72, which illustrates freight transfers between trucks, heavy-lift cargo drones, and last-mile distribution modes. This figure is foundational because it shows how existing airport infrastructure integrates seamlessly with both middle-mile and last-mile logistics. This approach aligns with earlier analyses that used hospitals and hospital-adjacent airports as last-mile gateways.

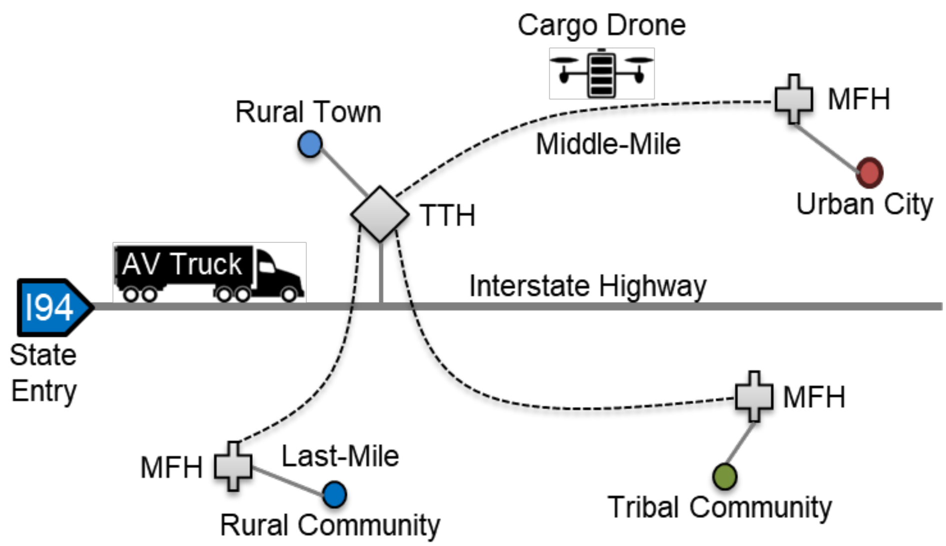


Figure 72: Proposed vision for AAM integration with MFHs and TTHs

GIS-Based Infrastructure Screening and Accessibility

The infrastructure evaluation relied on a GIS-based spatial optimization framework to determine which airports maximized accessibility while minimizing truck travel. The complete analytical workflow is documented in Figure 73. It shows how population centers, road networks, and airport locations were connected into a unified origin–destination (OD) model. This workflow ensured that infrastructure feasibility reflected actual road connectivity and travel constraints, not straight-line assumptions.

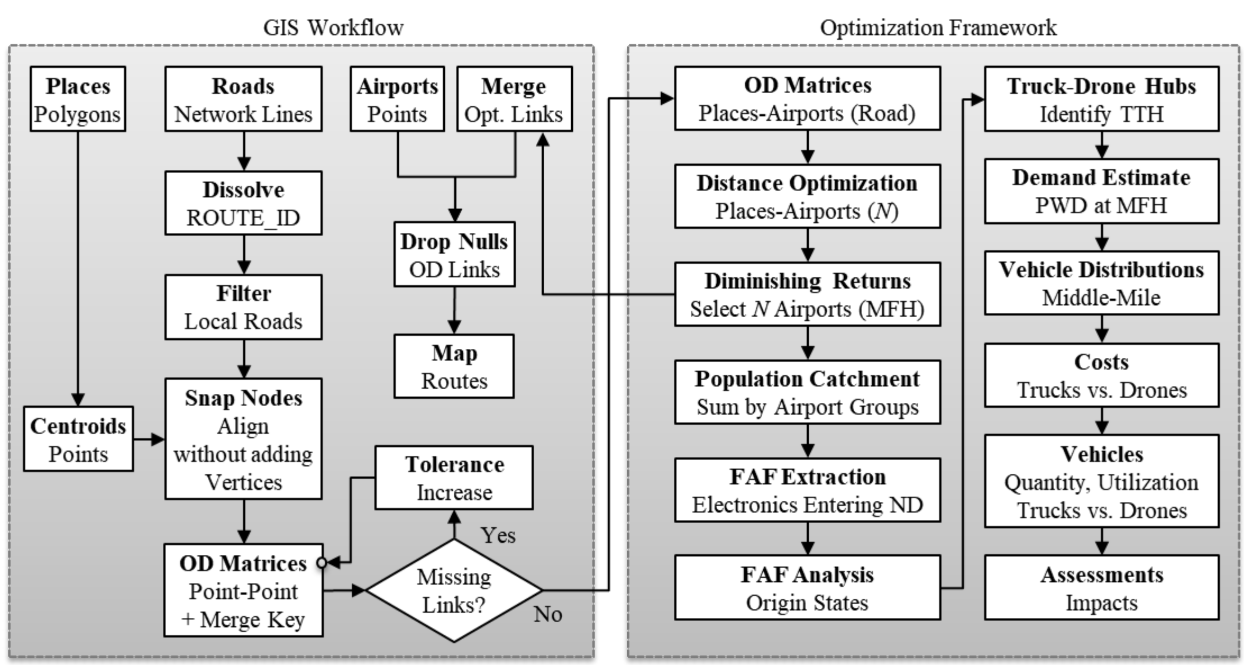


Figure 73: The analytical workflow to leverage airports for middle-mile and last-mile logistics

Input data sources are summarized in Table 20. It includes the Highway Performance Monitoring System (HPMS), Bureau of Transportation Statistics (BTS) airport datasets, ESRI populated places, and the Freight Analysis Framework (FAF) commodity flows. The integration of these datasets ensured consistency with the market analysis that also relied on FAF-based demand estimation and hospital-centric routing.

Table 20: Data Utilized in this Study

Data	Description	Content	Source
Roads	Shapefile of lines representing ND road network geometry.	Extracted 349,585 road segments from the ND layer of the HPMS geodatabase containing layers of individual state road segments.	HPMS (BTS 2023)
Airports	Shapefile of points representing U.S. airports.	Extracted 281 of 19,850 ND airports from the U.S. Department of Transportation (USDOT) Bureau of Transportation Statistics (BTS) dataset and selected 89 public use airports.	BTS (BTS 2022)
Places	Shapefile of polygons representing populated places in the U.S.	Extracted 406 polygon representations of ND populated places from 31,616 in the ESRI USA Census Populated Places database.	ESRI (ESRI 2023)
Commodities	Weight and value of U.S. commodities transported.	Extracted data from 1.1 million records for pharmaceuticals imported to ND and exported from ND by trucks.	FAF 5.6 (BTS 2024)
Truck Costs	The operational costs of traditional diesel trucking.	A longitudinal survey by the American Transportation Research Institute (ATRI) of trucking operational costs.	ATRI (Leslie and Murray 2023)

Optimal Number and Placement of Freight Hubs

A key infrastructure finding was that only a limited number of airports are required to achieve most of the accessibility benefits. Using linear programming, the study iteratively selected *N* airports that minimized the average road distance to all populated places. Figure 74 plots the average drive distance as a function of the number of MFHs. It reveals a clear point of diminishing returns at approximately 20 airports. Increasing hub count beyond this threshold yielded less than a 3% additional reduction in travel distance. This result has direct policy relevance. In particular, infrastructure planners can support statewide AAM operations without widespread airport upgrades. This finding synergizes with earlier market analysis results showing that freight demand (whether hazardous materials or pharmaceuticals) is spatially concentrated. Infrastructure deployment, therefore, benefits from selective intensification rather than ubiquitous coverage.

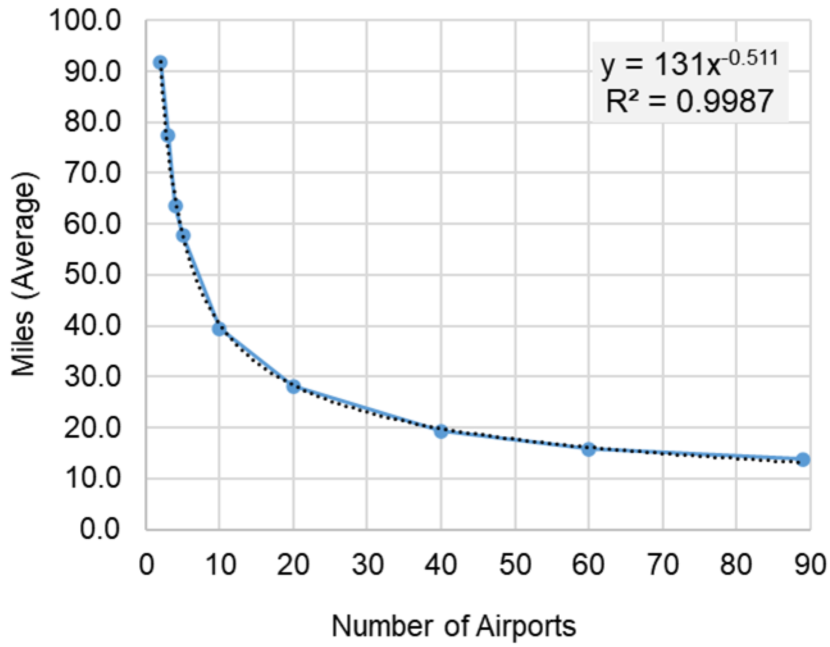


Figure 74: Average drive distance as a function of the number of MFHs selected

Integration with Interstate Freight and Healthcare Networks

The study further evaluated how existing infrastructure aligns with long-haul truck corridors and healthcare-driven demand. Figure 75 and Table 21 identify dominant origin states and interstate entry points for high-value electronics entering North Dakota. Based on this analysis, two airports (West Fargo and Richardton) were designated as TTHs because of their proximity to Interstates I-29 and I-94, and their distances from congested commercial airports.

