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URBAN AIR MOBILITY AND SPATIAL TWINS: BRASÍLIA AS A TESTBED FOR UAM-UTM NETWORK IMPLEMENTATION

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ABSTRACT

This paper examines the potential of Brasília as a pilot city for the implementation of an Urban Air Mobility (UAM) network, structured by eVTOLs, UAVs, and low-altitude airspace management systems (UTM). The study adopts a qualitative and applied approach, organized into three axes: regulatory analysis, morphological and territorial assessment, and simulations conducted at TransLab/UnB. The literature review encompasses international frameworks (FAA, EASA, NASA, ICAO) and Brazilian regulations (ANAC, DECEA), as well as recent studies on digital twins, scheduling algorithms, and territorial impacts of UAM.

Brasília offers unique conditions: the linearity of the Eixão, low vertical density, central green strips, and functional zoning compatible with vertiports. The concept of a spatial twin was adopted as a normative device, projecting the road network into the airspace. The proposed corridor is vertically stratified into four layers by UAV classes and supported by a hierarchical infrastructure of vertihub, vertiports, and vertistops. Simulations compared scheduling algorithms (*Round Robin* and *Genetic Algorithm*), showing the superior robustness of the former under heavy traffic and adverse weather conditions, while optimized versions of the latter reduced maximum delays by 60%.

The findings indicate that UAM can function as an integrative infrastructure, reducing travel times, redistributing centralities, and strengthening the territorial cohesion of the RIDE. Beyond a modal innovation, the model proposes a new regime of urban and regional connectivity, replicable from Brasília's experience.

Keywords: Urban Air Mobility; Spatial Twin; BR-UTM; Multiscale Urban Integration, Pilot City Deployment.

GENERATIVE AI USAGE STATEMENT

The authors declare that the use of generative AI tools was restricted to technical support activities, without compromising the originality, analysis, and conclusions presented in the work. All information obtained through these resources was carefully evaluated and integrated into the study, ensuring methodological rigor and academic integrity. Connected Papers, Gemini and Perplexity, were used for automated research, enhancing the search for references related to the study topics, and MacGPT Version 3.21, as well as DeepL were used to review the text and translate it into English.

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1 INTRODUCTION

Urban Air Mobility (UAM) has emerged as a strategic alternative to the structural limitations of terrestrial transport systems. Based on electric vertical takeoff and landing aircraft (eVTOLs), unmanned aerial vehicles (UAVs), and digital air traffic management systems (UTM), UAM enables the reorganization of urban and regional flows in three dimensions, with reduced physical and environmental impact (Cohen, Shaheen & Farrar, 2021; Garrow, German & Leonard, 2021). International studies led by NASA, FAA, and EASA have demonstrated that structured air corridors can provide significant gains in scalability and safety (Goodrich & Theodore, 2021; SESAR, 2023).

In Brazil, regulatory advances by the Department of Airspace Control (ICA 100-37, DECEA, 2024) and the National Civil Aviation Agency (ANAC, 2024) position the country to consolidate this emerging transport mode. However, local planning instruments - such as the Distrito Federal Urban Transport Master Plan (PDTU-DF) and the Sustainable Urban Mobility Plan (PMUS-DF) - still fail to incorporate the aerial dimension, remaining limited to road-based paradigms (Rolnik, 2011; Delfim, 2020).

Brasília presents spatial and institutional attributes that qualify it as a pilot city for UAM. Its linear morphology, clear hierarchical road system, and low vertical density favor the deployment of air corridors over the Eixão with minimal ground-level interference. The central green strips and flat topography constitute natural routes compatible with DECEA standards (DECEA, 2025) as well as international separation criteria (Brunelli, Ditta & Postorino, 2022). At the same time, its designation as a UNESCO World Heritage Site restricts physical interventions, reinforcing the relevance of heritage-compatible and low-impact solutions such as vertical corridors.

The territorial challenge is equally significant: the Integrated Development Region of the Federal District and Surroundings (RIDE) exhibits deep socioeconomic disparities, reflected in average commuting times of 78.6 minutes per day and estimated annual losses of up to 1.9% of regional GDP due to traffic congestion (Vianna & Young, 2022). In this context, UAM must be understood not merely as a modal innovation but as a multi-scalar framework capable of reconfiguring connectivity between the core and the periphery, redistributing centralities, and reducing the social costs of mobility (Andrade & Balbim, 2022).

