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Lunch Peaks and Risk Singularities: Temporal Demand Concentration and Safety Limits in High-Density Urban Drone Logistics

Yang XU
Hong Kong Center of Social Sciences

Abstract

Based on large-scale operational data from Shenzhen's commercial drone delivery network and high-resolution Monte Carlo simulations, this study examines the interaction between delivery efficiency and safety in dense urban low-altitude airspace. Empirical results show that drone logistics achieves a 40–50% reduction in delivery time relative to ground transport, with substantially lower temporal variance. However, demand for instant retail is highly time-concentrated, with lunch peaks reaching nearly 300% of the daily average. Under free-flight operating modes, this temporal concentration drives airspace density beyond critical capacity thresholds, triggering a nonlinear escalation of collision risk, termed a *risk singularity*. The findings demonstrate that safe scaling of urban drone logistics requires a transition from decentralized free flight to infrastructure-mediated, capacity-aware airspace governance.

Keywords Urban Air Mobility; Low-Altitude Economy; Temporal Demand Concentration; Risk Singularity; Airspace Capacity Management

1 Introduction

1.1 Urban Traffic Saturation and the Vertical Spatial Turn

The trajectory of modern urban development has been fundamentally shaped by a logic of densification. As megacities across the Global South and East continue to absorb population, the carrying capacity of ground-based transportation networks is approaching a theoretical asymptote—a point of physical saturation beyond which marginal investments in surface infrastructure yield rapidly diminishing returns. At this threshold, congestion costs, land scarcity, and environmental externalities increase nonlinearly, rendering conventional horizontal expansion both economically inefficient and socially unsustainable.

Against this backdrop, the vertical dimension of urban space has re-emerged as a critical frontier for spatial reconfiguration. In particular, airspace below 1,000 meters—and more precisely, the ultra-low-altitude layer below 120 meters embedded within dense "urban canyons"—has transitioned from a marginal, loosely regulated zone into a focal point of strategic urban experimentation. Once occupied primarily by birds, building envelopes, and sporadic recreational activity, this layer is now being re-territorialized as a commercially viable and institutionally governed economic domain: the Low-Altitude Economy (LAE).

The theoretical promise of Urban Air Mobility (UAM) and unmanned aerial logistics lies in their ability to decouple physical movement from the friction inherent in surface transport. By exploiting near-Euclidean paths, unmanned aerial systems (UAS) can, in principle, bypass traffic signals, road congestion, pedestrian interference, and stochastic delays that plague last-mile delivery. For time-sensitive and high-value goods, this vertical bypass offers not merely speed gains, but a shift toward algorithmic predictability in urban logistics.

However, the transition from sparse pilot operations to dense, commercial-scale deployment introduces a qualitatively different regime of risk. Existing aviation paradigms—historically grounded in the principles of "see and avoid"

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and sparse traffic separation—were never designed to accommodate the extreme operational densities envisioned for megacities such as Shenzhen or New York. The projected volume of simultaneous low-altitude operations exceeds the processing capacity of traditional Air Traffic Management (ATM) systems by orders of magnitude, necessitating a fundamental rethinking of urban airspace governance.

1.2 Shenzhen as a Living Laboratory for Intelligent Aviation

Shenzhen, the core technological hub of the Guangdong–Hong Kong–Macao Greater Bay Area, has emerged as a global forerunner in this transformation. More than a testbed, the city functions as a full-scale urban "living laboratory" for intelligent aviation. Unlike many European or North American cities—where regulatory caution and public skepticism confine drone logistics to rural corridors or suburban enclaves—Shenzhen has deliberately embedded UAM operations within its densest urban fabric.

This trajectory has been enabled by a distinctive institutional configuration characterized by strong governmental coordination and enterprise-driven execution. Supported by exceptional legislative autonomy, Shenzhen has authorized large-scale commercial drone logistics in high-density districts such as Longgang and Longhua. Within this framework, private platforms—most prominently Meituan and SF Express—operate inside a centrally managed digital infrastructure known as the Smart Integrated Low-Altitude System (SILAS).

The empirical scale of this experiment is unprecedented. By the end of 2022, Meituan's drone network had completed over 120,000 commercial delivery orders. By late 2024, cumulative operations exceeded 450,000 orders across 53 designated routes, reflecting exponential growth in both demand and operational maturity. This level of sustained, high-frequency activity allows researchers to move beyond speculative modeling and examine the real-world dynamics of a heavily loaded urban low-altitude network. As such, Shenzhen provides a uniquely robust empirical foundation for engineering-grade analysis within an SSCI-oriented interdisciplinary framework.

1.3 The Dialectical Paradox of Efficiency and Risk

This study offers a systematic and critical examination of the technological and managerial trade-offs embedded within the "Shenzhen model." While the macroeconomic potential of large-scale drone logistics is substantial, our central argument is that operational scalability generates a nonlinear accumulation of safety risk driven by temporal demand concentration.

The logic of "instant retail"—notably food and medical delivery within 15-minute service windows—imposes a rigid biological rhythm on urban logistics networks. Demand is not evenly distributed across time; instead, it clusters sharply during lunch (11:00–13:00) and dinner (17:00–19:00) peaks. During these windows, traffic density within localized airspace volumes can surge to several times the daily average.

Under such conditions, early UAM advocates' preferred model of decentralized "free flight"—where individual drones autonomously plan point-to-point trajectories using onboard detect-and-avoid (DAA) systems—becomes mathematically fragile. The number of potential conflict pairs increases combinatorially with traffic density, while the geometric constraints of urban canyons severely limit available maneuvering space.

Crucially, the urban environment itself is adversarial. Signal occlusion, aerodynamic turbulence, and microclimatic variability undermine the assumptions embedded in standard collision risk models, which typically presuppose Gaussian navigation errors and open-sky conditions. In dense city centers, Global Navigation Satellite System (GNSS) errors exhibit heavy-tailed distributions driven by multipath reflections, while localized wind shear further erodes nominal safety buffers. As a result, separation standards derived from manned aviation lose validity precisely when traffic demand is highest.

This paper identifies and formalizes the resulting systemic phenomenon as a *Risk Singularity*. Beyond a critical density threshold, collision risk no longer scales linearly with traffic volume but undergoes a phase transition, rapidly exceeding the Target Level of Safety (TLS) defined by international aviation standards. We demonstrate that sustaining safe expansion of the low-altitude economy therefore requires a paradigmatic shift: from stochastic, decentralized path planning toward deterministic, infrastructure-mediated airspace design.

Specifically, we validate the necessity of transitioning to a dynamic *Tube-Network* architecture—a structured, four-dimensional (3D space + time) corridor system enforced by SILAS. By imposing strategic, pre-flight constraints through centralized scheduling and dynamic geofencing, this approach decouples operational density from collision risk, enabling high-throughput urban air mobility while maintaining safety levels comparable to those of conventional manned aviation.

In doing so, this study integrates advances in collision risk modeling with the latest regulatory and infrastructural developments in Shenzhen, offering both a theoretical framework and a practical blueprint for the safe scaling of intelligent aviation in high-density urban environments worldwide.

