VOD (Low-Altitude Traffic-Led Development): International Comparisons and the Chinese Approach

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Abstract: Low-altitude transportation technologies are driving urban transportation systems from two-dimensional networks toward three-dimensional structures. As an extension of transit-oriented development (TOD) into the low-altitude dimension, vertical-oriented development (VOD) integrates urban functions around vertical take-off and landing facilities, offering a new pathway for high-density cities to alleviate congestion and optimize spatial structure. By constructing a three-dimensional analytical framework of space, institution, and industry, this study examines differentiated international paths, including Osaka's air-rail integration, Paris's corridor coupling, Dubai's platform empowerment, and Coventry's transferable pilot. It identifies challenges in China's local practice, such as airspace planning coordination, cross-departmental governance barriers, weak business-model resilience, and limited social acceptance. It then proposes a systemic path of spatial restructuring, institutional innovation, and industrial synergy, emphasizing the transition of VOD from conceptual validation to system integration through modernized airspace governance, networked spatial organization, and diversified industrial ecosystems. The study expands the theoretical connotation of traffic-led development and provides theoretical support and practical references for high-quality development of China's low-altitude economy and urban spatial restructuring.

Keywords: low-altitude economy; urban air mobility (UAM); vertical-oriented development model (VOD); international comparison; China's path

Rapid global urbanization has intensified traffic congestion and spatial-resource scarcity in large cities [1]. TOD, centered on rail transit, relies on planar development along linear infrastructure and therefore faces constraints in high-density built-up areas and complex terrain, including land scarcity, high costs, and social differentiation [2]. At the same time, two-dimensional transport networks are approaching capacity saturation and have difficulty meeting diversified, high-frequency, and time-sensitive travel demand. Low-altitude transport technologies represented by eVTOL are developing rapidly and may reduce the dependence of urban transport on surface space, supporting a three-dimensional transformation of urban mobility. The low-altitude economy has therefore been regarded as a strategic force for restructuring urban space, improving integrated operating efficiency, and cultivating new growth poles.

Some international metropolitan areas have already explored low-altitude transport pilots and have preliminarily formed low-altitude transport-oriented development models characterized by air-ground integration, data-driven operation, and multi-actor collaboration. Practice emphasizes vertical take-off and landing sites as core nodes that integrate low-altitude and ground transport networks, urban functional layout, and regional industrial ecosystems. The American Planning Association's advanced air mobility planning report explicitly proposes the VOD concept, which essentially builds a vertical development system organized around vertiports and reshapes urban spatial structure and regional patterns [3]. Compared with TOD, existing VOD research still focuses heavily on technology standards, airspace management, and business models [4-9], and lacks a systematic urban perspective.

This paper constructs a space-institution-industry framework by integrating spatial planning, institutional economics, and industrial ecosystem theory. It selects Osaka, Paris, Dubai, and Coventry for international comparison, identifies differentiated paths, and proposes a VOD development path for China that is oriented to local conditions, forward-looking, and operational.

1 Literature review and construction of the analytical framework

1.1 Connotation evolution and core characteristics of the VOD model

VOD originates from TOD, but differs fundamentally because the transport tool, eVTOL, and the carrier, low-altitude airspace, change the organization and operation of urban mobility. Its core facility is the vertical take-off and landing site, or vertiport. By building an air-ground-rail multimodal linkage system and a composite three-dimensional functional unit, VOD promotes the organic integration of the low-altitude economy and urban operations. Its core characteristics include three aspects.

First, VOD integrates three-dimensional space and distributed network layout. It breaks through TOD's planar radial structure and relies on roofs, transport hubs, green space, waterfront space, and other potential spaces to organize distributed vertical take-off and landing nodes and low-altitude routes. Second, VOD requires complex institutional environments and cross-departmental coordination. Low-altitude operations involve airspace allocation, safety supervision, noise management, data privacy, civil aviation, territorial spatial planning, transportation, housing and urban-rural development, emergency management, ecology, and data governance, and thus rely highly on multi-level collaborative governance [7-8]. Third, VOD is driven by scenarios and integrated with diversified industries, including emergency response, culture-tourism sightseeing, logistics, medical rescue, and public governance [9-15].