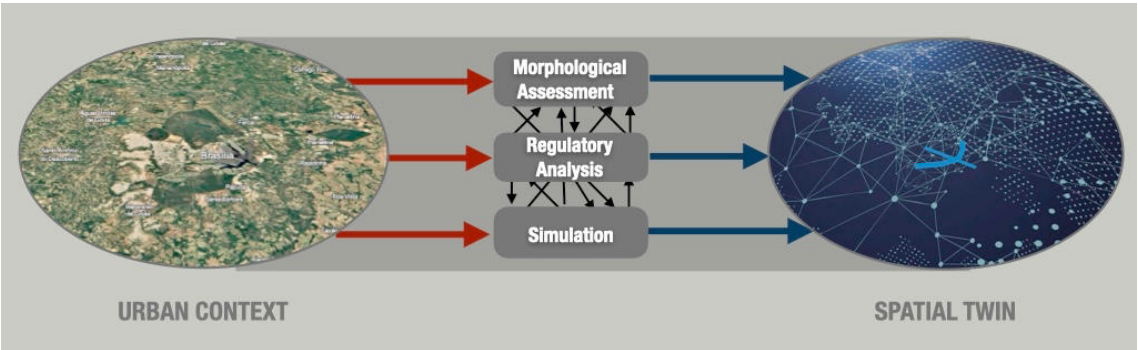


Figure 1: Research design and methodological workflow

The objective of this study is to examine the potential of Brasília as a testbed for UAM through two complementary axes: (i) the design of an aerial corridor over the Eixão, structured as a layered vertical airspace by UAV class, and (ii) the concentric expansion of vertiport networks, connecting the Pilot Plan to the RIDE. The research adopts a qualitative and applied approach combining

normative analysis, morphological assessment, and simulations conducted at TransLab/UnB with the aim of proposing spatial, functional, environmental, and regulatory criteria for the safe and scalable deployment of UAM in metropolitan contexts.

2 METHODOLOGY AND LITERATURE REVIEW

2.1 Literature Review

Recent research on Urban Air Mobility (UAM) has evolved along three main fronts: regulatory frameworks, technical foundations of modeling and simulation, and territorial impacts.

In regulatory terms, agencies such as the FAA (2023) and EASA (SESAR Joint Undertaking, 2023) have advanced guidelines for the integration of low-altitude airspace, while NASA developed the UAM Maturity Levels model, relating technological, institutional, and community readiness (Goodrich & Theodore, 2021). ICAO established interoperability parameters between UTM and ATM for safe operations in dense areas (ICAO, 2015). In Brazil, the Department of Airspace Control (DECEA) defined in ICA 100-37 (2024) the criteria for establishing air corridors, complemented by ANAC regulations (RBAC-E94) and the SISANT and SARPAS NG platforms, which compose the BR-UTM ecosystem.

From a technical perspective, the literature highlights both airspace design and scheduling algorithms. Garrow, German and Leonard (2021) compare UAM to autonomous ground transport systems, emphasizing its superior efficiency in dispersed urban contexts. Cohen, Shaheen and Farrar (2021) synthesize the historical evolution and challenges of the sector, while Brunelli, Ditta and Postorino (2022) propose the application of digital twins to urban air networks. In Brazil, research conducted by TransLab/UnB is testing the Eixão corridor with vertical stratification by UAV classes, modular vertiport allocation, and scheduling algorithms. Results show that simple approaches, such as *Round Robin*, can outperform more complex heuristics under heavy traffic and adverse weather, particularly when supported by optimization through generative AI models.

On the territorial dimension, Picon (2015) discusses the *new materiality* of digital environments in reshaping urban form, while West (2017) proposes scaling laws linking morphology and systemic efficiency. These approaches provide a conceptual foundation for analyzing how UAM reorganizes flows and centralities across scales. In Brazil, Rolnik (2011) and Delfim (2020) point to the limits of fragmented metropolitan governance, Andrade and Balbim (2022) emphasize the need for new planning methodologies, and Jatobá (2018) highlights the social costs of commuting in the RIDE. Local research at TransLab/UnB introduced the concept of the spatial twin as a normative extension of the road network into airspace and analyzed the integration of UAM and ATM within the BR-UTM context. Together, these contributions reinforce UAM as more than a modal innovation: it represents an integrative, multi-scalar framework with the potential to reduce territorial disparities and enhance connectivity.