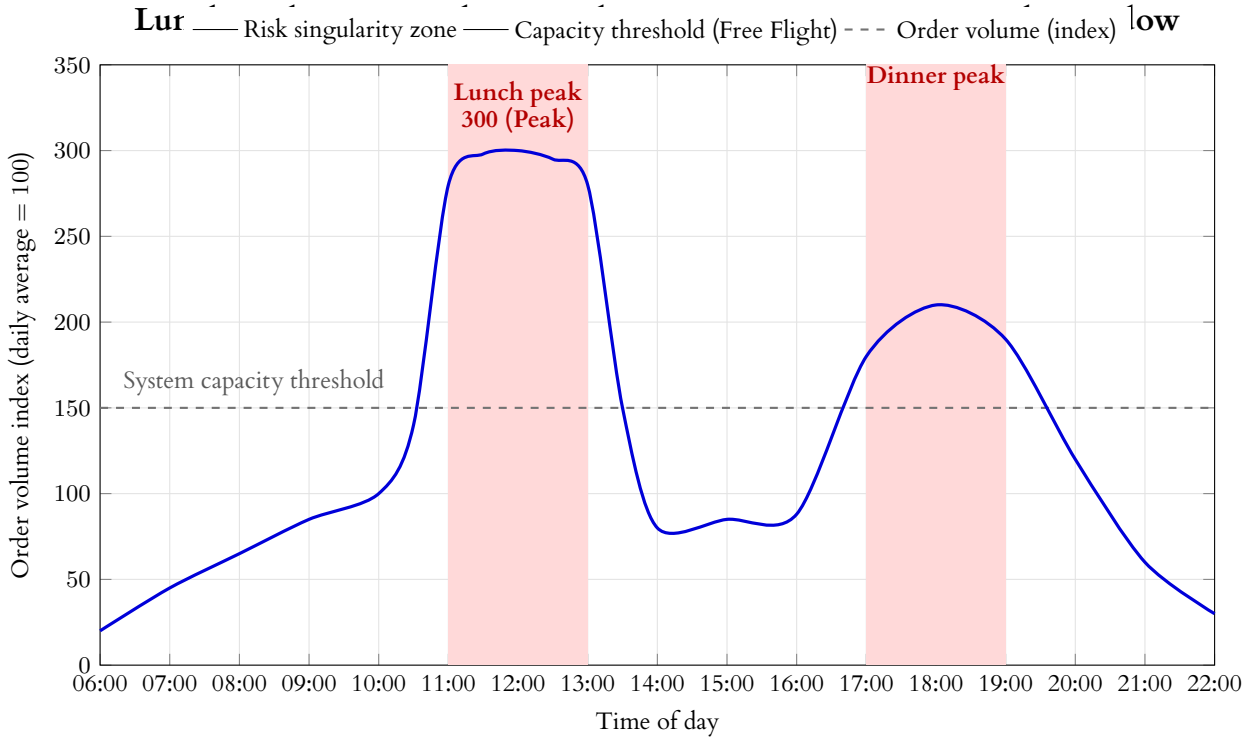


Figure 1: Hourly order-volume distribution for a Shenzhen service area (index normalized to daily average = 100). The lunch peak (11:00–13:00) reaches nearly 300% of the daily average, creating a critical risk window in which airspace density can push conflict probability into a nonlinear growth regime.

Data source: Meituan Drone Network.

2 Literature Review: The Evolution of Urban Air Mobility and Collision Risk Modeling

To situate Shenzhen's operational evidence within the broader intellectual landscape, it is necessary to place urban air mobility (UAM) and low-altitude airspace governance in their evolving scholarly context. Over the past decade, the field has shifted rapidly from speculative "flying car" imaginaries to a rigorous engineering and governance discipline focused on integrating unmanned aerial systems (UAS) into the national airspace system (NAS). This transition has produced three interlocking strands of research that are directly relevant to this study: (i) the move from separation-by-isolation to integration-by-design, (ii) the evolution and limitations of collision risk models (CRMs) under urban-canyon conditions, and (iii) the efficiency debate surrounding last-mile logistics, where throughput and congestion interact with safety in nontrivial ways.

2.1 From Isolation to Integration: The Paradigm Shift in Low-Altitude Airspace

Historically, aviation safety was built upon the principle of *isolation*. Commercial airliners operate in controlled classes of airspace with strict vertical and lateral separation from general aviation and terrain, while conflict management is achieved primarily through strategic separation orchestrated by human controllers. This architecture assumes comparatively low traffic density, predictable trajectories, and a control hierarchy designed for manned operations.

The low-altitude economy, by contrast, is *integrative* by construction. Its core applications—urban drone logistics and high-density UAM—require aircraft to operate in immediate proximity to buildings, crowds, and one another, within constrained volumes of airspace. The resulting operational regime resembles neither classical controlled

airspace nor traditional general aviation; it is a new "urban commons" whose safety must be engineered under density, heterogeneity, and complex boundary conditions **ref1**.

Early UAM research was dominated by platform-centric concerns: eVTOL propulsion, battery energy density, acoustic footprints, and vehicle certification pathways **ref1**. More recent work has pivoted toward the operational layer, particularly the challenge of high-density UAM (HD-UAM). A central idea in this literature has been the adaptation of "free flight" principles originally proposed for higher-altitude ATM. Under a free-flight logic, individual aircraft select near-optimal trajectories with decentralized conflict resolution, leveraging onboard autonomy and detect-and-avoid (DAA) capabilities. Proponents argue that advances in sensing (e.g., LiDAR, optical flow, ADS-B-like solutions) and AI-enabled decision-making would allow tactical deconfliction without rigid routing, maximizing flexibility and local efficiency **ref1**.

Yet an emerging consensus from fast-time simulations and dense-network studies suggests that DAA-based free flight encounters a *saturation boundary*. As density increases, tactical maneuvers introduced to avoid a first conflict can generate secondary conflicts with other aircraft, producing cascade dynamics and, in extreme cases, deadlocks where vehicles freeze, hover, or execute repeated avoidance loops **ref1**. These phenomena are not merely implementation defects of DAA algorithms; they reflect structural constraints in crowded geometry with limited maneuvering space.

This recognition has driven renewed interest in *structured airspace design*. A prominent stream proposes corridor-based designs, often categorized as "air lanes," "routes," and "tubes," each trading freedom for capacity control and safety guarantees **ref5**. In this taxonomy, the tube concept represents the most constrained—and theoretically safest—architecture: a network of virtual 4D corridors that functions as an "aerial highway system," enabling strategic scheduling and separation enforcement at the infrastructure layer rather than the vehicle layer. The present study adopts this design logic and asks a more precise question: under what empirical demand loads and urban-canyon uncertainties does free flight cease to be a defensible operating regime, and when does a tube-network transition become necessary rather than optional?