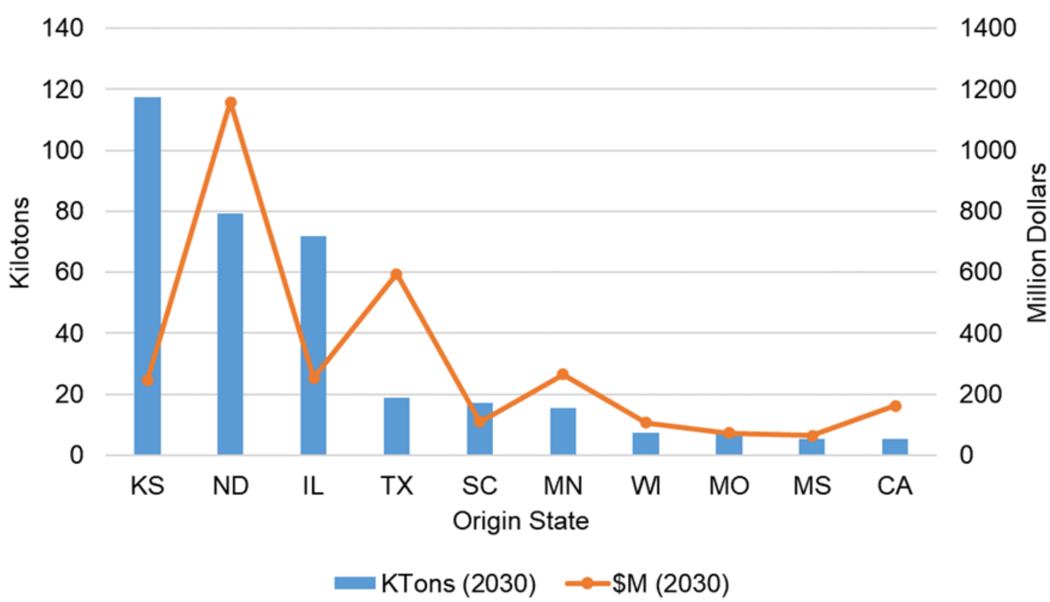


Figure 75: Top 10 origin state of electronics forecasted to arrive in North Dakota by truck

Region	Kilotons	$M	Interstate
South	222.7	1299.1	I29
East	91.6	1506.9	I94
West	226.3	226.3	I94

Table 21: Weight and Value by Origin State Region

Figure 76 maps the selected MFHs and TTHs alongside population catchments, Native American communities, and major roadways. This spatial configuration demonstrated strong overlap with earlier healthcare-focused analyses, where hospital airports served as critical nodes for last-mile pharmaceutical delivery. The infrastructure network, therefore, supports both middle-mile freight aggregation and last-mile healthcare distribution. This enables shared use of assets across commodity classes.

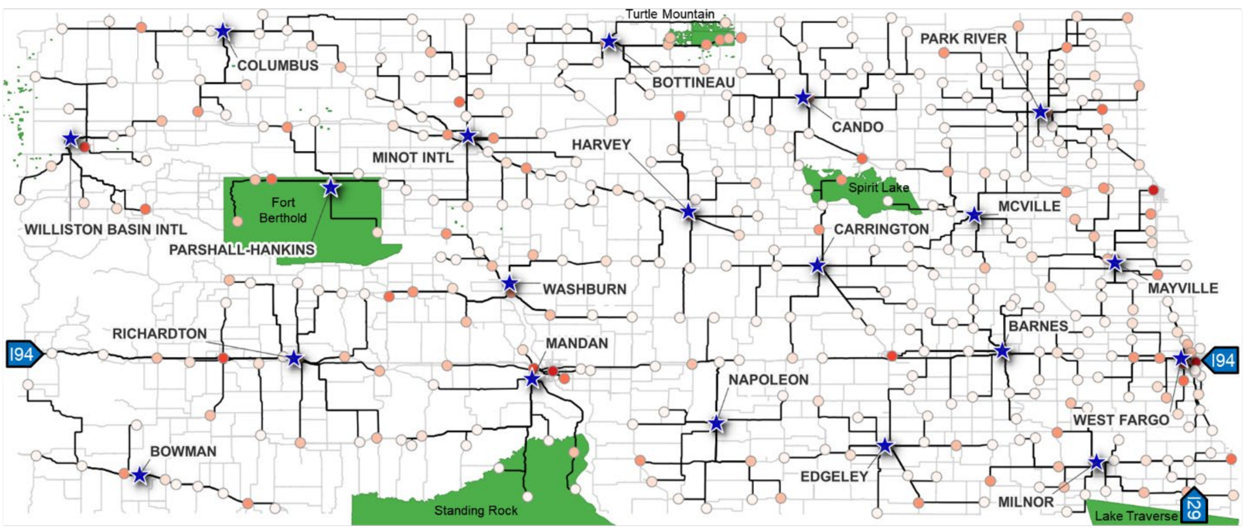


Figure 76: Selected multimodal freight hubs and their population catchment

Capacity Utilization and Cost Implications

Infrastructure suitability was further evaluated through vehicle utilization and cost performance. This analysis recognized that infrastructure readiness depends on operational efficiency. Figure 77, Figure 78, and Figure 79 compare truck and drone utilization, cost per ton, and underutilization rates across all MFHs. The results show that drones consistently achieved lower underutilization rates than trucks, especially at lower-volume hubs. This outcome is infrastructure-relevant because it implies that airports serving smaller populations (often unsuitable for frequent truck service) can still sustain economically viable AAM operations. This finding complements prior rural last-mile results, where truck underutilization drove higher costs for pharmaceutical delivery.

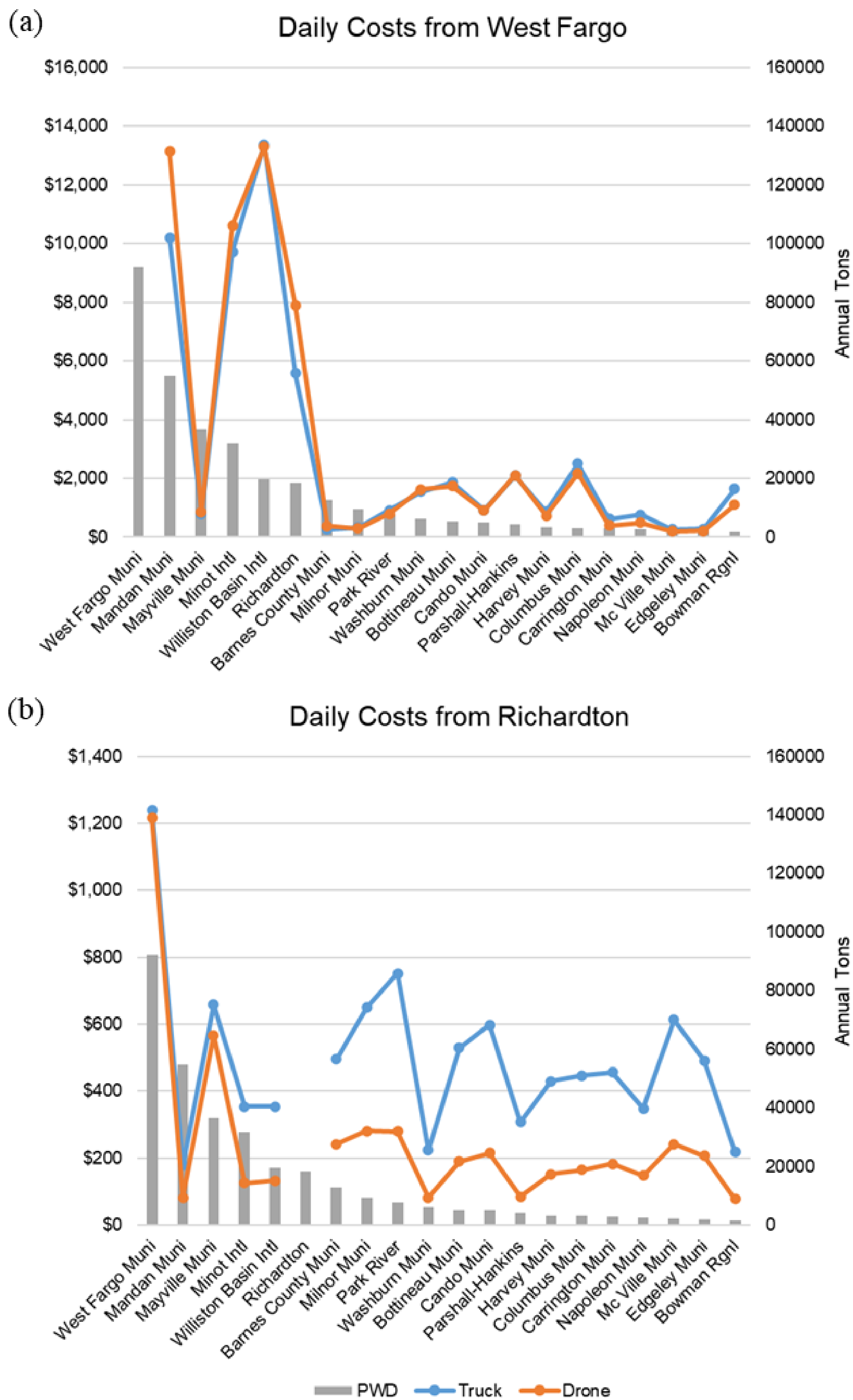


Figure 77: Daily costs for trucks and drones transporting from TTHs at a) West Fargo, and b) Richardton