1.2 Development-stage theory of the VOD model

With the maturation of technology, institutions, and markets, VOD has evolved through three stages of conceptual germination, concept integration, and practical exploration, and is moving toward network integration. In the first stage, from the late twentieth century to the early twenty-first century, no clear development and operation model had yet formed, but two ideas had emerged: hub-oriented development and urban low-altitude transport tools. TOD had matured as an intensive development concept, while personal air vehicles and low-altitude aviation technologies were tested in limited scenarios such as vertical-lift sightseeing and emergency rescue [16-17].

In the second stage, from the 2010s to the early 2020s, battery, materials, autonomous driving, and related technologies promoted eVTOL from concept to engineering prototype. In 2016, EHang's manned autonomous aircraft completed public verification [18], and Uber proposed an urban air mobility operating framework and vertiport network concept [19-20]. NASA and other institutions began to study UTM systems, and attention shifted from single-aircraft flight to systematic operation [19-20]. China also promoted low-altitude airspace management and classified management, while TOD and UAM gradually integrated [21-22]. In the third stage, since the early 2020s, pioneering cities have explored diversified practices, including Osaka's embedded modular vertiport verification [23-24], Dubai's dedicated vertiport network and urban brand building [25-27], and Coventry's mobile modular Air-One demonstration [28]. Future VOD will develop toward networked integration, with low-altitude traffic networks serving as new infrastructure that deeply connects with urban energy, data, and functional systems (Fig. 1).

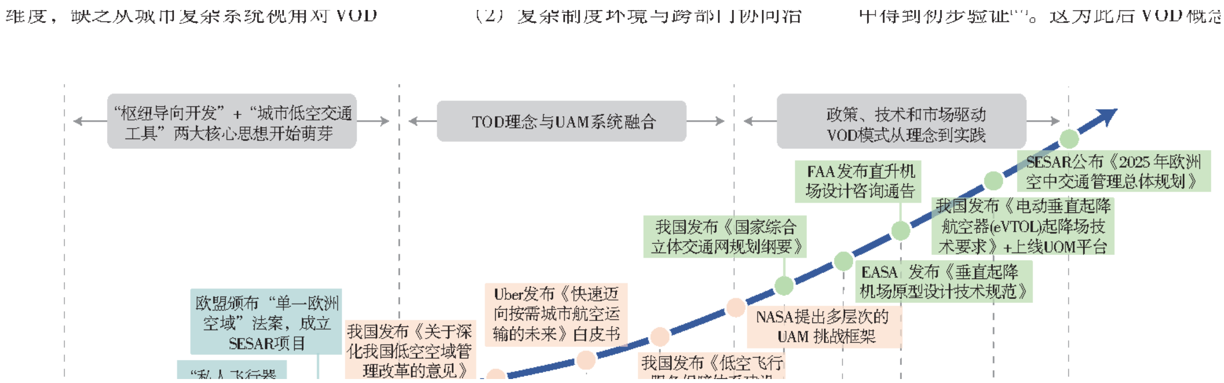

Fig. 1 Development stages of VOD models.

1.3 A three-dimensional framework of space-institution-industry

To overcome fragmented research, this paper constructs a three-dimensional analytical framework of space, institution, and industry (Fig. 2). It emphasizes their interaction and provides a unified perspective for explaining the complex logic of VOD implementation and operation.