2.2 Collision Risk Models in Urban Contexts: Foundations, Extensions, and Broken Assumptions

Quantifying aviation safety has long relied on probabilistic risk assessment (PRA) and collision risk modeling. The canonical foundation is Reich's framework, originally developed for structured traffic flows (e.g., transoceanic routes) to estimate mid-air collision (MAC) risk as a function of traffic intensity, navigation performance, and separation standards **ref1**. A representative lateral collision risk expression can be written as:

$$N_y \;=\; P_y(S_y)\, P_z(0)\, \lambda_x \left(\frac{v_y}{S_y} + \frac{v_x}{S_x} \right), \tag{1}$$

where $P_y(S_y)$ denotes the lateral overlap probability under lateral separation S_y, $P_z(0)$ is the vertical overlap probability (often evaluated at zero vertical separation), λ_x is the encounter rate along-track, and the velocity terms capture relative motion components. While analytically elegant, the Reich model assumes quasi-parallel tracks and steady-state motion—conditions that rarely hold for UAM trajectories, which are discontinuous, polygonal, and frequently re-optimized around obstacles.

Alternative approaches include the "gas model," motivated by kinetic theory, in which aircraft are treated as particles moving stochastically within a bounded volume. Collision probability becomes a function of particle density, relative speed, and collision cross-section. Gas models are attractive for non-structured airspace (including free flight) but can systematically overestimate risk when aircraft exhibit coordinated intent, shared constraints, or implicit flow regularities **ref1**.

For urban low-altitude operations, the most consequential limitation is not the choice between Reich and gas metaphors; it is the violation of baseline distributional assumptions. Many classical CRMs presume that total system error (TSE) is approximately Gaussian and stationary. In urban canyons, this assumption becomes unsafe in two distinct ways:

1. **Non-Gaussian navigation error.** GNSS performance in dense high-rise environments is strongly distorted by multipath reflections, non-line-of-sight reception, and intermittent signal blockage. Empirical studies report heavy-tailed and sometimes multimodal error distributions (e.g., Gaussian mixtures), implying that extreme deviations ($> 6\sigma$) occur far more frequently than a normal model would predict **ref1**; **ref8**. In operational terms, this means that "rare" position excursions are not rare enough to ignore at HD-UAM densities.

2. **Highly dynamic trajectories.** Urban drone paths are seldom straight segments; they are obstacle-avoiding polylines requiring frequent heading changes and high-frequency maneuvers. These dynamics violate the steady-motion assumptions embedded in many CRMs and complicate the mapping between separation minima and overlap probability **ref1**.

Recent UAS-oriented extensions of classical CRMs attempt to address these issues by introducing explicit position-uncertainty volumes (e.g., error spheres/ellipsoids) and by incorporating multirotor maneuver characteristics into encounter geometry **ref9**. Building on this line, the present paper adopts a hybrid approach: it retains the interpretability of Reich-style reasoning for structured separation while replacing Gaussian navigation error with empirically motivated heavy-tailed uncertainty in urban canyons. This modification is central to our argument that conventional separation standards can appear adequate under open-sky assumptions yet fail catastrophically during peak density windows in real cities.

2.3 The Last-Mile Efficiency Debate: Speed, Energy, and Congestion Externalities

A parallel literature evaluates whether UAS logistics meaningfully improves last-mile performance. The classic "last-mile problem" notes that the final delivery segment can account for up to half of total logistics cost, motivating interest in airborne delivery as a means of bypassing ground friction **ref1**. Comparative analyses often find that drones can outperform diesel trucks on travel time and, under certain conditions, on energy and emissions.

However, comparisons become more nuanced when the alternative is not diesel vehicles but electric two-wheelers (e-bikes), which dominate urban delivery ecosystems in China. While drones can avoid surface congestion, they face substantial energy costs during hover and when compensating for wind disturbances. Empirical and modeling studies suggest that environmental and energy advantages are highly sensitive to drop density, route straightness, and the share of time spent hovering or waiting **ref1**. Induced power during hover can exceed cruise energy costs, implying that any airspace congestion that forces qu

3 Methodology and Data Sources

This study employs a mixed-methods research design that integrates large-scale operational data analysis with probabilistic simulation modeling to evaluate safety and efficiency in high-density urban drone logistics. Empirical evidence derived from real-world commercial operations is combined with Monte Carlo based collision risk assessment in order to capture rare but safety-critical events that cannot be directly inferred from historical logs alone. The methodological architecture follows established aviation safety evaluation practices, while explicitly incorporating the environmental and institutional specificities of dense urban airspace.

3.1 Study Area: Shenzhen as an Urban UAM Testbed

The empirical investigation focuses on Shenzhen's Longgang and Longhua districts, which together constitute a representative "Goldilocks zone" for urban air mobility experimentation. These districts are sufficiently dense to exhibit genuine metropolitan constraints, including high-rise building clusters, mixed residential commercial land use, and intense on-demand delivery pressure, yet they are located outside the heavily restricted terminal airspace associated with Shenzhen Bao'an International Airport and the Hong Kong Flight Information Region **ref1**. This spatial positioning enables sustained low-altitude operations without the confounding influence of conventional air traffic control constraints.

Within this setting, the Bantian Service Circle in Longgang District serves as the primary case study. The area contains concentrated technology parks such as Xinghe World alongside high-density residential communities, all supported by a mature logistics topology composed of rooftop drone ports and ground-based automated locker systems. The physical morphology of the Bantian area is characteristic of an "urban canyon," defined by narrow street corridors flanked by buildings ranging from 60 to 150 meters in height. This geometry generates persistent challenges for navigation accuracy, wireless communication, and aerodynamic stability, making the area an appropriate stress-test environment for high-density UAM operations.

3.2 Operational Data Collection and Vehicle Parameterization

The core dataset consists of operational logs from Meituan' s drone delivery network, covering the commercial launch phase from early 2021 through December 2022, with publicly disclosed operational statistics from 2023 2024 used for calibration and scale validation **ref1**. All records were aggregated and anonymized to protect commercial confidentiality while preserving sufficient temporal and spatial resolution for system-level analysis.

The data include temporally resolved order records that allow reconstruction of hourly demand patterns and identification of peak-load windows. By the end of 2024, cumulative deliveries exceeded 450,000 orders, confirming that observed demand rhythms persist beyond pilot-scale deployment and remain stable under scaled operations **ref2**. In addition, the dataset contains three-dimensional flight telemetry, including latitude, longitude, altitude, flight duration, and velocity profiles, enabling reconstruction of operational trajectories and encounter geometries. Delivery performance is assessed through comparative analysis of drone and ground courier delivery times for identical origin destination pairs, providing a benchmark for efficiency and variability. Local meteorological conditions, including wind speed, direction, and visibility, are obtained from micro-weather stations integrated into the SILAS infrastructure, allowing direct coupling between atmospheric disturbances and operational risk **ref1**.