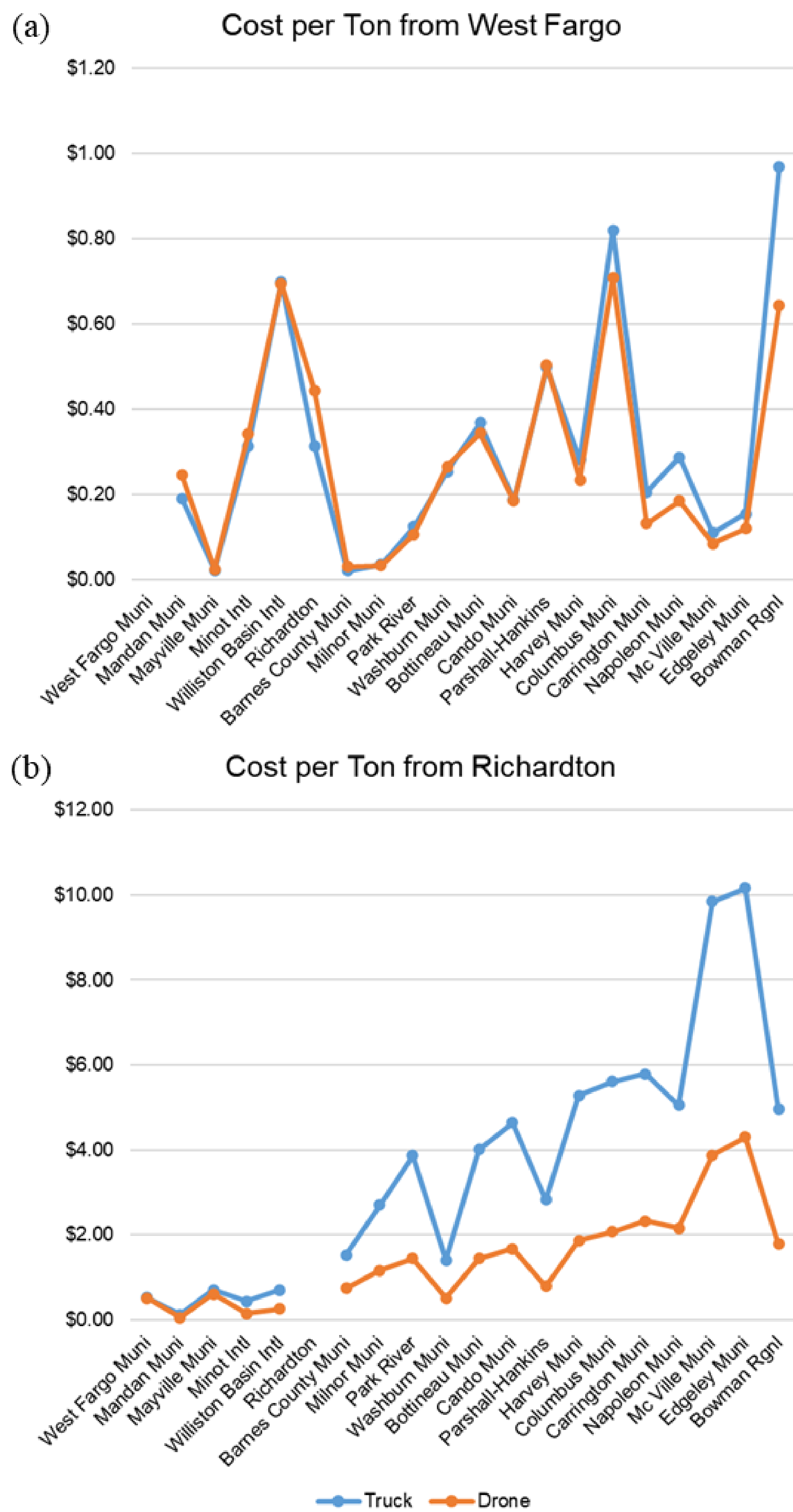
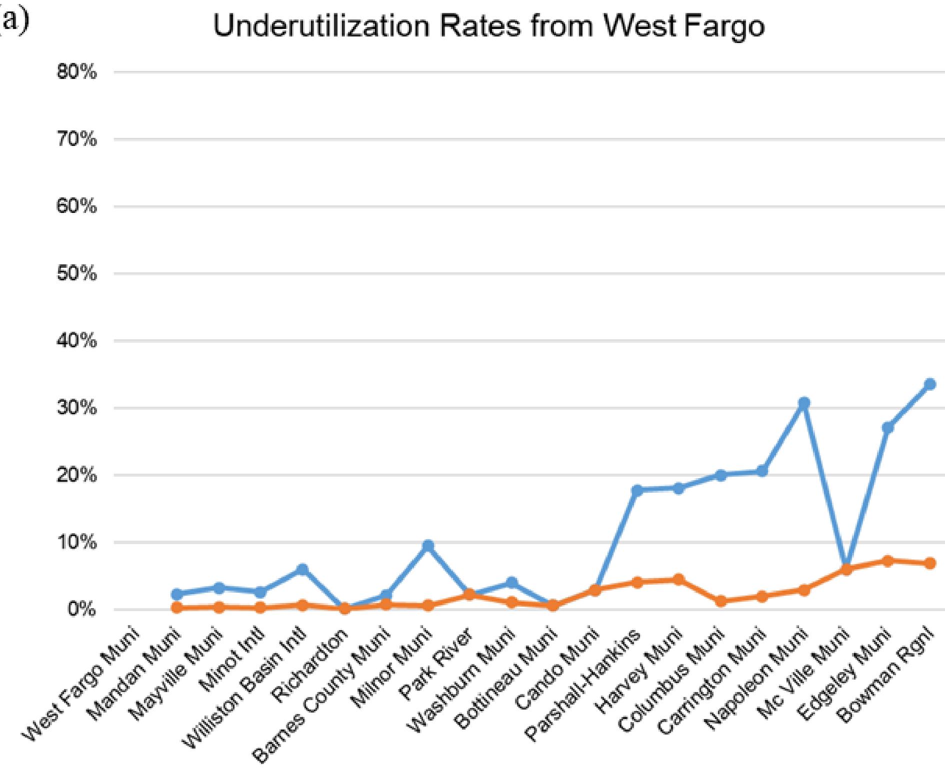


Figure 78: Cost per ton for trucks and drones transporting from TTHs at a) West Fargo, and b) Richardton

(a)



(b)

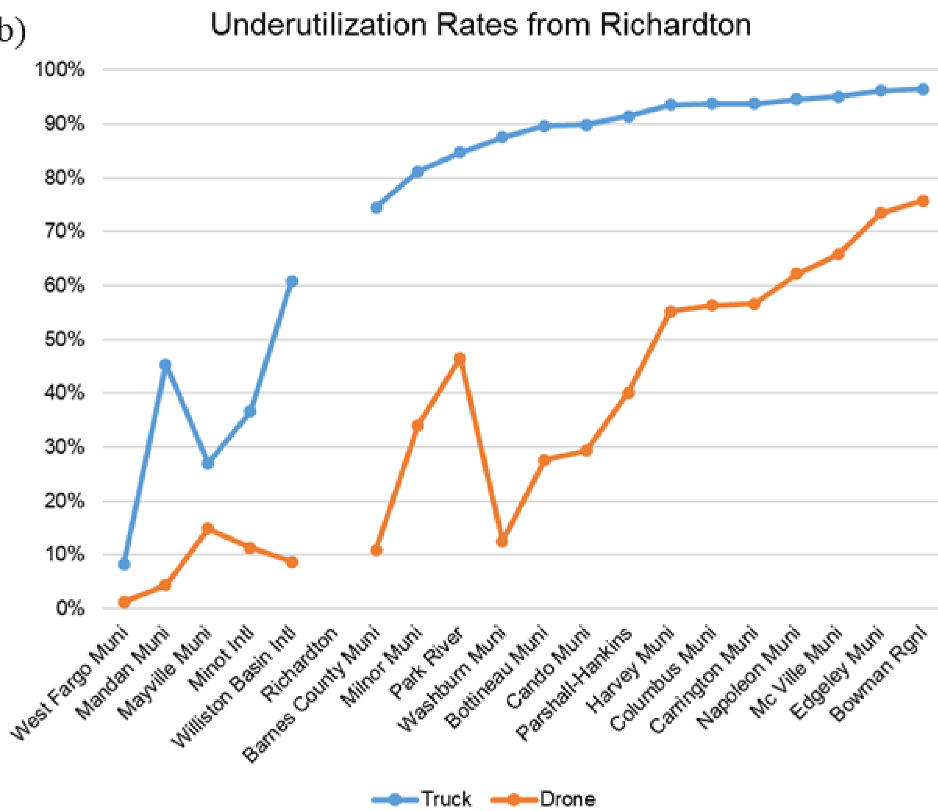


Figure 79: Underutilization rates for trucks and drones transporting from TTHs at a) West Fargo, and b) Richardton

Infrastructure Implications for AAM Deployment

Collectively, analysis outcome establishes that infrastructure is not the binding constraint for AAM freight deployment. Existing airports, when strategically selected and lightly upgraded, can support middle- and last-mile AAM networks that serve hazardous materials, pharmaceuticals, and high-value electronics. The infrastructure model emphasizes reuse, scalability, and compatibility with healthcare and logistics assets already in place.
Within the broader report, this infrastructure evaluation subsection provides the physical and spatial foundation linking technology readiness and market demand. It shows that AAM can achieve the primary objective of this study (preserving ground transportation infrastructure by shifting freight to air) without waiting for large-scale new infrastructure investments. Furthermore, AAM deployment in this manner will simultaneously enable healthcare access, safety improvements, and rural connectivity.

2.3.2 Urban Vertiport Integration for Congestion-Reducing AAM Freight

This subsection evaluates urban infrastructure readiness for freight-oriented AAM (Bridgelall 2024). The analysis extends the prior rural and middle-mile infrastructure evaluations to dense metropolitan environments. It demonstrates how existing urban airports and strategically placed vertiports can be integrated to divert truck traffic away from congested gateways. The objective is to show that urban AAM deployment can reuse infrastructure assets already present in cities (airports, trade gateways, and logistics districts) while complementing local hospital- and airport-centric networks established in earlier sections.

Urban freight congestion is framed as a gateway problem, not a last-mile inefficiency alone. Trucks serving airports, seaports, and border crossings concentrate delay, emissions, and pavement wear in limited urban zones. The study positions electrified and autonomous aircraft (EAA) cargo shuttles as a means to bypass these bottlenecks by relocating freight handling to less congested facilities while preserving service reliability. The proposed logistics concept appears in Figure 80. It illustrates how EAA shuttles can connect busy trade gateways with underutilized regional airports and remote vertiports. This figure anchors the infrastructure logic by showing that congestion relief arises from spatial redistribution of freight activity, not from adding capacity to already constrained roadways.

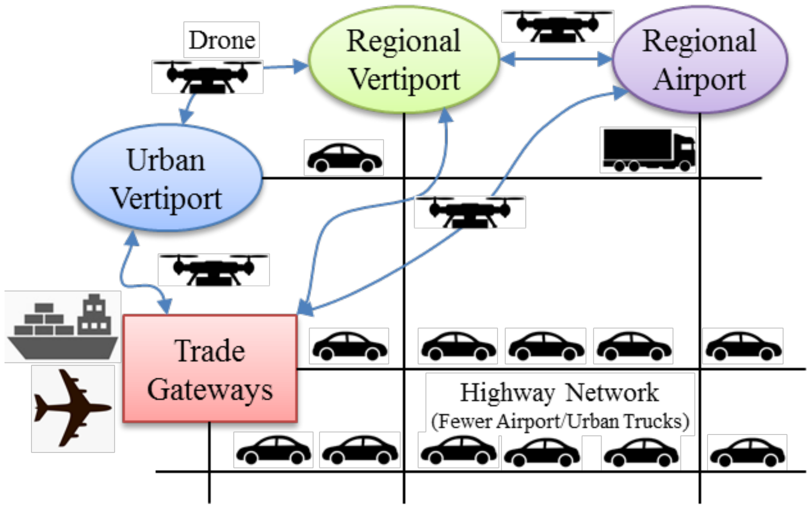


Figure 80: Proposed logistics to divert truck traffic away from busy trade gateways

Urban Infrastructure Reuse and Spatial Feasibility

The infrastructure assessment relies on existing airports and potential vertiport locations embedded within MSAs. Using the FAF data and census-based MSA definitions, this study demonstrates that most U.S. MSAs contain multiple airports within approximately 100 miles of one another, as visualized in Figure 81. This spatial proximity implies that eVTOL and short-runway EAAs can already support intra-MSA and inter-MSA transfers without extensive new aviation infrastructure. The finding aligns with earlier hospital- and airport-based analyses by showing that airside access is not the limiting factor in urban environments.