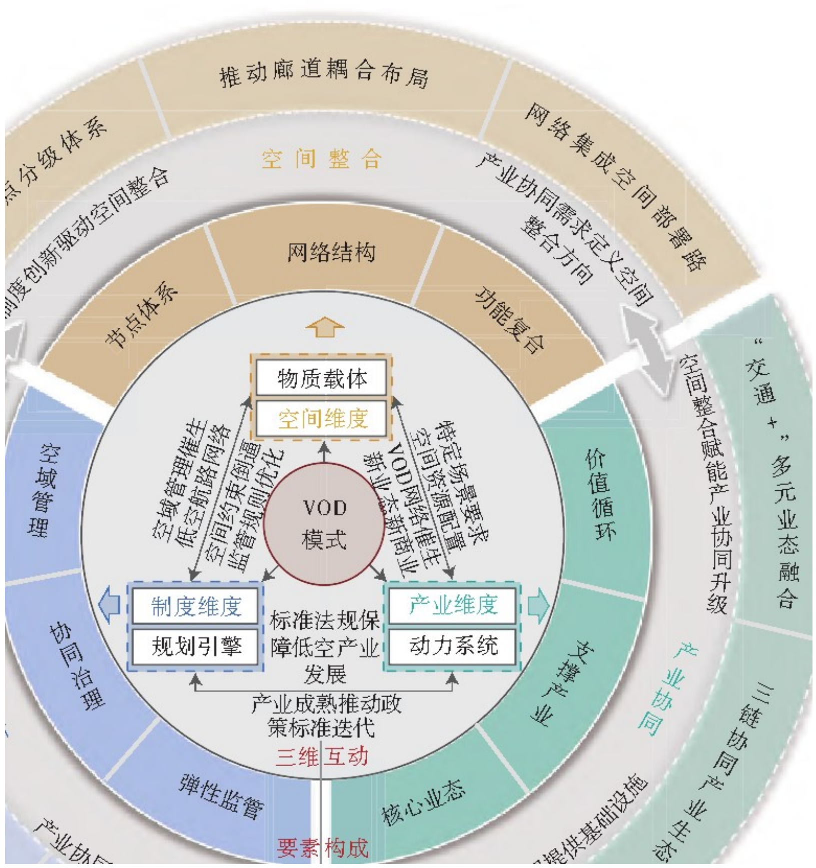

Fig. 2 Three-dimensional framework of space-institution-industry.

1.3.1 Spatial dimension: material carrier and morphological basis of VOD

The spatial dimension is the material basis for realizing VOD. It determines the structural efficiency of low-altitude networks. Key elements include node type and site selection, evolving from centralized hubs dependent on airports or high-speed railway stations to distributed nodes using roofs, parking lots, and other latent spaces;

route organization and terminal networking, which connects nodes through low-altitude routes and links them with ground and underground transport systems; and functional integration and three-dimensional development, which seeks extreme functional compounding in the vertical direction so that vertiports become urban airborne gateways integrating commerce, office, residence, and public services.

1.3.2 Institutional dimension: key guarantee and regulatory engine for VOD implementation

The institutional dimension provides the rules environment for VOD operation. Its core lies in forward-looking, coordinated, and flexible institutional arrangements. Airspace management rules and standards must cover airspace classification, dynamic allocation, noise control, safety standards, and airworthiness certification, thereby ensuring safe and efficient sharing of airspace [36-37]. Technical standards issued by agencies such as the FAA and EASA provide important references for standardizing VOD infrastructure [33]. Low-altitude airspace planning, including route structures, airspace layers, and node layout, is an important link for improving carrying capacity and operational efficiency [38]. Cross-departmental governance mechanisms are also essential for connecting approval-oriented governance with routine collaborative management [39-40]. Policy pilots and regulatory sandbox tools are especially important in the early stages of technology application, providing room for trial under controllable risk [41-42].

1.3.3 Industrial dimension: sustainable operating capacity of VOD

The industrial dimension concerns VOD's economic feasibility and ecological resilience. Core businesses and market cultivation generate initial value through commuting, emergency logistics, cultural-tourism sightseeing, medical emergency services, and similar scenarios [10-12]. Supporting industries and ecosystem construction depend on MRO, distributed energy-supply networks, flight data service platforms, talent training, insurance, and finance. The business model determines sustainability. International experience shows that VOD must expand non-aeronautical income and build sustainable profitability through commercial retail, advertising, exhibition, property development, and related services attached to vertiports, forming a virtuous value cycle of traffic attraction and commercial realization [43].

1.3.4 Systemic framework: interaction and collaborative evolution among the three dimensions

The spatial, institutional, and industrial dimensions are interdependent and constitute an organic system. In the space-institution interaction, spatial planning provides fine-grained low-altitude route networks, while dense urban space also requires more detailed regulatory rules. In the institution-industry interaction, clear airworthiness certification and operation regulations are prerequisites for eVTOL development, while industrial maturity and scaling continually drive improvement of standards and policies. In the industry-space interaction, specific application scenarios, such as rapid logistics, require node layouts and functions that are able to cover broad areas efficiently, forming a model in which route layout and industry demand mutually reinforce one another. Overall, VOD is an ecosystem formed by spatial integration, institutional innovation, and industrial collaboration.