Vehicle performance is parameterized using the specifications of Meituan' s fourth-generation logistics drone (M-Drone IV), a six-rotor platform optimized for dense urban delivery. The assumed operational envelope includes a maximum payload of 2.5 kilograms, a full-load range of approximately 10 kilometers, and a typical cruise speed of 10 12 meters per second inferred from observed delivery times. The characteristic rotor span is approximately 1.0 1.5 meters, and the platform is certified for operation under wind conditions up to Beaufort scale 5, moderate rainfall, and ambient temperatures ranging from -20°C to 60°C **ref1**. These parameters define the physical bounds for both empirical interpretation and simulation-based risk evaluation.

3.3 Risk Modeling Framework and Simulation Design

To quantify safety performance under varying traffic densities, a high-fidelity simulation environment representing the Bantian low-altitude airspace is constructed. The framework integrates geometric, aerodynamic, and probabilistic components to capture the dominant drivers of collision risk in dense urban canyons.

The urban environment is represented using OpenStreetMap building footprints augmented with municipal LiDAR scans to generate a voxel-based three-dimensional city model. This representation captures both large-scale canyon geometry and fine-grained vertical discontinuities, such as rooftop structures and towers, that are operationally relevant for low-altitude flight **ref1**.

Aerodynamic disturbances are modeled using a Lattice Boltzmann Method (LBM) solver to resolve microscale airflow patterns induced by urban morphology. The simulation explicitly identifies regions of flow acceleration and wake turbulence generated by building edges and narrow gaps, which are known to destabilize multirotor aircraft during approach and departure phases **ref1**. Outputs from the LBM solver are used to introduce stochastic perturbations into simulated drone trajectories.

Traffic demand is injected according to empirically observed temporal distributions derived from Meituan' s operational data. Extreme surge scenarios are explicitly modeled, most notably the lunch peak between 11:00 and 13:00, during which order volumes reach approximately 300% of the daily average. This ensures that simulated traffic densities correspond to realistic stress conditions rather than uniform or idealized flows.

Collision risk is estimated through Monte Carlo simulation with $N = 10^7$ iterations, a scale chosen to resolve rare-event probabilities consistent with aviation Target Levels of Safety **ref1**. A collision event is defined as a Near Mid-Air Collision (NMAC), occurring when the Euclidean distance D_{ij} between any two drones falls below a critical collision radius R_{col}. Formally, an NMAC is registered when

$$D_{ij} < R_{\text{col}} = R_{\text{phys}} + \epsilon_{\text{nav}},$$

where R_{phys} denotes the physical radius of the drone and ϵ_{nav} represents navigation uncertainty.

In the urban canyon context, ϵ_{nav} is not treated as a fixed margin or Gaussian random variable. Instead, it is modeled as a stochastic quantity whose distribution depends on local GNSS multipath severity and turbulence intensity, exhibiting heavy-tailed behavior consistent with empirical urban navigation error measurements. This modeling choice is critical for capturing tail-risk amplification under high-density conditions and provides the analytical foundation for identifying the "risk singularity" phenomenon examined in subsequent sections.

3.4 Methodological Rationale

The integration of real operational data with large-scale probabilistic simulation reflects a deliberate methodological trade-off. Historical logs alone cannot reveal the likelihood of extremely rare but catastrophic events, while purely synthetic simulations risk detachment from real demand rhythms and infrastructure constraints. By anchoring simulation inputs in Shenzhen's observed operations and extending them through Monte Carlo analysis, this approach achieves both empirical relevance and safety-critical resolution, establishing a robust foundation for evaluating alternative airspace architectures under realistic urban loads.

4 The Shenzhen Model: Regulatory Architecture and Infrastructure-Embedded Governance

The operational data analyzed in this study are the product of a highly specific institutional configuration commonly referred to as the "Shenzhen Model." Unlike the laissez-faire innovation-first approach historically observed in the United States, or the precautionary and restrictive regulatory stance prevalent in many European jurisdictions, Shenzhen has adopted a pragmatic, infrastructure-first strategy that tightly couples regulation, digital systems, and commercial operations. This model treats low-altitude airspace not as an abstract legal construct, but as an engineered public utility whose safety and capacity are co-produced by law, computation, and physical infrastructure.

4.1 Legislative Breakthroughs and Institutional Innovation

A decisive turning point in the evolution of Shenzhen's low-altitude ecosystem occurred in 2024 with the enactment of the *Regulations of the Shenzhen Special Economic Zone on Promoting the Low-Altitude Economy*. This legislation represents a watershed moment in global aviation governance, as it provides one of the first explicit statutory definitions of ownership, usage rights, and management authority for airspace below 120 meters **ref10**. By resolving long-standing legal ambiguity surrounding low-altitude airspace, the regulation establishes a clear institutional foundation for large-scale commercial operations.

Prior to this reform, individual drone flights were subject to fragmented approval processes involving military, civil aviation, and public security authorities, rendering high-frequency logistics operations economically infeasible. The new regulatory framework replaces flight-by-flight authorization with a notification-based system for certified commercial operators within designated zones. This shift dramatically reduces regulatory transaction costs while simultaneously strengthening centralized oversight. Crucially, the legislation redefines responsibility allocation by anchoring safety accountability within a centralized traffic management authority, thereby enabling system-level risk governance rather than aircraft-level compliance alone.

From an institutional economics perspective, the Shenzhen regulation internalizes externalities associated with congestion and collision risk by transforming low-altitude airspace from an open-access commons into a managed infrastructure domain. This transformation provides the legal precondition for enforcing deterministic traffic structures, such as pre-defined corridors and time-slot allocation, which are otherwise unenforceable under traditional aviation law paradigms.

4.2 The Digital Substrate: SILAS as an Urban Airspace Operating System

The regulatory framework of the Shenzhen Model is inseparable from its digital backbone, the Smart Integrated Low-Altitude System (SILAS). Developed by the Guangdong Hong Kong Macao Greater Bay Area Digital Economy Research Institute (IDEA) and released in pilot form in August 2024, SILAS functions not merely as a monitoring dashboard but as a full-stack operating system for low-altitude urban airspace **ref11**. Its core function is to render airspace computable, observable, and governable in real time.

At the data layer, SILAS integrates heterogeneous information streams, including unmanned aircraft oversight platforms, remote identification signals, broadcast surveillance data, and 5G-A sensing inputs. Through multi-source data fusion, the system constructs a unified situational awareness map that captures both cooperative and non-cooperative aerial objects. This continuous state estimation is essential for maintaining operational coherence in dense environments where line-of-sight monitoring is impossible.

A distinctive feature of SILAS is its reliance on Shenzhen's ultra-dense 5G infrastructure, comprising more than 80,000 base stations distributed across the metropolitan area. Leveraging 5G-Advanced technology, these stations

operate as passive sensing nodes capable of detecting aerial targets through signal reflection analysis. This capability enables effective monitoring of unauthorized or unidentified drones and significantly reduces enforcement blind spots in urban canyons, where traditional radar systems are ineffective.