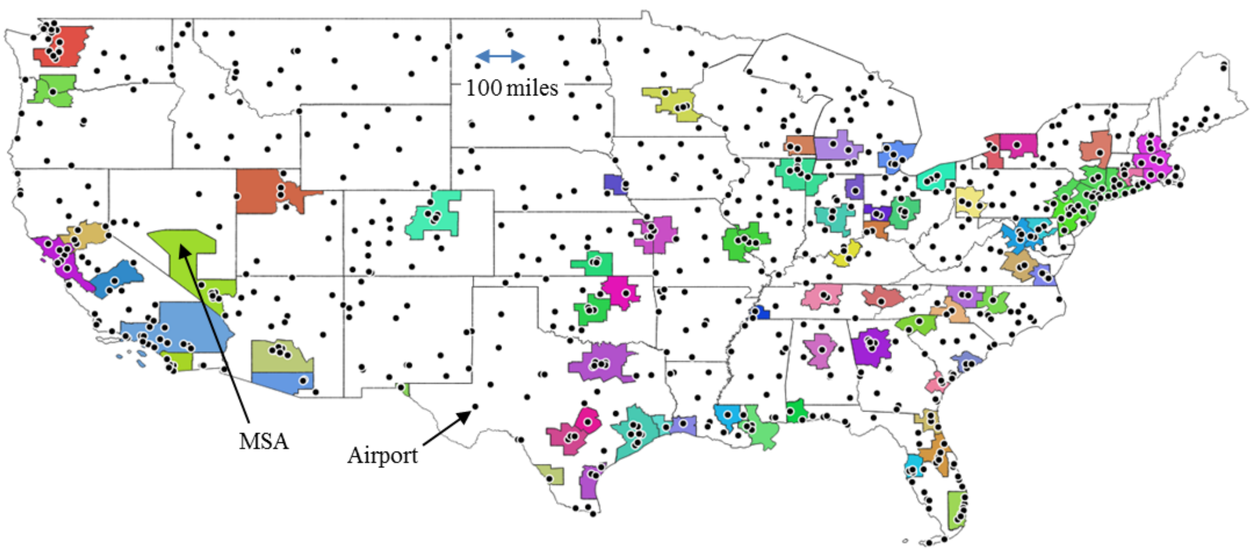


Figure 81: Spatial distribution of MSAs and airports

The analytical workflow that links FAF commodity flows, MSA geography, and airport locations is documented in Figure 82. This figure is central because it shows how national freight datasets are transformed into infrastructure-relevant insights through data cleaning, MSA harmonization, and spatial aggregation. The same workflow logic underpins earlier middle-mile and last-mile studies. It ensures methodological consistency across rural and urban contexts.

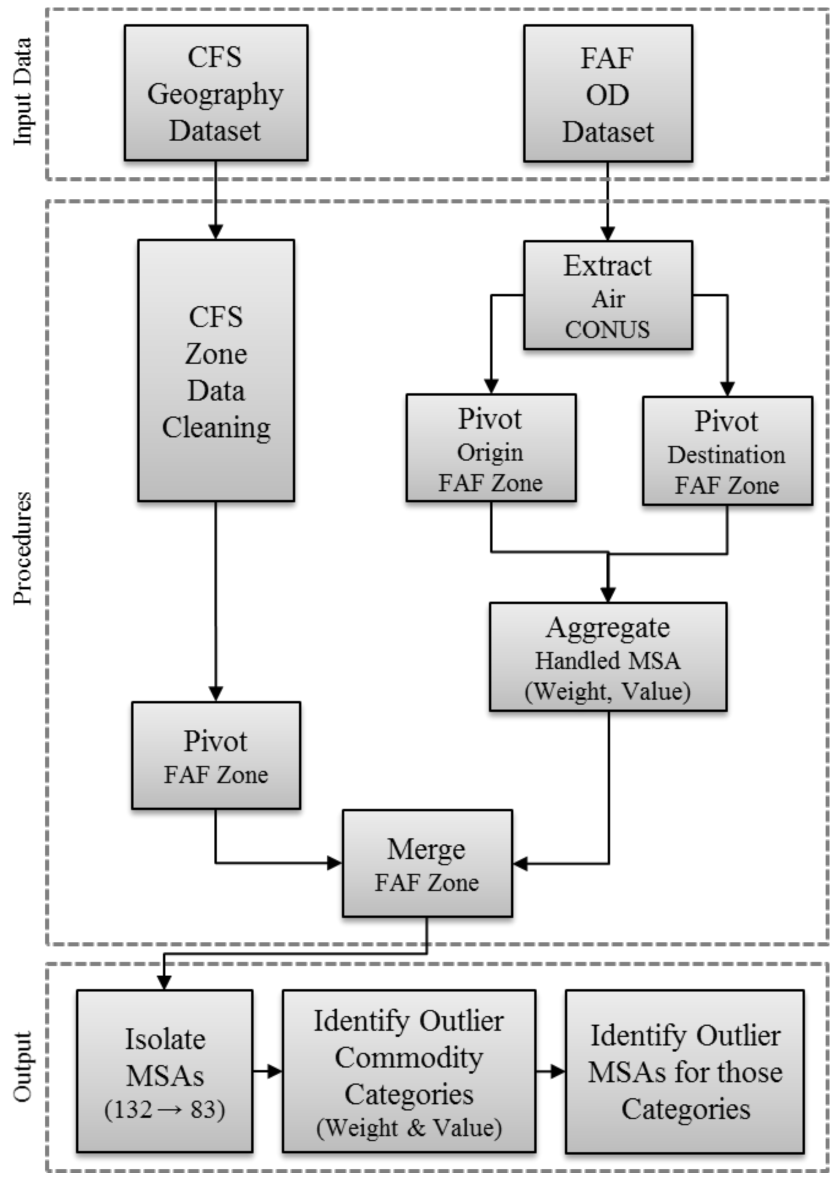


Figure 82: Input datasets and analytical workflow

Commodity–Infrastructure Alignment in Urban Markets

Urban infrastructure prioritization is guided by commodity characteristics that favor air transport. Scatter analysis of air-moved commodities by weight and value, shown in Figure 83, identifies electronics as the dominant outlier. Electronics exhibit high value density and strong time sensitivity. This makes them well suited to EAA shuttles that remove trucks from congested corridors serving airports and logistics hubs. The study's identification of electronics reinforces earlier market analyses that highlighted similar commodity classes for middle-mile AAM.

The concentration of air-compatible commodities within a small number of MSAs further informs infrastructure deployment. Figure 84 presents weight histograms showing that a few MSAs dominate air-moved electronics and related categories. This concentration implies that targeted infrastructure integration at a limited number of urban nodes can yield disproportionate congestion relief. The result parallels earlier findings in hazardous materials and pharmaceuticals, where a small set of regions accounted for a large share of demand.

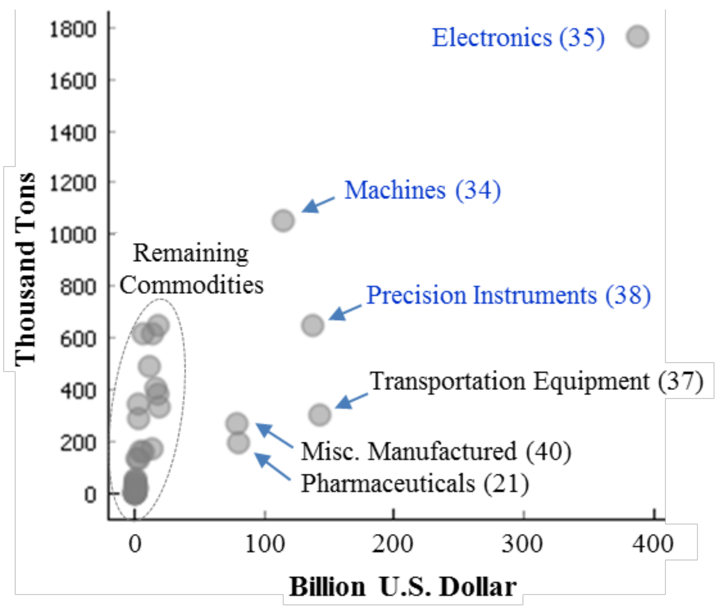


Figure 83: Commodity category outliers by weight and value moved by air

Table 22 summarizes the top MSAs by weight for six outlier commodity categories and translates those weights into semitrailer-equivalent truck counts. This table directly links infrastructure decisions to roadway impacts by quantifying how many trucks could be removed from urban traffic streams if EAA shuttles handled airport-bound freight. For example, the analysis shows that deploying EAA services in Los Angeles and Chicago alone could remove more than 21,000 semitrailer trucks per year from each MSA's roadway network. This quantification strengthens the infrastructure case by tying airport and vertiport deployment to measurable congestion and pavement benefits.

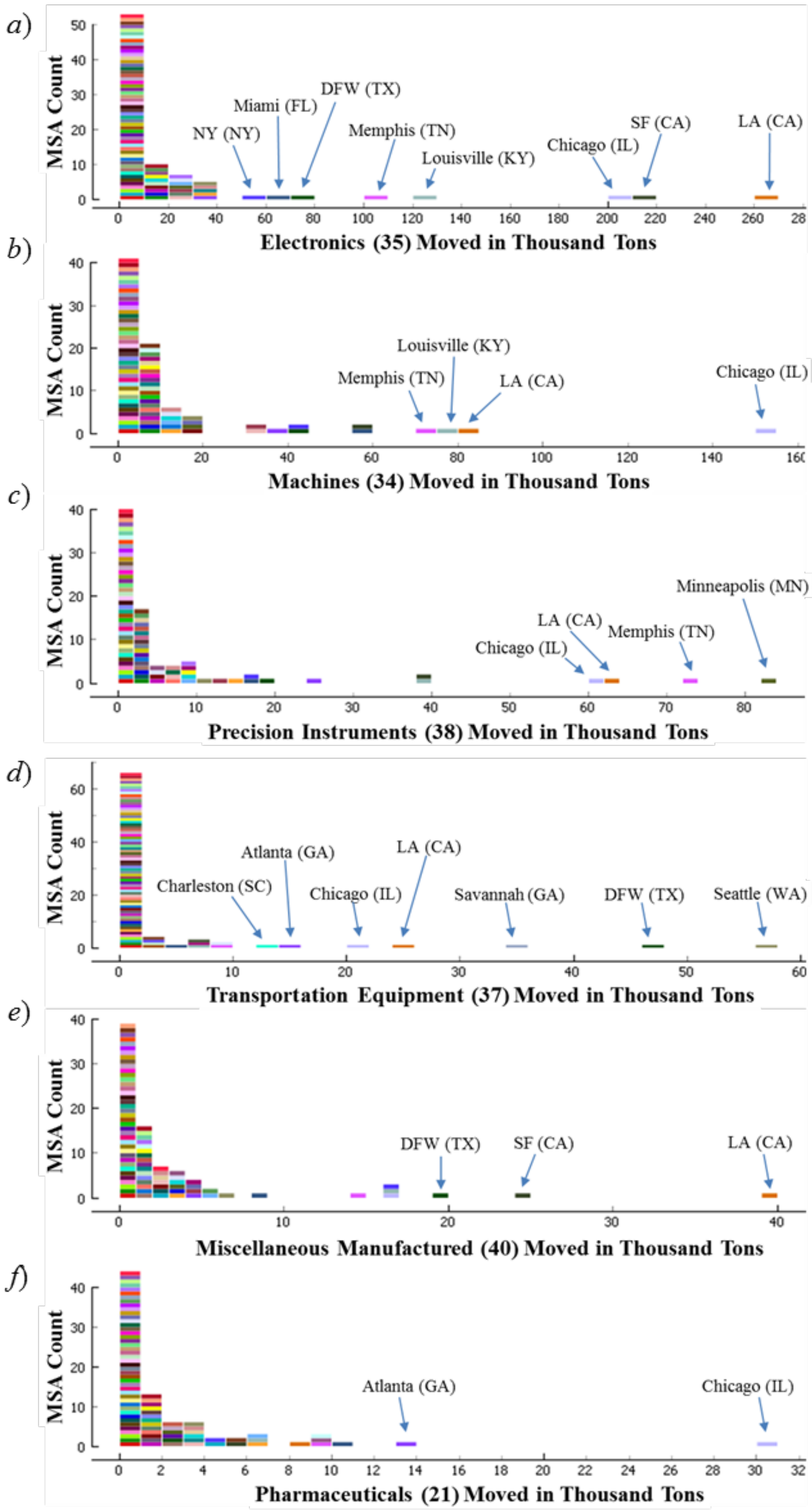


Figure 84: Weight histogram of MSAs for the outlier commodity categories moved by air