In summary, the literature indicates that UAM development requires the articulation of digital platforms, federative regulations, and urban planning foundations. In this regard, Brasília emerges as a singular case for experimenting with urban air networks, combining favorable spatial conditions, territorial centrality, and regulatory maturity.

2.2 Methodology

The study adopts a qualitative and applied approach structured along three complementary axes:

Regulatory Analysis: Survey and examination of national and international regulations governing UAV operations in urban airspace. Brazilian instruments include ICA 100-37 (DECEA), RBAC-E94 (ANAC), SISANT, and SARPAS NG; international references include U-Space, UAM ConOps, and ICAO Doc 10019. Together, they ensure alignment with the BR-UTM ecosystem.

Morphological and Territorial Assessment: Evaluation of Brasília's road network, functional zoning, and territorial conditions, using secondary data from the Distrito Federal Urban Transport Master Plan (PDTU-DF) and the Sustainable Urban Mobility Plan (PMUS-DF). This analysis identified viable corridors, low-density areas, and zones compatible with vertiports and vertistops.

Modeling and Simulation: Development of pilot scenarios at TransLab/UnB, focusing on the Eixão corridor. The design included layered vertical airspace structures segmented by UAV classes (Classes 1–3 and eVTOLs), defined access and escape zones, and tested scheduling algorithms, namely *Round Robin* and *Genetic Algorithm*. Simulations considered Brasília's typical climatic conditions and operational safety parameters, enabling performance comparison in terms of throughput, waiting times, and robustness under stress conditions.

This methodology integrates spatial, regulatory, and operational dimensions, testing the pertinence of the spatial twin concept as a normative device for urban airspace governance. At the same time, it ensures alignment with the BR-UTM digital ecosystem, reinforcing the potential for scalability and replication of the model in other metropolitan contexts.

3 TERRITORIAL AND SOCIOECONOMIC CONTEXT

The Federal District combines administrative centrality, a high concentration of service activities, and income levels above the national average. However, the Integrated Development Region of the Federal District and Surroundings (RIDE) reveals structural inequalities, with strong dependence on daily commuting flows to the Pilot Plan. The average commuting time in the region reaches 78.6 minutes per day, resulting in estimated economic losses of up to 1.9% of regional GDP from road congestion (Vianna & Young, 2022; PDTU/PMUS-DF, 2024).

These indicators reinforce the pertinence of UAM as a low-impact infrastructure capable of reducing social costs and enhancing metropolitan integration. By introducing new aerial centralities through vertiports and corridors, the proposed model addresses longstanding territorial disparities, connecting the peripheral and the core areas without requiring large-scale road interventions.

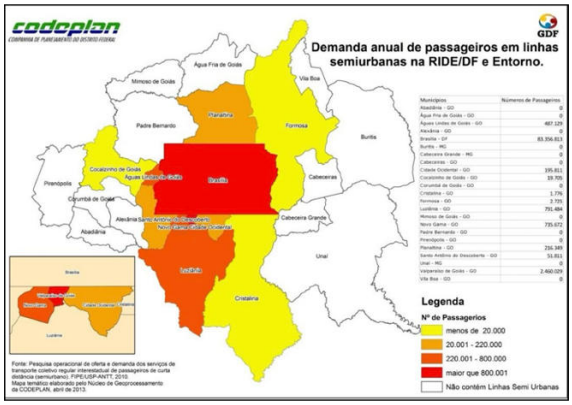


Figure 2: Socio Economic Distribution and Commuting flows in the RIDE
Source: FIPE/USP - ANTT (2010)

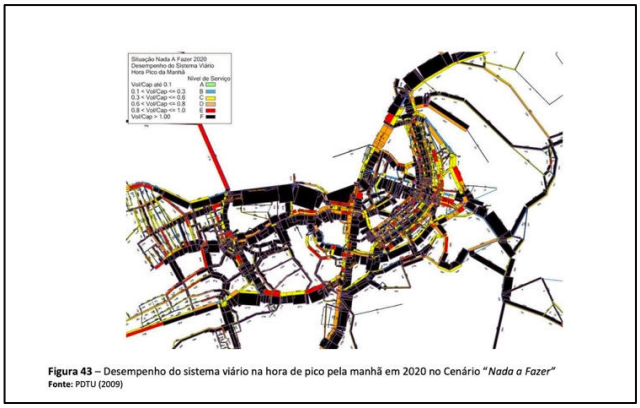


Figure 3: Traffic performance Surrounding Zone, AM peak
Source: LabTrans/UFSC - FEPESE (2025).