Beyond geometry, SILAS embeds semantic information into its three-dimensional airspace representation. Zones are annotated with contextual attributes such as "school area," "privacy-sensitive zone," or "temporary restriction due to public events." This semantic layer allows regulatory constraints to be dynamically encoded into the airspace itself, enabling automated compliance rather than post hoc enforcement. High-performance spatiotemporal computation within SILAS supports microsecond-level conflict detection and constraint propagation, a prerequisite for managing large volumes of concurrent flights.

4.3 From Regulation to Computation: Enabling Deterministic Airspace Control

The Shenzhen Model differs fundamentally from conventional air traffic management in that regulatory authority is exercised through computational constraint enforcement rather than human mediation. SILAS acts as a centralized temporal and spatial reference, synchronizing all participating aircraft to a shared system clock and a common operational state. This synchronization is essential for implementing deterministic traffic architectures, such as four-dimensional trajectory corridors and dynamic geofencing.

Within this framework, commercial operators such as Meituan do not navigate an open sky but operate within a digitally discretized airspace grid. Flight plans are evaluated not only for individual feasibility but also for system-level compatibility with existing traffic, environmental conditions, and regulatory constraints. As a result, conflict resolution is increasingly shifted from tactical, in-flight avoidance to strategic, pre-departure planning. This shift represents a fundamental reallocation of cognitive and computational burden from onboard autonomy to centralized infrastructure.

The significance of this transition lies in its scalability. Human-centered air traffic control systems face inherent cognitive limits that render them unsuitable for managing hundreds of low-altitude flights per square kilometer per hour. By contrast, infrastructure-embedded governance enables algorithmic enforcement of separation, prioritization, and access control at a scale commensurate with urban logistics demand. In this sense, Shenzhen's approach parallels historical transitions in ground transportation, where traffic lights, lanes, and signal systems replaced informal negotiation at intersections.

4.4 Institutional Preconditions for the Tube-Network Paradigm

The dynamic tube-network architecture proposed in this study is not merely a technical optimization but an institutional artifact made possible by Shenzhen's governance model. The enforceability of virtual corridors, adaptive buffer zones, and time-slot allocation presupposes both legal authority over low-altitude airspace and a real-time digital infrastructure capable of broadcasting and enforcing constraints. Without these preconditions, tube-based airspace would remain a theoretical construct rather than an operational reality.

SILAS provides the necessary control primitives for such an architecture by enabling dynamic expansion and contraction of corridor boundaries in response to wind conditions, navigation uncertainty, and traffic load. Regulatory legitimacy, established through the 2024 legislation, ensures that compliance with these constraints is mandatory rather than voluntary. Together, law and infrastructure form a tightly coupled governance stack in which safety emerges from systemic design rather than individual pilot or algorithmic competence alone.

This integration of regulation and computation marks a departure from aviation paradigms that treat safety as an emergent property of aircraft-level reliability. Instead, the Shenzhen Model conceptualizes safety as an infrastructural outcome, produced through the deliberate design of airspace, information flows, and institutional authority. It is within this context that the subsequent empirical analysis of congestion, collision risk, and the "risk singularity" phenomenon must be interpreted.

4.5 Global Relevance and Transferability

While Shenzhen's institutional configuration is shaped by its unique legal status and technological endowment, the underlying logic of infrastructure-embedded governance has broader implications for global urban air mobility. As cities worldwide confront the challenge of scaling low-altitude operations beyond experimental pilots, the Shenzhen Model offers a concrete demonstration that high-density UAM is not primarily constrained by vehicle technology, but by governance architecture.

The key transferable insight is not the replication of specific regulations or platforms, but the recognition that safe scaling requires a co-evolution of law, digital infrastructure, and operational design. In this sense, Shenzhen functions as a full-scale urban laboratory whose outcomes extend beyond local policy relevance, providing a reference framework for the future integration of intelligent aviation systems into metropolitan environments.

5 Operational Efficiency and Airspace Congestion: Empirical Evidence

A central promise of the low-altitude economy is the decoupling of urban logistics from ground-level congestion. By lifting freight flows into the vertical dimension, urban air mobility is expected to bypass the friction inherent in surface transportation networks. Empirical analysis of Meituan' s operational data confirms the existence of substantial efficiency gains under routine conditions, while simultaneously revealing the emergence of a qualitatively new form of congestion in low-altitude airspace under peak demand.

5.1 Efficiency Gains: Speed and Temporal Determinacy

In the dense urban fabric of Longgang District, surface transportation is constrained by a high effective friction coefficient generated by traffic signals, pedestrian interactions, security checkpoints, and circuitous road geometries. By contrast, drones operating at altitudes of approximately 80 100 meters exploit near-Euclidean flight paths that are largely invariant to ground-level obstacles. Operational data from the Bantian Service Circle demonstrate a marked reduction in delivery times for comparable origin destination pairs.

For deliveries within a three-kilometer service radius, ground-based couriers exhibit an average delivery time of approximately 28 30 minutes. More importantly, delivery times display substantial variance, with a standard deviation in the range of $\sigma \approx 5$ 8 minutes. This dispersion reflects the stochastic nature of elevators, access control systems, pedestrian density, and road traffic conditions. In contrast, drone-based deliveries over identical origin destination pairs achieve an average delivery time of approximately 15 minutes, with a dramatically lower standard deviation of $\sigma \approx 1$ 2 minutes. The delivery process typically consists of a 7 9 minute flight segment followed by a 2 3 minute automated handover at ground-based lockers **ref1**.

These figures correspond to an efficiency improvement of roughly 40 50% relative to ground delivery. From a systems perspective, the reduction in variance is at least as significant as the reduction in mean delivery time. Whereas courier delivery times fluctuate unpredictably in response to local conditions, drone flight durations are algorithmically determined and remain stable except under extreme meteorological disturbances. This temporal determinacy constitutes the core value proposition of "instant retail," in which predictability is as critical as speed.

5.2 Temporal Concentration of Demand and Emerging Congestion

Despite these efficiency gains, the system faces a structural bottleneck rooted not in technology but in human behavior. Demand for instant retail, particularly food delivery, is inherently non-uniform over time and follows a pronounced circadian rhythm. Analysis of order timestamps reveals a distinct bimodal distribution characterized by sharp temporal concentration.

The primary surge occurs during the lunch peak between 11:00 and 13:00, during which order volume rises to nearly 300% of the daily average **ref1**. A secondary, more diffuse peak is observed during the dinner window between 17:00 and 19:00. Outside these intervals, particularly during mid-afternoon hours from 14:00 to 16:00, airspace utilization remains minimal. As a result, system load is dominated by short, intense bursts rather than sustained uniform demand.

This temporal concentration transforms airspace utilization dynamics. During the lunch peak, dozens of drones may depart simultaneously from a small number of merchant hubs within the Bantian Service Circle. Within a localized area of approximately two square kilometers, aircraft density increases abruptly, producing a transient but severe load on the low-altitude airspace. Under the prevailing free-flight operating mode, individual drones independently optimize point-to-point trajectories. As traffic density rises, the probability of intersecting flight paths increases nonlinearly, with the number of potential conflict pairs growing approximately as $\frac{n(n-1)}{2}$ **ref1**.