Table 22: MSA Rank by Weight of Outlier Commodity Categories Moved by Air

MSA	Electronics	Machines	Precision Instruments	Transportation Equipment	Misc. Manufactured	Pharma.	Sum (Thousand Tons)	Semitrailer Equivalent
Chicago (IL)	200.1	151.3	60.7	20.5	16.5	30.3	479.2	21,299
Los Angeles (CA)	262.6	81.0	62.6	24.0	39.2	8.7	478.2	21,251
San Francisco (CA)	218.4	59.3	38.5	7.0	24.2	5.3	352.7	15,674
Memphis (TN)	100.2	71.2	73.4	8.7	15.0	9.9	278.3	12,371
Louisville (KY)	124.0	77.8	39.6	7.9	16.9	6.9	273.2	12,141
DFW (TX)	78.9	40.6	18.6	46.2	19.9	2.7	206.9	9,197
Miami (FL)	69.9	55.5	17.4	4.8	8.3	10.2	166.0	7,378
New York (NY)	54.9	41.6	16.3	3.5	16.5	4.0	136.8	6,082
Atlanta (GA)	39.8	38.1	24.5	14.7	4.8	13.4	135.4	6,016
Seattle (WA)	31.9	18.4	10.1	57.7	6.7	3.6	128.3	5,704
Minneapolis (MN)	22.3	15.7	82.1	1.0	3.3	2.2	126.5	5,623
Savannah (GA)	0.8	0.7	0.5	34.6	0.1	0.1	36.8	1,635
Charleston (SC)	2.8	2.2	1.2	13.5	0.7	0.5	20.8	926

Prioritizing Urban Nodes for EAA Deployment

The study ranks MSAs by potential congestion reduction impact using cumulative weight thresholds. Figure 85 shows that fewer than 10% of MSAs account for approximately 25% of the total weight of air-moved outlier commodities. This finding supports a phased urban deployment strategy in which EAA infrastructure investments focus on the highest-impact cities first, with diminishing returns beyond that set.

The infrastructure logic mirrors earlier hospital- and airport-based networks by emphasizing reuse and redistribution. In rural contexts, underutilized airports serve as gateways to healthcare facilities. In urban contexts, underutilized or peripheral airports and remote vertiports serve as buffers between dense trade gateways and regional logistics networks. In both cases, AAM leverages existing assets to avoid costly new construction while achieving system-level benefits.

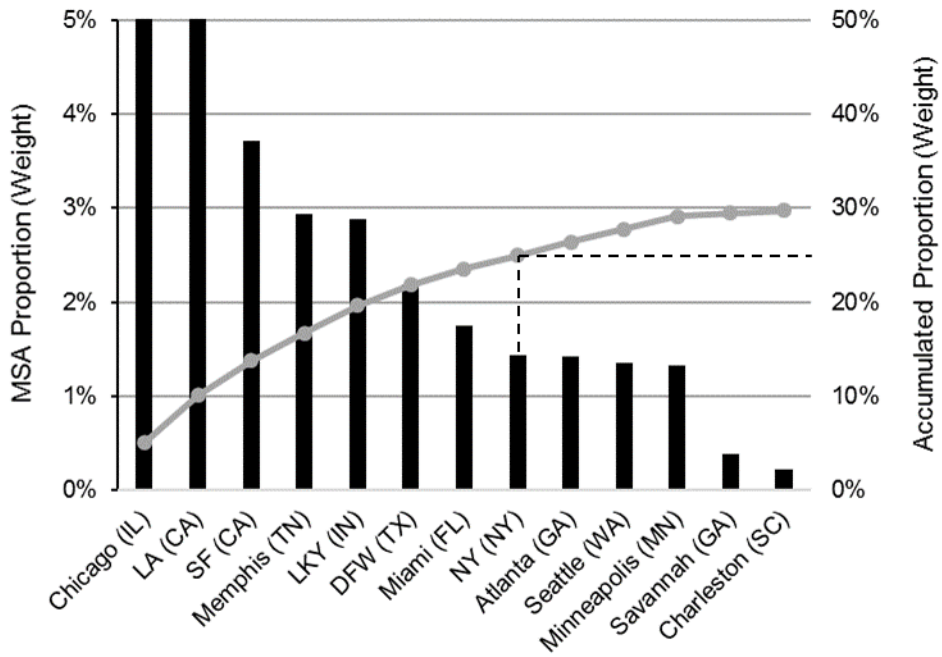


Figure 85: MSA impact ranking for EAA cargo service deployments

Integration with Broader Urban Logistics Systems

The urban infrastructure evaluation also considers compatibility with existing logistics ecosystems. By shifting air-transportable freight from trucks to EAAs, urban planners can relocate freight processing to less congested facilities, enabling synergies with fulfillment centers, warehouses, and autonomous trucking services. The study notes that increasing belly cargo capacity on passenger flights will further amplify these benefits, as EAAs reduce truck dependency around major airports during peak periods (IATA 2024) (Kulisch 2021).

From a policy perspective, the infrastructure model aligns with sustainability objectives by reducing truck-related pollution, noise, and roadway wear in dense urban areas (Justin, Payan and Mavris 2022) (Wang, et al. 2020). The reuse of existing airports and the selective addition of vertiports also lower barriers to adoption by minimizing land-use conflicts and capital intensity.

Infrastructure Implications for Urban AAM Deployment

Collectively, this section establishes that urban infrastructure is sufficiently mature to support targeted AAM freight deployment today, provided that planners focus on high-impact commodities and MSAs. The analysis shows that congestion reduction does not require ubiquitous vertiport networks or wholesale redesign of urban logistics. Instead, it emerges from strategic integration of EAAs with existing airports and freight gateways. This is consistent with the infrastructure reuse principles demonstrated in rural healthcare and middle-mile freight studies. This section demonstrates that AAM can preserve ground transportation infrastructure at multiple scales (by relieving rural inefficiencies, intercepting middle-mile truck flows, and mitigating urban congestion) using largely the same classes of existing assets. This continuity provides a strong foundation for the subsequent regulatory section, where airspace integration, certification, and policy alignment become the remaining determinants of deployment feasibility.

2.4 Regulatory Review

2.4.1 Regulatory Readiness and Adoption Preconditions

This subsection evaluates regulatory readiness as a prerequisite for AAM deployment (Bridgelall 2023). It serves as a conceptual and empirical precursor to the more extended regulatory synthesis that follows in the next subsection. That synthesis examines airspace integration, certification pathways, and policy alignment in detail. In this subsection, the objective is to identify which national conditions most strongly predict early AAM adoption. It frames where regulatory progress is most likely to occur and where targeted policy intervention may be required.

The analysis defines AAM adoption pragmatically as the presence of national-level drone regulations that legalize operations under a common set of rules. It recognizes such regulations as a necessary, though not sufficient, condition for future AAM integration. This framing aligns with earlier sections of the report. It demonstrates that technology, market demand, and infrastructure can often be repurposed from existing assets, whereas regulatory capacity cannot be substituted or bypassed.

Conceptual Framing: Regulation as the Binding System Constraint

While prior sections showed that existing airports, hospitals, and logistics facilities can support AAM operations with limited modification, regulatory readiness emerges as the system-level gatekeeper. Without enabling rules, neither middle-mile nor last-mile AAM networks can operate at scale, regardless of technical feasibility or market demand. The study, therefore, positions regulation as the first national signal of institutional readiness. It is consistent with the roles of organizations such as the International Civil Aviation Organization and International Air Transport Association in setting global aviation norms.

Data Assembly and Indicator Scope

The study assembled a unique global dataset covering 204 nations. It combines a binary target variable indicating whether drone operations were legally regulated with 36 candidate indicators spanning economic, governance, social, environmental, land-use, technology, and transportation domains. The indicators and their sources are documented in Table 23 and Table 24. They list variables such as gross domestic product (GDP), governance effectiveness, regulatory quality, logistics performance, air traffic activity, population density, and technology access.

Table 23: Drones, Economic, Social, Environmental, and Governance Attributes Selected

	Attribute	Description	Dataset	Year	N
Drones	Fly	Drone use regulated (target feature)	CAA Web	2022	222
	Designs_LN	Number of drone designs	VFS	2022	222
Economic	POP_M_LN	Population in millions (LN)	UN-WPP	2022	237
	POP_Gr	Population growth (annual %)	WB-PI	2021	222
	GDP_B_LN	GDP in $billion (LN) (current US$)	WB-WDI	2021	217
	GDPP_LN	GDP per capita (LN) (current US$)	WB-WDI	2021	217
	GDP_Gr	GDP growth (% since 2015 US$)	WB-GEP	2021	217
	Unemploy_LN	Unemployment (% of labor force)	WB-SDG	2020	261
	Arrivals_LN	Number of tourism arrivals	WB-WDI	2020	266
Environ-ment	SPI	Social progress index	SPI	2021	168
	EQI-SPI	Environmental quality index	SPI	2021	168
	CO2_KT_LN	CO2 emissions (kilotons), LN	WB-WDI	2019	266
Governance	Gov_Eff	Governance effectiveness index	WGI	2019	214
	Polit_Stab	Political stability index	WGI	2019	214
	Reg_Qual	Regulatory quality index	WGI	2019	214
	Laws	Rule-of-law index	WGI	2019	214

Table 24: Land Use, Technology, and Transportation Attributes Selected

	Attribute	Description	Dataset	Year	N
Land Use	Land_SqKM	Land area (sq. km)	WB-WDI	2019	268
	Urban_SqKM_LN	Urban area (sq. km), LN	WB-WDI	2010	268
	UrbanPop	Urban population (% of total)	WB-SDG	2020	261
	UrbanGr	Urban population growth (annual %)	WB-SDG	2020	261
	Rural_SqKM	Rural area (sq. km)	WB-WDI	2010	266
	Ag_SqKM	Agricultural land (sq. km)	WB-WDI	2018	266
	Rural_r	Rural/land area ratio	Derived	2010	266
	Urban_r_LN	Urban/land area ratio	Derived	2010	268
	Ag_r_LN	Agricultural/land area ratio	Derived	2010	266
	Forest_PCT_LN	Forest/land area ratio	WB-WDI	2019	266
	POP_SqKM	Population density (persons/sq-km)	WB-J	2016	242
	Land_Type	Landlocked (L), open ocean border (W), island (I)	Google	2022	222
Tech.	Electric_Cost	Cost to get in % of income per capita	WB-DB	2019	191
	ATM100K_LN	ATMs per 100,000 adults	WB-J	2016	242
	Phone100	Mobile phone subscriptions per 100 persons	WB-J	2016	242
Transportation	LPI	Logistics performance index	WB-WDI	2018	266
	Infr_Qual	Infrastructure quality index	WB-WDI	2018	266
	Air_Cargo_LN	Air freight (million ton-km), LN	WB-WDI	2019	266
	Air_Pax_LN	Air passengers (year)	WB-WDI	2019	266
	Port_TEU_LN	Port traffic, 20-ft equivalent units (TEU)	WB-WDI	2019	266
	Road_Deaths	Road traffic mortality (per 100,000)	WB-WDI	2019	266

The target variable was derived through a systematic review of each nation's civil aviation authority, using references from the International Civil Aviation Organization and International Air Transport Association to identify authoritative regulatory sources. Nations were classified as adopters if a defined set of operational rules permitted drone use, even if those rules imposed strict limitations.

