LAPP v0.2

Lorenz Airspace Protocol Proposal: Market-Based Low-Altitude Airspace Coordination for eVTOL Operations

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Abstract

This paper introduces the Lorenz Airspace Protocol (LAPP), a coordination framework for dense low-altitude electric vertical takeoff and landing (eVTOL) traffic operating between 1,000 and 1,800 feet above ground level. LAPP combines a heading-based altitude stratification scheme (the hemispheric rule, extended to eight directional sectors) with a market-based slot allocation mechanism using sealed-bid second-price (Vickrey) auctions at route turn points. The protocol reserves capacity for emergency and public-safety operations at zero cost, funded by commercial auction revenues. We present results from an agent-based reference simulator demonstrating that: (1) a lane tolerance of 5–7° minimizes conflicts under uniform traffic assumptions; (2) stricter tolerances beyond this optimum increase conflicts due to turn-point clustering, producing a characteristic U-shaped tradeoff curve; (3) auction-based allocation achieves superior allocative efficiency compared to first-come-first-served (FCFS), directing scarce slots to highest-priority traffic; and (4) layer transition dynamics introduce a new category of vertical conflict whose precise characterization requires higher-fidelity simulation than the present reference implementation provides. LAPP is proposed as an open protocol standard for interoperable eVTOL airspace coordination, with a revenue model that funds infrastructure through market-priced slot allocation.

Keywords: eVTOL, urban air mobility, airspace protocol, Vickrey auction, traffic management, UTM, low-altitude operations, market-based allocation

1. Introduction

The emergence of electric vertical takeoff and landing (eVTOL) aircraft has created an unprecedented challenge for airspace coordination. Unlike conventional aviation, which operates in well-established controlled airspace with mature separation standards, eVTOL vehicles are expected to operate in dense clusters at low altitudes—between 500 and 2,000 feet above ground level—over populated urban areas. This altitude band is currently unstructured: it sits below the floor of most Class B and C airspace and above the practical ceiling of most ground-based obstacles. It is, in effect, unclaimed sky.

The scale of the coordination problem is qualitatively different from anything existing air traffic management (ATM) systems were designed to handle. Current proposals from major eVTOL manufacturers (Joby Aviation, Archer Aviation, Lilium, EHang) assume that airspace coordination will be provided by some combination of FAA modernization, NASA’s Unmanned Traffic Management (UTM) framework, and bilateral agreements between operators. This assumption creates a dangerous gap: no entity is currently building the interoperable coordination layer that would allow heterogeneous eVTOL fleets from different manufacturers to share low-altitude airspace safely and efficiently.

This paper proposes the Lorenz Airspace Protocol (LAPP) to fill that gap. LAPP is not an aircraft design, a specific vehicle, or a proprietary system. It is an open protocol specification—analogous to TCP/IP for internet traffic or ADS-B for aircraft surveillance—that defines how eVTOL vehicles coordinate their use of shared airspace. Any aircraft implementing the LAPP stack can operate in LAPP-managed airspace, regardless of manufacturer.

LAPP makes three key contributions. First, it extends the conventional hemispheric altitude rule to an eight-sector system with empirically determined lane tolerances, providing heading-based vertical separation without requiring centralized control. Second, it introduces a market-based allocation mechanism—sealed-bid second-price (Vickrey) auctions—for resolving contention at route turn points, replacing the first-come-first-served (FCFS) approach used in conventional ATM with a mechanism that allocates scarce airspace to the operators who value it most. Third, it reserves capacity for emergency and public-safety operations at zero cost, funded by commercial auction revenues, addressing equity concerns inherent in market-based airspace allocation.

2. Related Work

2.1 NASA UTM and FAA Integration

NASA’s Unmanned Traffic Management (UTM) concept of operations, developed through a series of Technical Capability Levels (TCL-1 through TCL-4), provides the most comprehensive existing framework for low-altitude airspace coordination. UTM envisions a federated system of UAS Service Suppliers (USS) that coordinate operations through a shared Flight Information Management System (FIMS). The FAA’s integration of UTM concepts into regulatory frameworks is ongoing, with Remote ID requirements (effective September 2023) representing the first operational mandate derived from UTM research.