4 MORPHOLOGY, SPATIAL TWIN, AND ZONING

The urban logic of Brasília, based on functional separation and hierarchical road design, provides a unique foundation for structuring three-dimensional airspace. The Eixão, a 13.8 km linear axis that organizes the Pilot Plan's internal flows, offers favorable technical conditions: low adjacent vertical density, central green strips averaging 45 m in width, and compliance with separation criteria defined in ICA 100-37 (DECEA, 2024). These characteristics enable the establishment of parallel,

bidirectional aerial corridors with minimal operational conflicts, while preserving the landscape of the modernist heritage site.

The concept of a spatial twin, developed at TransLab/UnB, extends the terrestrial road grid into the aerial domain, transforming the Eixão into a normative axis for vertical circulation. Unlike simulation-oriented digital twins, the spatial twin functions as a normative device, ensuring continuity between ground and aerial systems and enabling interoperability between UTM and ATM.

Beyond the central axis, the aerial network allows concentric expansion toward the RIDE, scaling frequency and coverage according to demand.

From a functional perspective, Brasília's zoning pattern supports the selective deployment of vertiports: the industrial and logistic areas for cargo, the commercial and administrative areas for passenger operations, and the green strips as continuous aerial mobility corridors. This compatibility derives from the modernist grammar of Brasília, where functional separation facilitates the incorporation of new layers of mobility with limited friction with existing land uses.

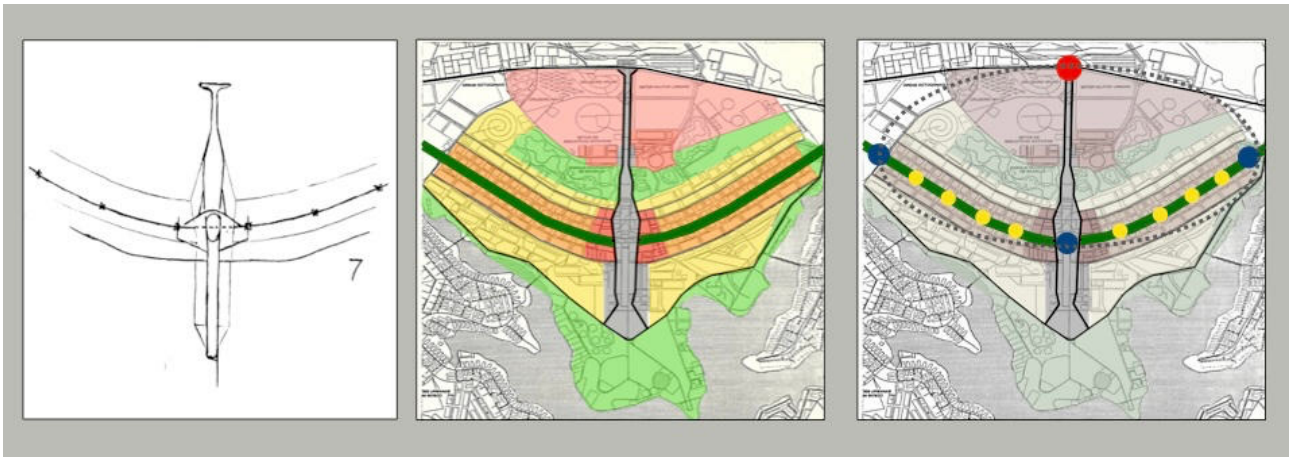


Figure 4: Eixão structure with zoning and green strip; potential Vertihub, Vertiport, Vertistop sites. Source: TransLab (2025)

5 DESIGN OF THE EIXÃO CORRIDOR.

The Eixão was selected as a pilot axis for the development of a UAM corridor in Brasília due to its linear morphology, centrality within the Pilot Plan, and compliance with national air safety criteria. Its central green strip, approximately 45 meters wide and flanked by adjacent low-rise buildings, enables the implementation of parallel, unidirectional aerial corridors with minimal physical interference. Overlaying the aerial route on existing infrastructure avoids land conflicts and ensures preservation of Brasília's modernist urban heritage, in line with UNESCO preservation requirements and ANAC guidelines.