The empirical evidence thus indicates that congestion in low-altitude systems is not spatially diffuse in the manner of road traffic, but temporally punctuated and spatially concentrated. This pattern gives rise to what this study terms a "risk singularity," in which efficiency gains achieved under average conditions are undermined by a rapid escalation

of interaction complexity during peak demand windows. The operational consequences of this phenomenon are examined in detail in the following section.

6 The Risk Singularity Phenomenon: A Mathematical Representation of Systemic Failure

The concept of the "risk singularity" constitutes the central theoretical contribution of this study. It describes a nonlinear phase transition in system safety that occurs when operational density in low-altitude urban airspace exceeds a critical threshold. Rather than increasing smoothly with traffic volume, collision risk undergoes an abrupt qualitative transformation, signaling the breakdown of decentralized conflict-resolution mechanisms under high-density conditions.

6.1 Defining the Singularity

Under low-density operating regimes, collision risk within a free-flight architecture remains approximately linear and negligible. When traffic density is below approximately 50 operations per square kilometer per hour, interactions between unmanned aircraft are sparse, and tactical Detect-and-Avoid (DAA) systems are sufficient to resolve occasional conflicts. In this regime, the system behaves as a weakly coupled ensemble, and local avoidance actions do not propagate globally.

Monte Carlo simulation results indicate, however, that once traffic density approaches or exceeds approximately 100 operations per square kilometer per hour, the system enters an unstable region **ref1**. At this point, the number of potential conflict pairs increases combinatorially according to the relationship $\frac{n(n-1)}{2}$, where n denotes the number of concurrently active aircraft. In the geometrically constrained environment of an urban canyon, this combinatorial explosion rapidly exhausts the available maneuvering space. As a consequence, the collision probability curve ceases to scale linearly with density and instead exhibits a pronounced inflection, rising sharply over a narrow density interval.

This inflection point defines what is termed the *risk singularity*. Analogous to critical points in phase transition theory, the risk singularity marks the boundary between a regime of stable, predictable operation and one characterized by systemic instability. Beyond this point, marginal increases in traffic load produce disproportionate increases in collision risk, rendering traditional safety assumptions invalid.

6.2 Simulation Evidence: Collapse of the Free-Flight Regime

Simulation outcomes during peak demand windows provide direct evidence of this systemic failure. During the lunch peak between 11:00 and 13:00, Monte Carlo simulations calibrated with observed demand patterns show that, under a free-flight operating model, the probability of a Near Mid-Air Collision (NMAC) in convergence zones near high-demand merchant hubs rises to approximately 1×10^{-4} **ref1**. This level exceeds the aviation Target Level of Safety of 1×10^{-7} per flight hour by three orders of magnitude, indicating a fundamental violation of acceptable risk thresholds.

Importantly, this failure cannot be attributed solely to sensor limitations or imperfections in autonomous avoidance algorithms. Rather, it is a geometric and topological failure of the operating space itself. When multiple aircraft converge simultaneously within narrow urban corridors toward shared nodes such as rooftop dispatch points, the degrees of freedom required for safe avoidance are depleted. Attempts by individual drones to resolve conflicts through evasive maneuvers generate secondary conflicts, producing cascades of interaction that resemble deadlock phenomena in distributed systems.

In such deadlock states, aircraft are forced to hover or retreat in place, transforming dynamic risk into static exposure. Hovering increases energy consumption, accelerates battery depletion, and prolongs exposure to environmental hazards such as wind shear and navigation error. The system thus enters a self-reinforcing loop in which congestion amplifies risk, and risk-induced delays further exacerbate congestion. This feedback structure explains why the observed escalation in collision probability is abrupt rather than gradual.

The emergence of the risk singularity demonstrates that free-flight architectures possess an intrinsic scalability limit in dense urban environments. Beyond a critical density, safety degradation is no longer a matter of incremental performance tuning but reflects a fundamental incompatibility between decentralized path optimization and the

geometric constraints of urban airspace. This insight motivates the transition to structured, deterministic airspace architectures examined in the subsequent section.

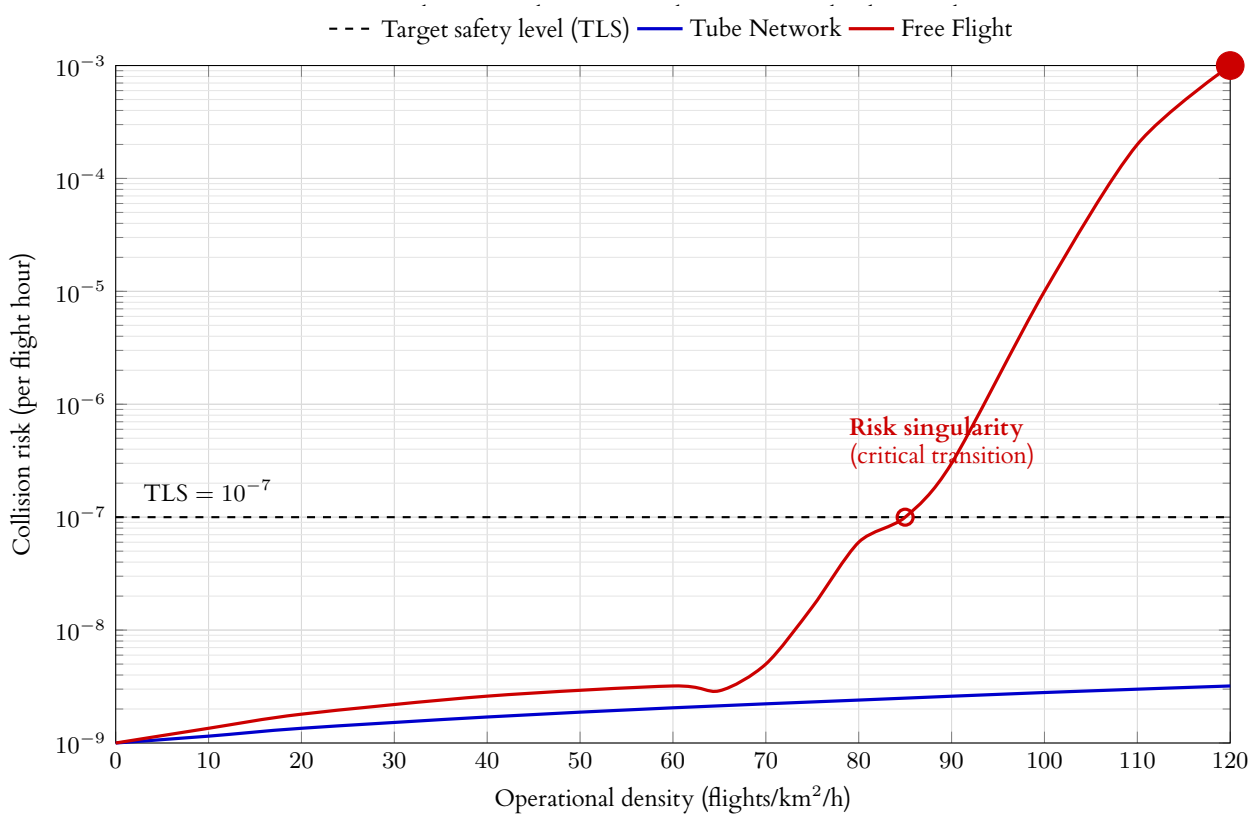


Figure 2: Relationship between operational density and collision risk under two airspace concepts. The "risk singularity" occurs where the Free Flight curve accelerates sharply and crosses the target safety level (TLS). The Tube Network remains approximately stable across the same density range, indicating safety robustness under structured operations.