2 International experience and multidimensional analysis of VOD models

Based on the space-institution-industry framework, this paper compares four representative cases: Osaka in Japan, Paris in France, Dubai in the United Arab Emirates, and Coventry in the United Kingdom.

2.1 Osaka, Japan: from station-city integration to an air-rail integrated path

Osaka relies on a mature rail network and the experience of station-city integration to explore a VOD path that embeds low-altitude facilities into existing transport hubs. Spatially, it takes embedded high-density rail hub integration as its core. The OSAKAKO demonstration vertiport is integrated around a rail station with candidate facilities, energy supply, and parking connections, forming an air-rail-ground three-dimensional transfer system and improving connection efficiency (Fig. 3). Institutionally, it relies on Japan's mature territorial comprehensive development and transport integrated planning system, incorporating low-altitude facilities into existing TOD governance. Industrially, it is driven by commuting and commerce, using the rail hub's passenger flow to provide high-end commuting services and expand retail and exhibition businesses.

Fig. 3 Osaka Osakako vertical take-off and landing airport.

2.2 Paris, France: air-ground-water multimodal linkage and low-impact coupling with historic districts
Paris explores a lightweight intervention path in the context of historic district protection and transport integration. Spatially, vertiports are prioritized along the Seine and existing transport hubs such as airports, railway stations, and ports, forming an air-rail-water-land corridor. This low-impact, highly integrated approach avoids direct disturbance to historic texture while addressing structural constraints such as weak connection efficiency and limited node carrying capacity [46-47]. Institutionally, the Paris regional mobility plan positions VOD as an operational enhancement that does not add surface occupation and can connect deeply with existing systems. Industrially, it focuses on high-value scenarios such as culture-tourism and airport connections (Fig. 4).

Fig. 4 Paris air-water transfer node.

2.3 Dubai, UAE: hub-driven platform development enabled by free-zone policies
Dubai uses its hub economy and free-zone institutional advantages to upgrade VOD into a transport-industry linked platform carrier [25]. Spatially, it prioritizes vertiport layout in airports, CBDs, coastal tourism zones, and ports, coupling these nodes with urban rail and road networks to form a port-airport-corridor-cluster pattern [26]. Institutionally, it relies on rapid release mechanisms within free zones and departments such as transport and safety authorities, with unified operation by the Roads and Transport Authority, reducing approval and supervision barriers. Industrially, it seeks to build a hub-oriented industrial platform connecting transport, logistics, MRO, conventions, commerce, and cross-border supply chains [27].

2.4 Coventry, UK: transferable VOD and low-cost verification under institutional flexibility

Facing technological and market uncertainty, Coventry developed an experimental VOD path characterized by lightweight intervention, rapid validation, and replicable deployment. Spatially, the Air-One demonstration site was deployed in an urban parking lot, connected with railway stations and core business districts, and adopted a modular configuration that was compact, rapidly deployable, transferable, and low-disturbance (Fig. 5). Institutionally, Coventry made full use of the General Permitted Development Order and temporary permit mechanisms to provide a low-risk institutional environment for real-scene operational verification without complex land-use change or permanent construction [48]. Industrially, it used trial operation and manufacturing-sector matching as entry points, introduced catering, retail, advertising, and other non-aeronautical services, and accumulated prototype verification and operational data through demonstrations and public participation.

Fig. 5 Coventry Air-One.

2.5 Summary of international experience

The four international cases show differentiated but comparable paths (Table 1). Their common trend is a shift from transport node to functional platform, from single-point trial to network construction, and from government-led development to market ecosystem. Successful VOD implementation depends on accurate siting and network construction at the spatial level, institutional flexibility and cross-departmental coordination at the institutional level, and scenario-based market cultivation and industrial ecosystem building at the industrial level.