5.1 Vertical Structure and UAV Classes

The corridor design is based on vertical stratification of the airspace into four layers of approximately 40 meters each, aligned with DECEA's classification for unmanned aircraft:

Layer 0 (0–40 m): not intended for cruising; used for takeoff, landing, and vertical access.

Layer 1 (40–80 m): Class 3 UAVs (light, up to 25 kg), mainly for last-mile deliveries and public services.

Layer 2 (80–120 m): Class 2 UAVs (medium, 25–150 kg), focused on logistics and regular operations.

Layer 3 (120–160 m): Class 1 UAVs (heavy, >150 kg and eVTOLs), with greater lateral and vertical separation.

This layered vertical airspace structure facilitates functional separation of traffic, minimizes collision risk, and simplifies management of takeoffs and landings. It also allows gradual scaling to higher densities as technology and regulation evolve.

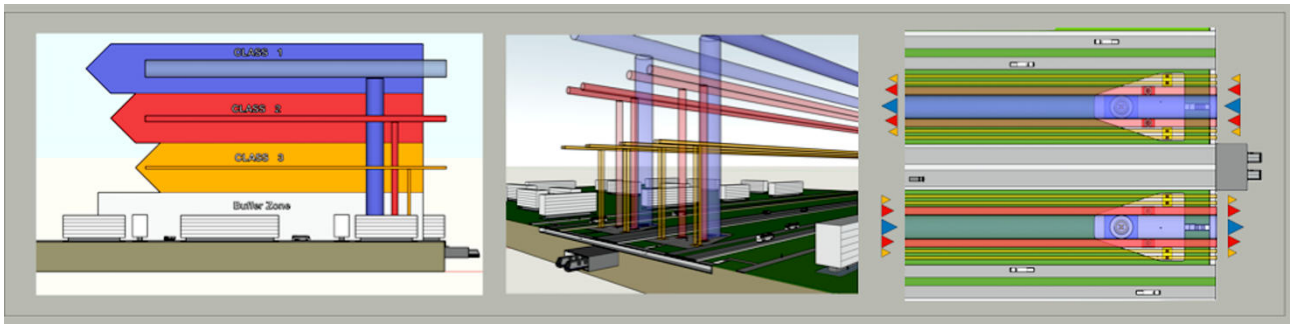


Figure 5: Diagrammatic Cross-Sections of the Eixão UAM Corridor and Vertiport Typologies Source: TransLab (2025)

5.2 Infrastructure: *Vertihub*, *Vertiports*, and *Vertistops*

The proposed system incorporates three levels of aerial infrastructure:

Vertihub: located at Brasília's Rodoferroviária, serving as a metropolitan logistics hub for cargo, maintenance, and integrated system management.

Vertiports: three main units positioned at the northern end, southern end, and central area of the Eixão (adjacent to the Pilot Plan Bus Terminal), each connecting directly to major demand hubs such as commercial, hospital, and administrative zones.

Vertistops: secondary access points distributed along the green strip of the Eixão, prioritizing areas of high functional density such as universities, hospitals, and civic centers.

This hierarchical design balances scalability, frequency, and coverage, ensuring robust logistics while limiting urban impact. Vertistops are conceived as modular, low-impact structures with reduced visual and noise footprint, leveraging existing underpasses to facilitate last-mile connections.