Machine Learning Framework and Model Selection

The methodological workflow, illustrated in Figure 86**,** applied a three-stage process. These were feature engineering, feature selection, and supervised machine learning. The framework trained 12 mature machine learning models, including tree-based, statistical, decision-boundary, and neural network approaches, and evaluated them using five complementary performance metrics. Those were areas under the receiver operating curve (AUC), classification accuracy, precision, recall, and F1 score.

Model performance results are summarized in Table 25, which shows that eight models exceeded accepted thresholds for strong predictive performance. The artificial neural network (ANN) model emerged as the best overall. It achieved an AUC of 0.923 and the highest composite score. The selection of ANN is significant because it suggests that AAM adoption correlates with nonlinear interactions among indicators, rather than simple threshold effects.

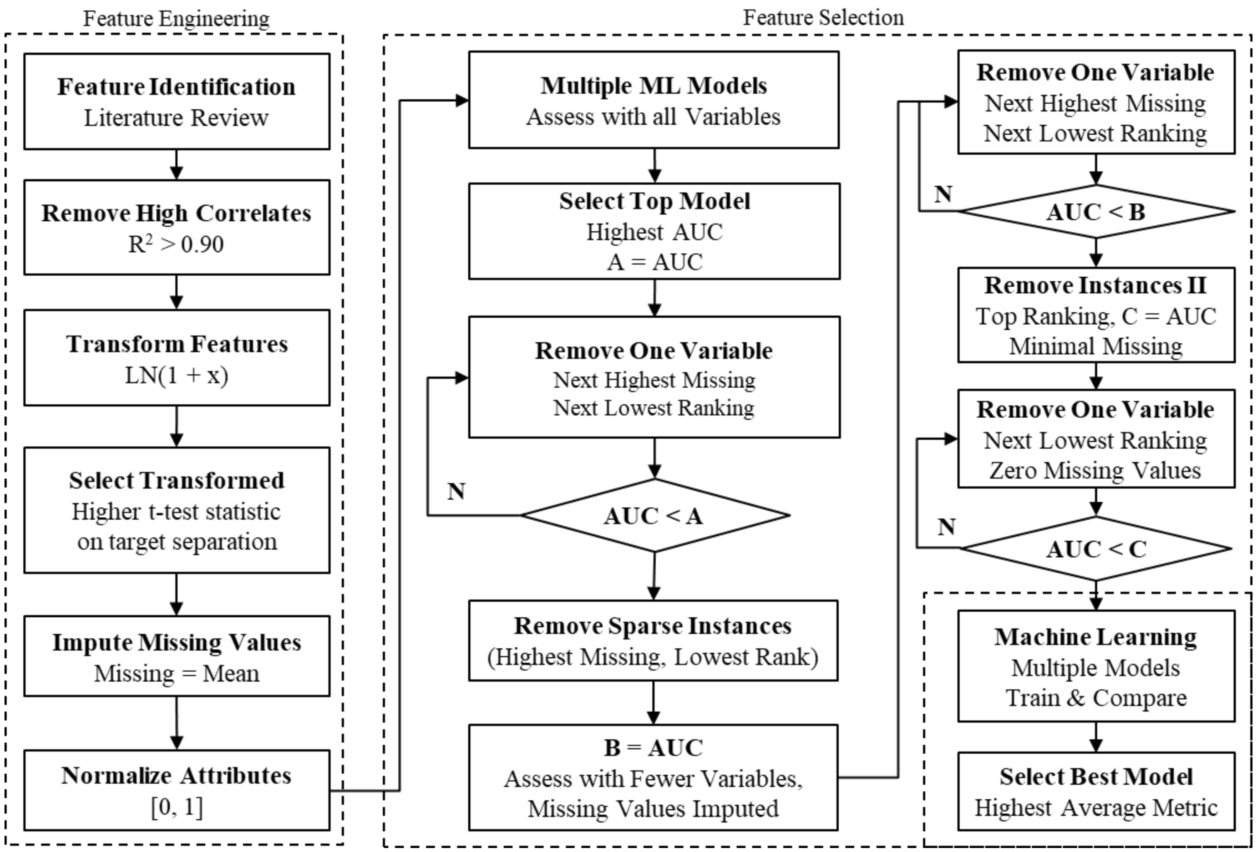


Figure 86: Feature engineering and machine learning workflow

Table 25: ML Model Performance Scores

Model	AUC	CA	F1	Pr	Rc	Mean	T&T
ANN	0.923	0.886	0.884	0.882	0.886	0.892	113.6
LR	0.912	0.873	0.864	0.867	0.873	0.878	6.5
SVM	0.885	0.867	0.861	0.860	0.867	0.868	10.0
NB	0.926	0.843	0.852	0.874	0.843	0.868	3.9
kNN	0.870	0.861	0.859	0.857	0.861	0.862	9.3
RF	0.889	0.855	0.850	0.848	0.855	0.859	47.0
Catboost	0.871	0.849	0.849	0.848	0.849	0.853	53.9
XGB	0.876	0.849	0.845	0.842	0.849	0.852	41.5
SGD	0.782	0.861	0.861	0.860	0.861	0.845	6.4
GB	0.853	0.837	0.835	0.832	0.837	0.839	36.9
AdaBoost	0.733	0.801	0.808	0.817	0.801	0.792	11.0
DT	0.658	0.795	0.793	0.791	0.795	0.766	6.1
No Skill	0.459	0.795	0.704	0.632	0.795	0.677	1.0

Key Predictors of AAM Adoption

The attribute importance ranking produced by the ANN model is shown in Figure 87. Two indicators dominated all others:

1. Gross Domestic Product (GDP)
2. Regulatory Quality Index (RQI) from the Worldwide Governance Indicators

These two variables accounted for the largest reductions in predictive performance when permuted. This indicated that they contributed the most explanatory power. GDP captured a nation's economic capacity to invest in new aviation systems, while RQI measured the government's ability to formulate and implement policies that support private-sector development.

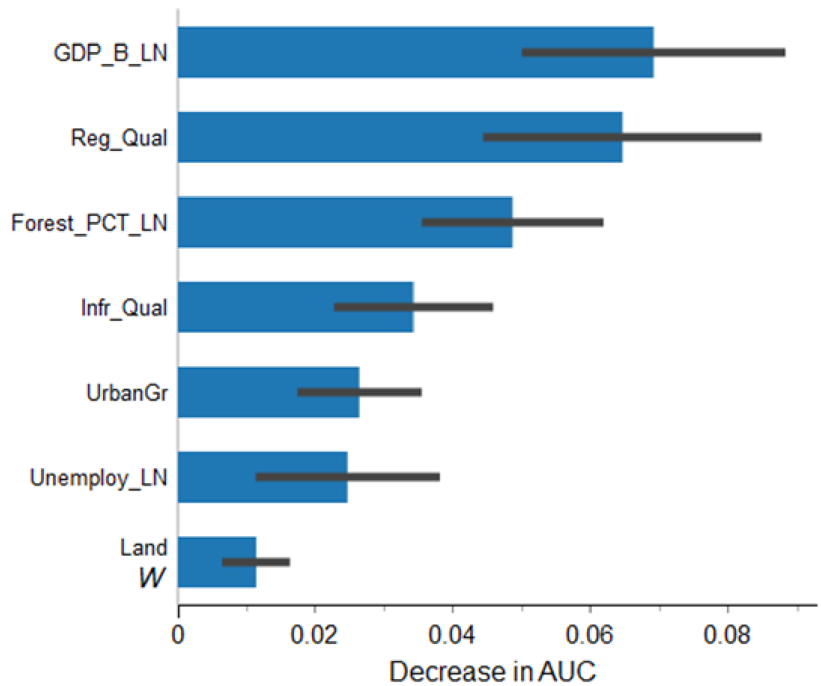


Figure 87: ANN feature ranking by AUC reduction

The joint influence of these indicators is visualized in Figure 88, which plots nations along normalized GDP and RQI axes. Nations in the upper-right quadrant (characterized by strong economies and high regulatory quality) were most likely to have legalized drone operations. Conversely, nations in the lower-left quadrant were least likely to have done so.

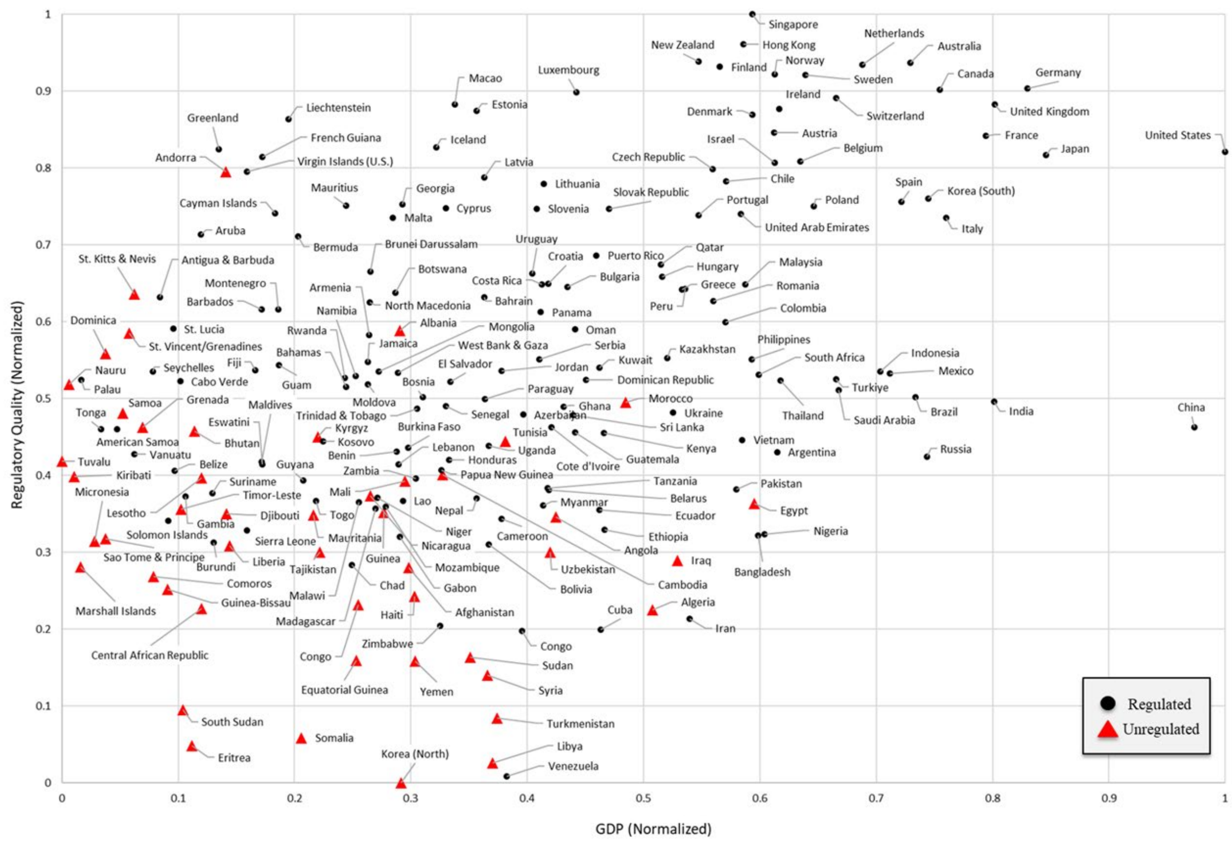


Figure 88: Normalized regulatory quality index and GDP among locations that did and did not regulate drone operations