Table 1 Comparison of VOD models in international cities

Representative model	Spatial integration	Institutional innovation	Industrial synergy	Applicable scenarios
Osaka: air-rail integrated embedded hub	Embedded into existing high-density rail hubs; node capacity up to about 100,000 passengers per year	Extends TOD coordination and renewal mechanisms, integrating airspace coordination, noise control and existing rules	Commuting plus commercial non-aeronautical revenue; non-aeronautical revenue target about 30%	High-density cities and mature rail-transit areas
Paris: corridor-coupled water-air linkage	Arranged along the Seine and existing transport nodes, forming an air-rail-water-land corridor; five planned nodes	Adapts to historic-area protection and Olympic temporary authorizations; pilots help refine rules	Culture-tourism and airport connections; about 30 test flights, more than 200 km accumulated, around 1,000 passengers	Historic cities, waterfront districts and high-load transport corridors
Dubai: hub-platform industrial matching	Vertiports prioritized at airports, CBDs and ports; planned capacity about 42,000 flights and 170,000 passengers per year	Free-zone rapid release and unified transport authority operation	Commuting and logistics supply chain; platform for high-end logistics and cross-border trade	International hub cities, free zones and industrial clusters
Coventry: transferable embedded pilot	Dedicated site plus modular movable facilities; about 15-month design-construction cycle and 11-week on-site construction	Uses GPDO temporary permits and fast-track approval for low-risk validation	MRO plus exhibition and business integration; more than 15,000 visitors and over 100 flight tests	Small and medium cities and renewal districts in technology validation stages

3 Optimization and implications for China's VOD development path based on three-dimensional coordination

3.1 Development status and core bottlenecks

3.1.1 Development status and exploration of local models

In recent years, with the promotion of national strategy and local practice, China's low-altitude economy has moved from concept validation to planning and implementation. Pioneering cities such as Shenzhen, Guangzhou, and Chengdu show local characteristics of spatial connection, scenario first, and network layout. Shenzhen is reconstructing a VOD system of hub integration and network coverage. It plans 56 hubs and more than 1,500 terminal take-off and landing points, prioritizes seven comprehensive hubs and three low-altitude experimental hubs, operates 120 low-altitude routes, and has gathered a substantial industrial ecosystem [24,49]. Guangzhou has explored a gradual path from minimum-unit VOD and corridor extension to network radiation in the Nansha Pearl Bay area, focusing on cross-border commuting, logistics, and tourism. Chengdu combines complex terrain with mountain logistics and emergency linkage, creating a trunk-line, branch-line, and terminal low-altitude logistics network and promoting normalized mountain distribution [50].

Table 2 Comparison of VOD models in Chinese cities

Region	Spatial layout	Institutional innovation	Industrial ecosystem	Characteristic path
Shenzhen	56 hubs plus over 1,500 terminal take-off and landing points; seven comprehensive hubs, three experimental hubs and one passenger hub	Establishes a low-altitude economy task group and pilots flexible control in airspace below 120 m	Public service and commercial operation advance together; 77.6 ten-thousand UAV freight flights; more than 250 routes; 28,000 helicopter passengers; over 1,700 enterprises; output value over RMB 90 billion	Hub coupling, network coverage and manufacturing leadership
Guangzhou	Minimum-unit VOD to corridor extension and network radiation; 22 functional zones, eight distributed nodes and 12,000 m of low-altitude routes	Aggregates cross-border low-altitude travel rules and full-airspace unmanned system demonstration-zone exploration; builds a RMB 10-billion low-altitude economy industry fund	Focuses on cross-border commuting, logistics and low-altitude tourism; builds an eVTOL assembly base	Bay-area collaboration, cross-border interconnection and financial empowerment
Chengdu	Trunk-branch-terminal low-altitude logistics network	Issues measures to promote the low-altitude economy industry	Mountain delivery normalized; single-route annual flights expected to reach 260, promoting logistics and emergency linkage	Terrain adaptation, logistics first and emergency linkage

3.1.2 Core bottlenecks and challenges

Compared with advanced international cases, China's VOD still faces several bottlenecks. First, spatial coordination between planning systems and networks is insufficient. Low-altitude routes, obstacle-free surfaces, and node capacities have not yet been systematically incorporated into statutory territorial spatial planning, leading to insufficient basis for siting and weak coordination between node systems and urban functional areas. Second, institutional governance chains are fragmented and regulatory flexibility is inadequate. Low-altitude transport is highly cross-boundary, but existing systems involve multiple departments, approval processes are long, and flight mission filing may require advance application, increasing institutional costs [39,52]. Standards for unified technology, equipment interoperability, electromagnetic compatibility, and data interfaces also lag behind. Third, business models remain singular and industrial ecosystem coordination is insufficient. Operations currently rely heavily on subsidies and demonstration projects, with high operating cost, weak consumer-market initiative, and incomplete coordination among transport services, MRO, energy supply, data services, insurance, and finance [33,54].