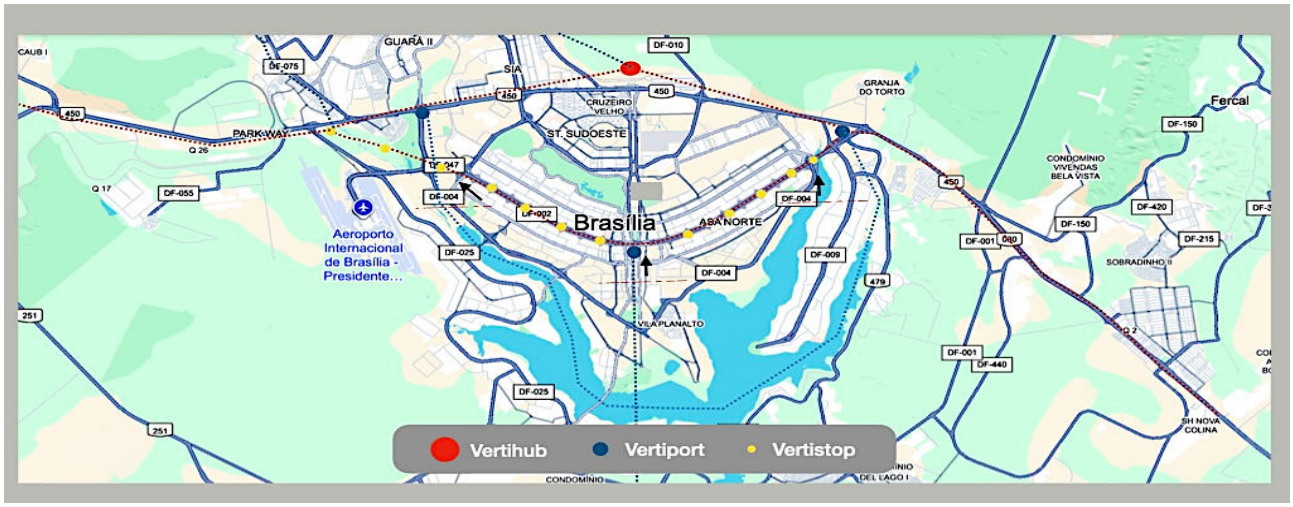


Figure 6: Vertihub, Vertiport-Vertistop locations along the Eixão

5.3 Scheduling Algorithms and Simulation

Simulations conducted at TransLab/UnB evaluated corridor operations under heavy traffic and adverse weather conditions. Two scheduling algorithms were compared:

Round Robin (RR): based on equitable allocation of takeoff slots in cycles.
Genetic Algorithm (GA): designed for global optimization of takeoff sequencing.

Results indicated that RR performed better under continuous traffic and adverse weather, achieving lower average waiting times (≈ 4 s per flight) and greater consistency in operations. GA, although adaptive, showed higher variability and longer delays on average. A refined version (GA v5), iteratively optimized with LLM support, reduced maximum delays by 60%, narrowing the performance gap while retaining adaptive capacity for complex scenarios.

5.4 Concentric and Scaled Expansion

The Eixão corridor is conceived as the nucleus of a concentric network progressively linking the Pilot Plan, secondary centers, and RIDE municipalities. Details of this territorial logic are developed in the following section.

This staged logic allows integration of distinct demand zones, supporting progressive scaling of the system and redistributing regional centralities. In this sense, Brasília reverses the usual logic: rather than adapting infrastructure to the new mode, it is the mode that adapts to existing conditions. The city becomes not only compatible with UAM but inherently predisposed to it. The "spatial twin" developed by TransLab/UnB, which digitally replicates the Eixão's hierarchy for aerial simulation purposes, is based on this premise: the city already contains, in its structural organization, a matrix for three-dimensional mobility.

This technical predisposition is further reinforced by a unique normative condition: Brasília is a UNESCO World Heritage Site. While this status imposes strict limits on physical transformation, it also favors non-invasive, low-visibility solutions—qualities intrinsic to UAM. Aerial operation through vertical corridors, with boarding and alighting at discrete points, avoids ground-level interventions and respects the spatial voids that define the city's original urbanism.

The integration of aerial mobility into Brasília's urban fabric also benefits from its functional segmentation. Clearly delineated zoning between administrative, residential, commercial, and institutional areas allows for differentiated access points based on specific demand profiles—passengers, medical services, light cargo or autonomous deliveries. The predictability of urban flows, inherited from modernist planning, adds advantage for operational safety and algorithmic modeling.

Unlike cities shaped by historical layering—marked by chaotic density, unplanned verticalization, and overlapping infrastructures—Brasília offers clarity. This clarity is not only formal but also functional, normative, and operational. It enables the design of an integrated, scalable, and replicable aerial grid. In this sense, the city already operates as infrastructure.

This is not about building a new mobility model over Brasília, but about activating, through UAM, the technical latencies embedded in its conception. The city originally planned for horizontal circulation becomes, now, a city reconfigured for vertical movement. And in this shift, it reaffirms its vocation as a pilot city: not a nostalgic icon of the past, but a platform for the mobilities of the future.