Importantly, many commonly assumed predictors performed poorly. Social progress, land-use characteristics, population density, technology access (electricity and mobile phones), carbon emissions, aviation traffic, port activity, tourism, and roadway fatalities all exhibited low or negligible predictive importance. This result challenges the assumption that infrastructure maturity or social development alone drives AAM readiness.

Implications for Infrastructure- and Market-Led AAM Deployment

These findings align directly with earlier sections of the report. Market analyses showed that AAM demand concentrates on specific commodities and regions. Infrastructure evaluations demonstrated that existing airports and hospitals can support deployment. However, this regulatory analysis shows that national institutional capacity ultimately determines whether those opportunities can be realized.

For freight-oriented AAM aimed at preserving ground transportation infrastructure, the results imply that early deployment will continue to cluster in economically strong nations with high regulatory quality, even when market need exists elsewhere. This divergence has implications for global supply chains, humanitarian logistics, and equity, particularly in regions where hazardous materials and pharmaceuticals would benefit most from aerial transport but where regulatory frameworks lag.

Positioning for Subsequent Regulatory Synthesis

As a precursor to the forthcoming regulatory section, this subsection establishes three critical foundations:

1. Regulation precedes integration: Airspace access, certification, and operational approval depend on baseline regulatory legitimacy.
2. Economic and governance capacity dominate: GDP and regulatory quality outperform all other indicators as predictors of adoption.
3. Targeted policy action matters: Improving regulatory quality may accelerate AAM adoption more effectively than investments in infrastructure or technology alone.

The next section builds on this foundation by examining how current regulatory regimes address airspace integration, vehicle certification, and operational scaling, and how emerging policies may either reinforce or relax the adoption patterns identified here.

2.4.2 Airspace Integration, Certification, and Policy Alignment for AAM

This section synthesized the most recent, AAM-specific developments in airspace integration, aircraft and operator certification, and policy alignment. It extends the earlier project findings that markets and infrastructure often exist today, while institutional readiness and rule alignment determine when freight shifts from roads to air at scale.

Certification Pathways Converged on "Powered-Lift"

In the United States, powered-lift integration moved from ad hoc approvals toward a stable, performance-based pathway. The FAA finalized the "Integration of Powered-Lift" rule in October 2024 and codified a 10-year special federal aviation regulation (SFAR) and related amendments (FAA 2024). The rule created an "alternate framework" for early cohorts of powered-lift pilots and instructors and clarified how powered-lift operations map into existing operating rules (Parts 91, 97, 135, and 136). It also tightened the linkage to the International Civil Aviation Organization (ICAO) expectations through a powered-lift type-rating structure.

This development mattered for freight-oriented AAM because it reduced one of the highest-friction barriers: a legally operable combination of aircraft category, pilot qualification, and operating rules. It also reinforced this report's earlier technology assessment logic. Energy limits and propulsion efficiency are bounds on range and payload. Certification now sets bounds on how and where those aircraft can legally operate in the near term.

In Europe, the European Union Aviation Safety Agency (EASA) continued to mature the VTOL certification basis through iterative means of compliance (MoC). EASA updated its special condition VTOL ecosystem in July 2025 with a fourth publication on MoC (EASA 2025). This document expanded and clarified compliance expectations across flight, crashworthiness, lift/thrust system installation, and high-voltage electromagnetic field hazards, among other topics. This MoC progression mattered because it translated high-level safety intent into testable design evidence. It also supported cross-jurisdiction alignment, which the FAA publicly emphasized in June 2024 as both agencies worked toward more closely aligned eVTOL certification and policy initiatives (FAA 2024).

The implication of these recent developments is that certification readiness now follows a predictable logic in both major regimes. However, the regimes still require heavy system evidence for batteries, high voltage, crashworthiness, and flight control integrity. That reality reinforces earlier findings that energy density constraints push manufacturers toward tightly integrated designs and conservative early operations.

Airspace Integration Shifted from Concept to "Scalable Operations" Mechanisms

AAM scaling required more than "permission to fly." It required repeatable, high-tempo operations in mixed traffic while meeting aviation-grade safety targets. Recent work converged on three technical–regulatory pillars:

- Detect-and-avoid, collision avoidance, and surveillance as the scalability core,
- Vertiport–airspace procedures became the integration unit,
- Unmanned aircraft system traffic management (UTM) and air traffic management (ATM) convergence became the policy direction.

Detect-and-Avoid, Collision Avoidance, and Surveillance

AAM integration increasingly treated conflict management as a system-of-systems problem that joined avionic performance standards, surveillance coverage, and service-provider interoperability. The Radio Technical Commission for Aeronautics (RTCA) committee documented current work that explicitly included automated collision avoidance system (ACAS Xr) for rotorcraft and AAM/UAM applications and described ongoing coordination with other committees on interoperability between collision avoidance and detect-and-avoid standards (RTCA 2025). NASA research similarly focused on mechanisms that enable routine multi-aircraft operations in non-segregated airspace. This highlighted the need to reduce dependence on voice and human-centric instrumented flight rule (IFR) interactions when scaling "many-to-one" or "many-to-many" operational concepts (NASA 2025).

The U.S. DOT's AAM National Strategy (December 2025) added an infrastructure and service implication that AAM may require expanded surveillance and conflict-management service levels in areas where current systems do not provide continuous coverage (USDOT 2025). The implication for freight AAM is that middle-mile freight corridors and rural networks can scale faster where surveillance, communication, and procedural predictability exist. Where they do not exist, the system must either add surveillance and services or constrain operations by procedure, schedule, or weather. Those constraints directly affect the truck-mile diversion potential established in the market analysis.

Vertiport–Airspace Procedures

Urban AAM integration increasingly treated the vertiport as the operational unit that couples ground throughput with airspace capacity. Research on integrating vertiport operations into airspace emphasized procedural coupling to UTM-style services and performance-based constraints that maintain separation and predictability near dense nodes (Schuchardt, et al. 2025). Peer-reviewed work also quantified vertiport operational plans and delays. They treated turnaround and scheduling as drivers of both safety and throughput, not only infrastructure design (Lee, et al. 2025).

On the infrastructure side, U.S. FAA materials explicitly framed early operations as leveraging existing heliports and airports with modifications, while also anticipating new vertiport facilities as demand grows (FAA 2025). Hence, earlier infrastructure evaluations showed that airports and hospital assets can anchor rural and regional AAM with modest changes. Urban scaling adds a second bottleneck, namely node throughput at vertiports and gateway facilities. Freight use cases can exploit off-peak windows and cargo-specific nodes to reduce that bottleneck.

UTM and ATM Convergence

ICAO materials increasingly framed AAM within an environment that connects UTM concepts with state air navigation and safety management expectations. ICAO's AAM environment and UTM framing emphasized AAM as part of the broader integration agenda rather than an isolated drone topic (ICAO 2025). In standards and interoperability, roadmap and gaps reporting from the American National Standards Institute (ANSI) continued to track standards that support service-provider interoperability and remote identification as foundational blocks for scaled low-altitude operations that include UAM/AAM contexts (ANSI 2025). NASA's AAM Mission and National Campaign also positioned integration research as a path to routine operations in cities and the NAS (NASA 2025). This reinforced a phased approach from early demonstrations to scalable operations. The implication from this research is that policy alignment is moving toward digital, service-supported operations. That direction complements freight objectives because service-provider coordination supports repeatable scheduling, corridor management, and predictable operations that displace truck trips.

2.4.3 Policy Alignment Expanded from FAA Rules to Multi-Level Governance

The U.S. policy posture now explicitly guides state, local, Tribal, and territorial (SLTT) actions. The Advanced Air Mobility National Strategy stated a two-phased approach and highlighted actions for SLTT governments, including modifications that can make existing heliports usable for AAM aircraft (USDOT 2025). This development directly connected to earlier project findings:

1) Market analyses identified concentrated MSAs and corridors for high-value commodities and safety-critical hazardous materials.
2) Infrastructure evaluations showed that airports and healthcare facilities can serve as immediate nodes.
3) The national strategy now addresses how communities can enable those nodes, which reduce implementation friction.

Europe and other jurisdictions pursued alignment by adopting or referencing VTOL frameworks. The U.K. CAA's adoption posture toward EASA VTOL and MoC signaled that alignment can propagate through regulatory borrowing rather than reinvention. This especially matters for cross-border supply chains (UKCAA 2024). The implication for this research is that the adoption model discussed earlier remains consistent with current policy evolution. National strategies and cross-regime certification frameworks reinforce that governance capacity drives near-term deployment locations.

2.4.4 Integrated Interpretation for Freight and Infrastructure Preservation

The earlier sections established a systems logic:

1. Energy density bounded aircraft performance.
2. Electrification efficiency and propulsion integration governed the feasible operating envelope.
3. Battery and hydrogen innovation trajectories indicated where the envelope may expand.
4. Markets concentrated by commodity and geography.
5. Infrastructure often existed and can be repurposed.

This section added the final binding layer: institutional integration capacity.

- Certification frameworks (FAA powered-lift; EASA VTOL MoC) reduced uncertainty for manufacturers and operators, but still demanded rigorous evidence on batteries, high voltage, crashworthiness, and flight control integrity (FAA 2024).
- Airspace scaling shifted toward detect-and-avoid performance standards, surveillance service levels, and vertiport-centric procedures (RTCA 2025).
- Policy alignment expanded from aviation authorities to SLTT governance and national strategies, which directly affect where freight nodes can be enabled quickly (USDOT 2025).

The operational consequence is that freight AAM can scale first in corridors and nodes where regulators can approve repeatable procedures, surveillance coverage supports predictable separation services, and vertiport/airport interfaces support throughput. Those conditions map closely to the earlier node-centric infrastructure strategy that reuses airports and healthcare assets.