3.2 A three-dimensional collaborative development path for VOD in China

Based on the space-institution-industry framework and international experience, China should build a systematic path that moves from pilot demonstration to system integration.

3.2.1 Spatial integration: building a node-hierarchy-corridor coupling-network integration spatial organization model

At the spatial level, China should follow an evolutionary path from point-like embedding to network integration. First, a three-level system of city, urban district, and community should be established, corresponding respectively to air-rail-ground transport hubs, composite commercial centers, and networked public-service nodes. Second, low-altitude corridors, waters, green space, and regional government-owned low-altitude routes should be prioritized to form an airspace structure of corridors, waterside guidance, and node support. Third, a networked, modular, and iterative deployment model should be formed. Early stages can rely on mobile and modular facilities to lower risk, and mature stages can gradually promote node functional compounding and system integration.

3.2.2 Institutional innovation: constructing a three-in-one system of planning coordination, flexible governance and collaborative supervision

At the institutional level, China should move from conditional permission to systemic coordination. Low-altitude elements should be legally integrated into territorial spatial planning, and routes, node layout, and obstacle-free protection should be incorporated into the multiple-plan integration system. Classification, grading, and layout guidelines should be prepared for VOD facilities, and vertiport allocation standards for different levels should be embedded in master planning and detailed planning, realizing statutory coordination among air, land, rail, and water. Cross-departmental collaborative governance platforms should be established to shorten the chain from approval to operation and to clarify the responsibilities of civil aviation, natural resource, transport, emergency management, public security, and market actors.

A flexible regulatory mechanism should also be formed. Following international experience such as Coventry's temporary authorization and Dubai's rapid-release mechanism, Chinese cities can develop regulatory sandbox tools, temporary permits, and staged authorization. For low-risk scenarios, simplified procedures can be explored; for high-density urban areas, stricter safety assessment, noise control, and data protection can be required. This will allow innovation to proceed under controllable risk while gradually accumulating institutional experience.

3.2.3 Industrial synergy: cultivating a scenario-driven and ecosystem-supported value cycle

At the industrial level, VOD should avoid relying solely on transport fares and should cultivate composite scenarios. Commuting, emergency rescue, logistics, cultural tourism, public governance, inspection, and medical services can be differentiated by city type and spatial condition. Around vertiports, commercial services, exhibition, advertising, energy supply, MRO, data services, insurance, finance, and talent training should be organized to form an integrated ecosystem. Local governments should guide platform enterprises, aviation manufacturing firms, real estate and commercial operators, and public service providers to participate in scenario co-creation, allowing VOD to move from demonstration traffic to sustainable operation.

4 Conclusion and outlook

As a low-altitude extension of TOD, VOD provides a new conceptual tool and implementation path for high-density cities to respond to transport congestion, land scarcity, and spatial restructuring. International cases show that successful VOD does not depend solely on eVTOL technology, but on the coordinated evolution of spatial organization, institutional governance, and industrial ecology. Osaka highlights embedded air-rail integration, Paris demonstrates corridor coupling under historic district protection, Dubai shows platform empowerment through hub economy and free-zone policy, and Coventry provides a transferable and low-cost pilot model.

For China, VOD development is entering a critical transition from isolated pilots to systematic integration. Future work should strengthen three aspects: integrating low-altitude routes, vertiports, and obstacle-free protection into territorial spatial planning; building flexible yet accountable regulatory systems through planning coordination, regulatory sandboxes, and cross-departmental supervision; and cultivating diversified industrial ecosystems driven by scenarios and supported by platform-based operation. These measures can support the high-quality development of the low-altitude economy and provide a spatial governance pathway for three-dimensional urban transformation.

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