7 Safety Risk Assessment in Urban Canyons

The term "urban canyon" accurately characterizes the operational environment encountered by low-altitude aircraft in dense metropolitan areas such as Shenzhen. Flight operations conducted between steel-and-glass high-rise structures introduce a set of safety-critical variables that are largely absent in rural or suburban drone deployments. These variables constitute the physical mechanisms that precipitate the early emergence of the risk singularity identified in the preceding section.

Unlike open environments, urban canyons impose severe geometric constraints on airflow, radio-frequency propagation, and line-of-sight sensing. As a result, disturbances that are secondary or negligible in sparse airspace become first-order drivers of collision risk under high-density conditions. Two mechanisms are particularly salient: microscale aerodynamic turbulence and non-Gaussian navigation errors induced by GNSS multipath effects.

7.1 Aerodynamic Hazards: Invisible Turbulence and Wind Shear

Urban wind fields are inherently chaotic. The interaction between atmospheric flow and dense building morphology generates highly heterogeneous microclimates characterized by sharp velocity gradients and rapidly fluctuating pressure fields. To capture these effects, the risk modeling framework employed in this study incorporates a Lattice Boltzmann Method (LBM) solver, which is well suited to resolving complex airflow patterns in confined geometries.

Simulation results indicate that buildings accelerate wind through narrow gaps via Venturi effects while simultaneously producing recirculation zones and vortices at sharp edges and corners. An unmanned aircraft transitioning

from the leeward side of a high-rise structure into an exposed windward corridor can experience abrupt and substantial changes in lift and drag. These transients occur over spatial scales comparable to the vehicle's rotor span and temporal scales shorter than the response time of many flight controllers **ref1**.

The implications for collision risk are nontrivial. During approach and departure phases, wind shear emerges as a dominant contributor to trajectory deviation. In high-density free-flight scenarios, a gust-induced lateral displacement on the order of five meters is sufficient to invalidate nominal separation assumptions. Such a deviation can instantaneously trigger cascading conflict alerts among nearby aircraft, eroding safety buffers that are presumed inviolable in conventional collision risk models. Importantly, these effects scale with traffic density: as the number of nearby aircraft increases, the probability that a single perturbation propagates into a multi-vehicle interaction rises sharply.

7.2 Navigation Hazards: Heavy-Tailed Errors from GNSS Multipath

In open-sky conditions, Global Navigation Satellite System (GNSS) positioning errors are commonly modeled as Gaussian random variables with standard deviations on the order of a few meters. This assumption underpins many existing collision risk models and separation standards. In urban canyons, however, the assumption is fundamentally violated.

The verticality and reflectivity of Shenzhen's built environment obstruct direct line-of-sight signals from navigation satellites. Receivers therefore rely heavily on non-line-of-sight (NLOS) signals reflected from glass façades and metallic surfaces. These reflections increase the effective signal path length, causing receivers to compute positions that are systematically displaced from the true vehicle location, producing so-called "ghost" positions **ref1**.

Empirical measurements in Shenzhen demonstrate that navigation error distributions in such environments are heavy-tailed rather than Gaussian. While mean positioning errors may remain within nominal bounds, the probability of extreme outliers exceeding 50 meters is statistically significant. Under a Gaussian model, such deviations would be vanishingly rare; in urban canyons, they are inevitable rare events. For an aircraft operating within ten meters of a building façade or another vehicle, a 20-meter ghost displacement is not a benign statistical anomaly but a direct precursor to collision.

Although Meituan employs visual navigation and SLAM-based localization to mitigate GNSS degradation, sensor fusion must operate under conditions of dynamic occlusion, variable illumination, and rapidly changing textures. These constraints limit the extent to which vision-based systems can fully compensate for GNSS multipath, particularly during transient maneuvers or in narrow corridors.

Comparative distribution analysis illustrates this effect clearly. Whereas open-sky navigation errors follow a near-normal distribution with rapidly decaying tails, empirically derived urban canyon error distributions exhibit pronounced kurtosis and fat tails. The probability mass in the tail region corresponding to errors greater than 20 meters is several orders of magnitude higher than predicted by Gaussian models. This tail behavior explains why standard safety buffers, designed under open-sky assumptions, fail to provide adequate protection in dense urban environments.

7.3 Implications for System-Level Risk

The combined presence of microscale aerodynamic disturbances and heavy-tailed navigation errors fundamentally alters the risk landscape of urban low-altitude operations. These factors act not as independent noise sources but as amplifiers of interaction complexity. Under low-density conditions, their effects are largely absorbed by available maneuvering space and tactical avoidance margins. As density increases, however, the same disturbances precipitate rapid degradation of separation assurance.

This analysis clarifies why the risk singularity emerges at significantly lower traffic densities in urban canyons than would be predicted by classical collision risk models. The failure is not a consequence of inadequate autonomy or sensing alone, but of a mismatch between stochastic environmental realities and airspace concepts predicated on smooth, Gaussian assumptions. Recognizing this mismatch is essential for understanding the limitations of free-flight architectures and motivates the structured airspace solutions examined in the subsequent section.

8 Solution: The Dynamic Tube-Network Architecture

To resolve the fundamental conflict between peak-density demand and stringent safety requirements in urban low-altitude operations, this study proposes and evaluates a paradigm shift from stochastic, free-flight path planning toward a structured and deterministic airspace design known as the Dynamic Tube-Network architecture. Rather than treating airspace as an open volume in which individual aircraft independently optimize trajectories, the proposed approach reconceptualizes urban airspace as an adaptive, networked system of constrained corridors governed by centralized flow control.

8.1 Conceptual Framework and Architectural Principles

The core concept of the tube-network architecture is to partition urban airspace into a set of virtual four-dimensional corridors, defined jointly in space and time. These tubes function as geofenced "aerial highways" that connect high-demand nodes such as shopping mall rooftops, logistics hubs, and residential delivery kiosks **ref1**. Aircraft are permitted to operate only within the boundaries of an assigned tube during an allocated temporal window, thereby transforming free-flight navigation into network-constrained motion.

A defining feature of the tube-network is structural separation. Tubes are spatially segregated from one another and from static obstacles through deliberate vertical and lateral layering. For example, to eliminate the possibility of head-on conflicts, northbound traffic may be assigned to a corridor centered at an altitude of 80 meters, while southbound traffic operates within a separate corridor at 100 meters. This vertical stratification removes entire classes of conflict at the geometric level rather than relying on real-time tactical avoidance.