6 UAM TERRITORIAL INFRASTRUCTURE: MULTISCALE BRASÍLIA-RIDE CONNECTIVITY

Implementing an Urban Air Mobility (UAM) network in the Federal District requires more than defining corridors across the central grid. Its feasibility and structural impact depend on articulation with regional flows, particularly RIDE municipalities, whose pendular dynamics and historic inequalities challenge conventional transport models.

The network designed by TransLab/UnB rests on two principles: (1) the activation of a ring-based system of peripheral vertiports connected to Brasília's radial axes; and (2) the multiscale organization of aerial flows according to regional demand, with differentiated use of vertical layers for passengers, services, and logistics.

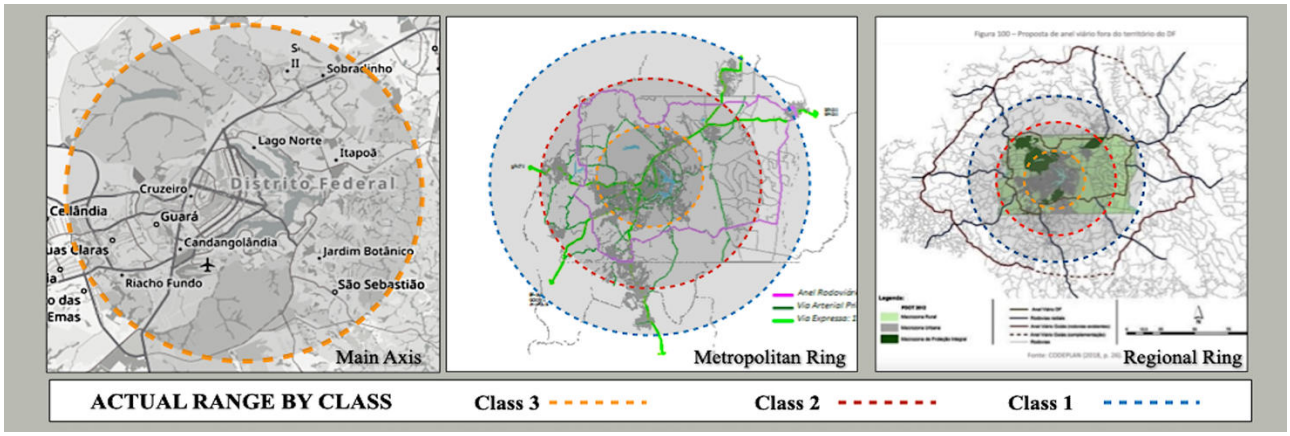


Figure 7: Multiscale UAM Coverage over Brasília–RIDE: Rings and Drone Class Ranges Source: TransLab (2025)

The first ring links the Pilot Plan with nearby satellite cities (Cruzeiro, Guará, Lago Sul, Sudoeste, Candangolândia) through short, high-frequency routes. Modular vertistops in transitional zones provide capillarity with minimal physical transformation. The second ring integrates intermediate centers (Taguatinga, Ceilândia, Águas Claras, Samambaia, Sobradinho), where denser urban fabric sustains mid-capacity bidirectional corridors with intermediate facilities for cargo and boarding. The third ring extends to periurban and rural RIDE municipalities (Planaltina de Goiás, Padre Bernardo, Valparaíso), connecting low-frequency routes with strong logistical potential, especially for agriculture and dispersed housing.

Functionally, the network operates as a vector of territorial convergence. Its vertical organization groups logistics drones, passenger eVTOLs, and service aircraft under predictable standards, while flexible access points and modular infrastructure enable phased deployment aligned with regulatory and technological maturation. The structure - central vertihub, regional vertiports, and vertistops - maximizes coverage with minimal land use: the main hub near Brasília's intermodal terminal coordinates flows, peripheral vertiports act as operational gateways, and vertistops on medians or institutional grounds add capillarity without compromising the landscape.

This aerial structuring (both radial and ring-based) not only reorganizes mobility patterns but redefines centrality. Instead of a single concentrative core, the UAM network multiplies access nodes and redistributes accessibility, expanding the capital's reach without expanding its footprint. Brasília thus ceases to be a mobility system restricted to the administrative city and becomes a strategic territorial infrastructure, connecting production and consumption, residence and services, center and periphery, within a dynamic of low altitude, high frequency, and multiscale integration.