3. RESULTS AND DISCUSSION

This study integrated evidence from technology assessment, market analysis, infrastructure evaluation, and regulatory readiness to examine whether AAM can meaningfully shift freight from roads to air in ways that preserve ground transportation infrastructure. Taken together, the results support a consistent and defensible conclusion. AAM delivers the greatest infrastructure-preservation benefits when deployment aligns with four binding conditions: energy density constraints, concentrated freight demand, reuse of existing nodes, and regulatory repeatability. None of these conditions alone is sufficient. Their interaction determines whether AAM can substitute for trucks at scale or remain a marginal logistics option.

3.1 Interpretation of Technology Readiness

Across all technology-focused analyses, energy density emerged as the primary performance constraint. Aircraft architecture, propulsion efficiency, and aerodynamic refinement improved utilization of onboard energy but did not remove the underlying limitation imposed by current energy storage technologies. Battery-electric configurations remained well suited for short- and medium-range missions with high trip frequency and predictable routing. However, longer-range and heavier payload missions will increasingly depend on hybrid or hydrogen-based concepts. Patent and bibliometric evidence reinforced this interpretation by showing that innovation activity concentrated on mitigating constraints (thermal management, interface stability, safety, and integration) rather than delivering near-term step changes in fundamental energy density.

This result has direct implications for freight planning. Viable AAM freight missions must fit within realistic payload–range envelopes rather than aspirational performance targets. As a result, early deployment favors routes where repeated operations can amortize energy limitations through high utilization, rather than one-off or highly variable missions. Technology readiness, therefore, shaped not only what aircraft can carry, but which freight markets and network structures remain credible in the near term.

3.2 Interpretation of Market Structure

Market analyses consistently showed that freight suitable for AAM does not distribute evenly across space or commodities. Instead, high-value, time-sensitive, and safety-critical freight clustered in a limited number of regions and corridors. Hazardous materials and pharmaceuticals stood out because they combined three characteristics that favor aerial substitution: high consequences of failure, relatively low weight-to-value ratios, and frequent, repeatable movements. These characteristics support willingness to pay for reliability. They justified shifting freight from roads even when costs remained higher than conventional trucking on a per-ton basis.

Importantly, both middle-mile and last-mile analyses demonstrated that concentration occurs at different spatial scales but follows the same logic. Middle-mile demand clustered around metropolitan regions and interstate gateways, while last-mile demand clustered around hospitals and healthcare catchments in rural regions. In both cases, a few nodes accounted for a disproportionate share of potential benefit. This concentration reduces uncertainty and supports phased deployment strategies that prioritize early impact rather than broad geographic coverage.

3.3 Interpretation of Infrastructure Feasibility

Infrastructure evaluations showed that lack of physical infrastructure is not the primary barrier to freight-oriented AAM. Existing airports, hospital-adjacent aviation facilities, and underutilized regional airfields already provide many of the assets required for operations. These assets support air-side access, security, utilities, and multimodal connectivity. By assigning distinct functional roles to these assets (such as freight hubs, transfer points, or healthcare gateways) the studies demonstrated how AAM networks can emerge through reuse rather than new construction.

This reuse strategy created continuity across rural, regional, and urban contexts. In rural settings, airports near hospitals anchored last-mile healthcare delivery. In regional settings, underutilized airports can intercept truck flows and redistribute freight by air. In urban settings, peripheral airports and vertiports can reduce congestion by relocating freight activity away from saturated gateways. Across all contexts, the same principle applied: node-centric design enables scalability, improves utilization, and shortens deployment timelines.

3.4 Interpretation of Regulatory Readiness

Regulatory analysis framed adoption as a system-level classification problem rather than a simple technology approval issue. Evidence showed that adoption depends on the presence of enabling governance structures that allow repeatable operations, predictable oversight, and scalable integration into existing airspace systems. National economic capacity and regulatory quality consistently outweighed other factors such as land availability or infrastructure density.

Recent regulatory developments in powered-lift certification, special conditions for vertical takeoff and landing aircraft, and national AAM strategies reduced uncertainty but did not eliminate it. These developments support early operations in constrained environments where procedures, surveillance, and institutional familiarity already exist. This finding reinforces the node-centric deployment logic observed in the infrastructure analyses. Repeatability tends to emerge first at established aviation nodes, which then serve as proving grounds for broader integration.

3.5 Combined Implications for Infrastructure Preservation

When interpreted together, the results clarify how AAM contributes to preserving ground transportation infrastructure. The largest benefits arise when AAM replaces repeated truck movements on fixed routes rather than sporadic or highly customized deliveries. Substituting even a fraction of truck trips in hazardous materials corridors, pharmaceutical supply chains, or congested urban gateways can reduce pavement loading, bridge fatigue, congestion, and exposure to high-consequence incidents. These benefits compound over time because they target the most infrastructure-intensive segments of the freight system.

At the same time, the results cautioned against overgeneralization. AAM does not eliminate the need for trucks, nor does it serve all freight equally well. Its value lies in selective substitution where energy limits, demand concentration, and institutional readiness align. Treating AAM as a targeted intervention rather than a universal replacement yields more credible planning outcomes and avoids unrealistic expectations.

3.6 Directions for Future Research

The integrated findings point to several priorities for future work. First, freight diversion should be translated into pavement and bridge preservation metrics using standard asset management frameworks. This enables direct comparison with conventional infrastructure investments. Second, end-to-end logistics models should explicitly account for handling, consolidation, and compliance costs to determine when aerial substitution truly displaces truck travel rather than adding complexity. Third, energy pathway scenarios should remain bounded by observed innovation trajectories rather than optimistic forecasts, particularly for batteries and hydrogen systems. Fourth, airport and vertiport interface design for freight throughput warrants deeper engineering analysis. This is because node performance ultimately governs system scalability. Finally, regulatory research should move toward corridor-level readiness assessments that integrate certification pathways, airspace services, and local governance capacity.

3.7 Synthesis

Overall, the combined results supported a coherent deployment logic. Freight-oriented AAM can preserve ground transportation infrastructure most effectively when it targets concentrated, high-consequence freight flows; reuses existing aviation and healthcare assets; operates within realistic energy constraints; and aligns with regulatory environments that support repeatable operations. Under these conditions, AAM functions not as a speculative technology, but as a selective, high-impact complement to surface freight systems.

4. CONCLUSIONS AND RECOMMENDATIONS

This report evaluated AAM as a freight logistics intervention with the primary objective of preserving ground transportation infrastructure. By integrating evidence across technology readiness, market structure, infrastructure feasibility, and regulatory conditions, the study reached several consistent conclusions. First, energy density remains the binding technical constraint that governs feasible AAM freight missions. Aircraft design, propulsion efficiency, and operational optimization improve performance at the margin, but they do not remove the fundamental limits imposed by current energy storage technologies. As a result, credible near-term AAM freight applications should concentrate on short- to medium-range routes with high trip frequency and predictable demand. Hybrid and hydrogen-based pathways offer potential expansion of this envelope, but they remain medium- to long-term options rather than immediate solutions.

Second, AAM-suitable freight demand is highly concentrated, not diffuse. High-value, time-sensitive, and safety-critical commodities (particularly hazardous materials and pharmaceuticals) cluster geographically and operationally. This concentration supports repeatable routes and sustained utilization. These are necessary for AAM to substitute for truck movements rather than merely supplement them. Both middle-mile and last-mile analyses confirm that a small number of nodes and corridors account for a disproportionate share of potential benefit.

Third, existing infrastructure is largely sufficient to support early AAM freight deployment. Airports, hospital-adjacent aviation facilities, and underutilized regional airfields already provide the essential physical assets required for operations. Strategic reuse of these nodes enables rapid deployment, reduces capital intensity, and aligns with both rural and urban logistics needs. Greenfield infrastructure development is not a prerequisite for initial impact.

Fourth, regulatory repeatability, not physical feasibility, is the dominant system-level gating factor. Adoption depends on the ability of regulatory institutions to certify aircraft, approve operations, and support scalable procedures within existing airspace systems. Recent progress in powered-lift certification frameworks and national AAM strategies reduces uncertainty. However, early deployment remains most feasible in jurisdictions with strong governance capacity and established aviation oversight.

Together, these conclusions indicate that AAM can meaningfully preserve ground transportation infrastructure when it is deployed selectively. The greatest benefits arise from substituting repeated truck movements on fixed routes, particularly where pavement wear, bridge loading, congestion, or safety risks are highest. AAM is, therefore, best understood as a targeted, high-impact complement to surface freight systems rather than a universal replacement.

Based on these conclusions, this research offers the following recommendations for policymakers, infrastructure owners, operators, and researchers:

1) Prioritize mission types that maximize infrastructure preservation. Early AAM freight deployments should focus on hazardous materials, pharmaceuticals, and other high-consequence commodities with repeatable demand patterns. These missions provide the

strongest justification for shifting freight from roads to air and deliver outsized infrastructure, safety, and reliability benefits.

2) Adopt a node-centric deployment strategy. Planning efforts should concentrate on a limited set of airports, hospital aviation assets, and intermodal transfer points where demand, accessibility, and regulatory readiness converge. Concentrating operations at these nodes will increase utilization, accelerate learning, and reduce deployment risk.
3) Align aircraft selection with realistic energy constraints. Operators and planners should avoid assuming near-term breakthroughs in energy density. Fleet selection and network design should reflect current and near-horizon performance bounds. Reserve hydrogen and advanced battery concepts for phased expansion as technical maturity improves.
4) Integrate AAM planning with infrastructure asset management. Transportation agencies should explicitly link AAM freight diversion scenarios to pavement and bridge preservation objectives. Quantifying avoided truck miles, axle loads, and fatigue cycles will enable AAM to be evaluated alongside conventional infrastructure investments.
5) Leverage regulatory progress through corridor-based pilots. Regulators and operators should focus on corridor-scale demonstrations where procedures can be standardized, monitored, and iteratively refined. These corridors can serve as templates for broader deployment as certification pathways and airspace integration mechanisms mature.
6) Invest in data collection and data-driven decision support tools. Continued development of data sources, GIS-based optimization, freight clustering, and adoption modeling tools will improve the precision of deployment decisions. These data and tools should integrate technology performance bounds, market demand, infrastructure availability, and regulatory conditions into unified planning frameworks.
7) Advance research on system-level impacts and scalability. Future research should extend beyond feasibility to quantify long-term system effects. These should include infrastructure life-cycle impacts, network resilience, and equity outcomes. Particular emphasis should be placed on understanding how AAM scales across multiple nodes and corridors without eroding its infrastructure-preservation benefits.

Overall, the evidence assembled in this report supports a clear and pragmatic conclusion. AAM can preserve ground transportation infrastructure if it is applied deliberately, grounded in realistic technical constraints, and aligned with concentrated freight demand and existing assets. By treating AAM as a selective logistics instrument rather than a universal solution, decision-makers can unlock meaningful near-term benefits while laying the foundation for broader integration as technologies and regulatory frameworks continue to mature.

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