Unlike physical road infrastructure, the proposed tubes are virtual and dynamically reconfigurable. The system continuously adjusts corridor dimensions in response to environmental uncertainty. During periods of elevated wind speed or degraded navigation quality, as indicated by high dilution-of-precision values, tube diameters are automatically expanded to accommodate increased positional uncertainty. Under calm conditions with stable sensing, tubes contract, increasing throughput without compromising safety **ref1**. In this manner, safety margins become adaptive rather than static, reflecting real-time risk conditions.

Access to each tube is governed by centralized flow control through a slot-allocation mechanism. Prior to departure, each aircraft must request a time slot from the supervisory traffic management system. If the available capacity of a tube is saturated, aircraft are held at origin nodes or designated holding points until a slot becomes available. This mechanism is analogous to packet scheduling in communication networks or block signaling in rail systems. Crucially, it relocates conflict resolution from the tactical airborne domain to the strategic pre-flight planning stage, where conflicts can be resolved deterministically rather than reactively **ref1**.

Conceptually, the resulting airspace resembles a three-dimensional network of semi-transparent corridors weaving between high-rise structures. Each corridor strictly bounds the permissible motion of aircraft, ensuring separation from buildings and other traffic flows while preserving predictable and repeatable trajectories.

8.2 Integration with the SILAS Digital Infrastructure

The feasibility of the dynamic tube-network architecture is contingent upon the presence of a robust digital airspace infrastructure. In Shenzhen, this foundational layer is provided by the Smart Integrated Low-Altitude System (SILAS), which enables real-time sensing, communication, and centralized control.

The architecture operates across multiple tightly coupled layers. At the physical layer, unmanned aircraft are equipped with onboard autonomy, visual sensors, and 5G communication modules capable of continuous state reporting. The network layer is formed by a dense deployment of more than 80,000 5G base stations, providing low-latency connectivity and distributed environmental awareness across the urban area. At the control layer, SILAS functions as the central coordinator, maintaining a real-time digital twin of the low-altitude airspace, generating dynamic geofences, and broadcasting operational constraints to airborne vehicles. At the application layer, commercial logistics platforms such as Meituan's fleet management system optimize delivery operations within the constraints imposed by SILAS, effectively solving a constrained network flow problem rather than performing unconstrained path search **ref1**.

This layered integration ensures that strategic airspace management decisions are consistently enforced across all operational levels, aligning individual vehicle behavior with system-level safety objectives.

8.3 Simulation-Based Validation

The performance of the tube-network architecture was evaluated under simulated peak-load conditions corresponding to the lunchtime demand surge between 11:00 and 13:00. In contrast to free-flight operations, which require resolving complex two- or three-dimensional convergence patterns, the tube-network reduces collision avoidance to a one-dimensional spacing problem along each corridor, where maintaining longitudinal separation between successive aircraft is sufficient to ensure safety.

Simulation results demonstrate a substantial improvement in safety performance. Even under extreme traffic densities, the enforcement of slot allocation and corridor confinement maintains the probability of near-midair collisions at negligible levels, with estimated collision probabilities remaining below $P_{col} < 10^{-7}$, consistent with target safety level requirements **ref1**. This represents several orders of magnitude improvement over free-flight scenarios operating at comparable densities.

The primary operational cost of this architecture is a modest increase in average delivery time, arising from potential queuing delays at tube entry points. These delays typically range from 30 to 90 seconds during peak periods. However, such delays are predictable and bounded, in stark contrast to the unbounded and unpredictable delays induced by deadlock situations in free-flight systems. From a system perspective, the trade-off is decisively favorable: a small, quantifiable delay is exchanged for the elimination of catastrophic collision risk and systemic instability.

9 Policy and Airspace Governance Implications: From Engineering to Governance

Conclusion

The urban drone logistics experiment conducted in Shenzhen has produced the world's first robust, large-scale empirical dataset capturing the dynamics of high-density low-altitude operations in a real metropolitan environment. The evidence is unequivocal. Urban drone delivery delivers a transformative efficiency gain of approximately 40–50% relative to ground-based logistics, enabling a new temporal regime of "instant" urban mobility. However, this efficiency is inseparable from operational density. The lunchtime demand surge reveals a critical failure mode: unmanaged free-flight operations, when exposed to the geometric and aerodynamic constraints of urban canyons, generate collision risks that exceed acceptable aviation safety thresholds. This study formalizes this nonlinear breakdown as a *risk singularity*.

The emergence of the risk singularity carries profound implications for airspace governance. It demonstrates that safety degradation in dense urban airspace is not primarily a consequence of insufficient sensing accuracy or suboptimal onboard autonomy, but rather the result of an inappropriate organizational paradigm. Incremental improvements in detect-and-avoid performance cannot resolve a fundamentally geometric and systemic instability. Beyond a critical density threshold, the airspace itself becomes the binding constraint.

From a governance perspective, this finding necessitates a paradigm shift. The future of urban air mobility does not lie in further decentralization of tactical decision-making, but in the structural redesign of airspace as a managed system. The dynamic tube-network architecture proposed in this study represents such a shift. By organizing low-altitude airspace into adaptive four-dimensional corridors governed by centralized flow control, cities can decouple traffic density from safety risk. In this model, airspace transitions from an unregulated commons into a regulated public utility, analogous to the historical evolution from open terrain to paved road networks.

This reconceptualization has direct regulatory implications. First, it suggests that aviation authorities should prioritize airspace architecture and traffic management rules over vehicle-centric certification alone. Safety assurance in dense urban environments must be achieved at the system level rather than delegated exclusively to individual aircraft. Second, it implies that digital infrastructure such as Shenzhen's Smart Integrated Low-Altitude System (SILAS) is not merely an operational aid but a core element of aviation safety regulation. Real-time digital twins, dynamic geofencing, and slot-based access control become regulatory instruments, not optional technological enhancements. Third, it reframes congestion management as a legitimate and necessary safety tool. Predictable, ground-based queuing delays are preferable to airborne deadlocks and cascading conflicts that compromise both safety and energy efficiency.

More broadly, the Shenzhen case illustrates how governance capacity determines the scalability of urban air mobility. Cities lacking integrated digital airspace management will encounter the risk singularity at substantially

lower traffic densities, constraining the economic viability of drone logistics. Conversely, cities that invest in centralized coordination platforms can safely unlock higher-density operations and capture the full efficiency dividend of low-altitude aviation.

As Shenzhen evolves from a pilot zone into a fully operational low-altitude city, the success of this transition will serve as a global reference point. The lesson is clear: the central challenge of urban drone integration is no longer how to make aircraft fly, but how to make them flow. Engineering innovation must therefore be matched by institutional innovation. Only by aligning airspace design, digital infrastructure, and regulatory authority can cities transform low-altitude airspace from a source of systemic risk into a foundation for sustainable urban mobility.

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Editor *Xin HUANG editor@jlae.org*