LAPP builds on UTM’s strategic deconfliction concept—pre-planned 4D trajectories submitted to a shared ledger—but diverges in two critical respects. First, LAPP replaces UTM’s implicit FCFS allocation with explicit market pricing, creating an economic signal for airspace scarcity. Second, LAPP specifies the coordination protocol itself (heading-based stratification, auction mechanics, transition procedures), whereas UTM deliberately leaves protocol details to the USS layer, creating potential interoperability gaps between competing USS providers.

2.2 EASA U-space

The European Union Aviation Safety Agency’s (EASA) U-space framework provides a regulatory structure for unmanned aircraft operations organized into four service levels (U1 through U4), with increasing levels of automation and integration. U-space’s concept of “geofencing” and dynamic airspace authorization is architecturally compatible with LAPP’s ledger-based approach. LAPP’s market mechanism could operate as a U3/U4 service within the U-space framework, providing the allocation logic that U-space’s regulatory structure requires but does not specify.

2.3 Market-Based Airspace Allocation

The application of auction theory to airspace management has been explored in academic literature, notably by Rassenti, Smith, and Bulfin (1982) for airport slot allocation, and more recently by Vossen and Ball (2006) for en-route traffic flow management. Castelli, Pesenti, and Ranieri (2011) proposed a combinatorial auction for European airspace sectors. LAPP adapts these approaches to the specific geometry of low-altitude eVTOL operations, where the coordination problem is characterized by high density, short flight durations, energy constraints, and the need for real-time clearing—conditions not addressed by slot-auction proposals designed for airlines operating on hourly timescales.

3. Protocol Specification

3.1 Altitude Stratification: The Extended Hemispheric Rule

LAPP divides the operational altitude band (1,000–1,800 ft AGL) into eight layers, each 100 ft apart, assigned to one of eight compass heading octants. Aircraft select their cruise altitude based on their direction of travel:

Layer	Altitude	Heading	Compass Range
L1	1,000 ft	North (N)	337.5° – 22.5°
L2	1,100 ft	Northeast (NE)	22.5° – 67.5°
L3	1,200 ft	East (E)	67.5° – 112.5°
L4	1,300 ft	Southeast (SE)	112.5° – 157.5°
L5	1,400 ft	South (S)	157.5° – 202.5°
L6	1,500 ft	Southwest (SW)	202.5° – 247.5°
L7	1,600 ft	West (W)	247.5° – 292.5°
L8	1,700 ft	Northwest (NW)	292.5° – 337.5°

Table 1: LAPP altitude layer assignments by heading octant.

This scheme eliminates head-on conflicts between opposing traffic flows (e.g., northbound at 1,000 ft and southbound at 1,400 ft are separated by 400 ft) and reduces crossing conflicts between adjacent flows (e.g., northbound and northeast are separated by 100 ft). Within each layer, aircraft travel on approximately parallel headings, reducing conflicts to overtake scenarios only.

3.2 Lane Tolerance

Aircraft are permitted to deviate from their layer's nominal heading by a configurable lane tolerance α. A flight whose required bearing falls within $\pm\alpha$ of a layer's nominal heading may use that layer for a direct route. Flights requiring bearings outside any layer's tolerance band must plan multi-segment routes with turn points (Section 3.3).

The choice of α governs a fundamental tradeoff. Larger tolerances allow more flights to proceed directly (reducing detour and energy cost) but permit greater heading divergence within a layer (increasing same-layer crossing conflicts). Smaller tolerances enforce near-parallel traffic within layers but force more flights through turn points, creating geometric chokepoints. Simulation results (Section 5) identify an empirical optimum at $\alpha \approx 5$–7°, with a characteristic U-shaped conflict curve as tolerance deviates in either direction.