7 TERRITORIAL AND NORMATIVE FRAMEWORK

The development of an Urban Air Mobility (UAM) system in Brasília requires not only technological solutions but also an integrative framework capable of articulating territorial, regulatory, and operational dimensions. The framework proposed here is structured into eight complementary components designed to guide the gradual and scalable implementation of the network.

7.1 Spatial Twin as Normative Basis

The first component is the adoption of the spatial twin as a normative device for airspace governance. Unlike traditional digital twins, which are primarily simulation tools, the spatial twin projects the terrestrial road grid into the aerial domain, turning the Eixão into a normative axis for vertical circulation. This strategy ensures continuity between ground and aerial systems, connects UTM to ATM, and reduces implementation costs by overlaying pre-existing corridors.

7.2 Vertical Structure and UAV Classes

The second component is the vertical segmentation of airspace into four layers of approximately 40 meters each, aligned with DECEA's classification of UAVs. This layered structure separates light, medium, and heavy UAV traffic, as well as eVTOL operations, ensuring predictability and safety. Transition zones (Layer 0) provide controlled access to cruising routes, reducing risks during takeoff and landing.

7.3 Hierarchy of Infrastructures

The third component establishes a hierarchy among vertihubs, vertiports, and vertistops. The central vertihub, located at Brasília's Rodoferroviária, functions as the metropolitan logistics node; three vertiports connect the Eixão's endpoints and central hub to key demand centers; and vertistops along the green strip provide modular, low-impact access and emergency points. This hierarchy guarantees flexibility and scalability, balancing logistics robustness with reduced urban footprint.

7.4 Concentric Integration with the RIDE

The fourth component organizes territorial expansion into concentric rings, linking the Pilot Plan first to nearby administrative regions, and subsequently to the municipalities of the RIDE. This staged logic calibrates frequency, coverage, and density according to distinct demand profiles, reducing longstanding spatial inequalities.

7.5 Zoning and Functional Compatibility

The fifth component addresses the compatibility of land uses with vertiport deployment. The industrial and logistic zones concentrate cargo operations, the commercial and administrative areas accommodate passenger flows, and the green strips sustain continuous aerial corridors. This compatibility stems from Brasília's modernist grammar, where functional separation facilitates the incorporation of new mobility layers with minimal land-use conflict.

7.6 Scheduling Algorithms and Artificial Intelligence

The sixth component incorporates scheduling algorithms for takeoff sequencing. Simulations showed that Round Robin provides greater robustness under heavy traffic, while optimized versions of Genetic Algorithms, developed with LLM support, reduce extreme delays by up to 60%. A hybrid model combining resilient baseline solutions with adaptive heuristics is proposed for progressive system maturity.

7.7 Federative and Regulatory Governance

The seventh component emphasizes institutional alignment with the BR-UTM ecosystem, integrating ANAC, DECEA, and digital platforms such as SISANT and SARPAS NG. Federative governance is indispensable for ensuring interoperability, safety, and legitimacy, especially in heritage-sensitive areas and metropolitan contexts involving multiple jurisdictions.

7.8 Sustainability and Heritage Compatibility

The eighth component includes environmental sustainability and heritage preservation criteria. The use of green strips as acoustic buffers, modular vertiports with reduced visual and acoustic impact, and compliance with UNESCO preservation requirements ensure that UAM integrates into Brasília's modernist landscape as both a heritage-compatible and low-impact solution.

8 CONCLUSION

Brasília brings together morphological and institutional attributes that qualify it as a pilot city for Urban Air Mobility (UAM). The linearity of the Eixão, its low vertical density, and the presence of central green strips create favorable technical conditions for the deployment of aerial corridors with minimal physical interference, in line with safety criteria established by DECEA and ANAC.

The proposal to articulate the Eixão aerial corridor with a concentric network of vertiports expands the territorial reach of the capital, connecting it to the RIDE and contributing to the reduction of the disparities in access to services and opportunities. This strategy reinforces the relevance of UAM as a scalable, interoperable, and low-impact mobility infrastructure, capable of complementing the road system and repositioning Brasília as a testbed for urban innovation.

More than a modal innovation, UAM emerges as a new connectivity regime, integrating physical and digital layers. By aligning local urban potential with national regulatory guidelines, the case of Brasília provides a replicable model of three-dimensional planning that projects the capital beyond its road-based limits and reaffirms its role as an experimental platform in the twenty-first century.

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