3.3 Turn-Point Routing

When no single layer's tolerance band includes the required bearing from origin to destination, the LAPP planner computes a multi-segment route. In the current specification (v0.1), routes are limited to two segments joined at a single turn point. The planner evaluates all valid layer pairs (L_i, L_j) and selects the pair whose turn point yields the minimum total path length. The turn point is the geometric intersection of the two layers' heading vectors projected from origin and destination respectively.

Turn points are the primary locus of contention in LAPP-managed airspace. Because multiple independent route plans may converge on geometrically similar turn points, the protocol requires a contention-resolution mechanism at these locations. This mechanism is provided by the auction system described in Section 3.4.

3.4 Market-Based Slot Allocation

LAPP manages contention at turn points through a sealed-bid second-price (Vickrey) auction. The mechanism operates as follows:

- **Spatial quantization.** The airspace is divided into cells (default: 60m × 60m). Each cell's turn-point capacity is managed independently.
- **Temporal windowing.** Each reservation covers a time window (default: 2.5 seconds) centered on the aircraft's estimated time of arrival at the turn point.
- **Bid submission.** When planning a route, each aircraft submits a sealed bid reflecting its priority value for each turn-point slot its route requires. Priority values are determined by the operator and may reflect passenger urgency, contractual obligations, or willingness-to-pay.
- **Vickrey clearing.** If multiple bids compete for overlapping time windows in the same cell, the highest bidder wins and pays the second-highest bid. This mechanism is incentive-compatible: each bidder's dominant strategy is to bid their true value, producing efficient allocation without strategic gaming.
- **Reroute on loss.** Aircraft that lose auctions either select alternative turn points (replanning with a different layer pair) or hold at their origin until a slot becomes available. The protocol limits replan attempts to prevent infinite loops.

3.5 Emergency and Public-Safety Reserves

Emergency-flagged aircraft (medical evacuation, law enforcement, energy-critical operations) receive infinite effective priority and pay zero auction cost. When an emergency aircraft claims a slot, any commercial reservation in that slot is displaced; the displaced aircraft is notified and must replan. A configurable percentage of system capacity is implicitly reserved for emergency operations by this displacement mechanism.

This design ensures that market-based allocation does not compromise safety-critical access. The cost of emergency reserves is borne by commercial operators through the displacement mechanism—functionally equivalent to a tax on commercial airspace use that funds public-safety access.

3.6 Layer Transition Dynamics

In physical operation, transitioning between altitude layers is not instantaneous. Aircraft climb or descend at a finite rate (constrained by propulsion capability and energy reserves), covering horizontal ground during the maneuver. During transition, an aircraft occupies altitude between its origin and destination layers and may conflict with traffic in either layer. The LAPP conflict model treats transitioning aircraft as present in both layers simultaneously for separation purposes.

This creates a tradeoff between climb rate and conflict exposure. Faster climb rates reduce transition time (and thus the window of dual-layer vulnerability) but consume more energy. Slower climb rates are energy-efficient per second but extend the exposure window. Simulation results (Section 5.3) inform minimum climb-rate recommendations for LAPP-compliant aircraft.

4. Revenue Model and Infrastructure Economics

LAPP's auction mechanism generates revenue as a natural byproduct of coordination. Every contested turn-point slot produces a clearing price paid by the winning bidder. This revenue flows to the protocol operator (the entity maintaining the airspace ledger, auction clearing engine, and regulatory compliance infrastructure). The model is analogous to a financial exchange: the protocol operator does not participate in the market as a buyer or seller of airspace; it operates the matching engine and collects transaction fees.

Revenue scales with three factors: traffic density (more aircraft create more contention), airspace scarcity (congested sectors produce higher clearing prices), and geographic coverage (more managed sectors generate more transaction volume). This creates a positive feedback loop: as eVTOL adoption increases, the protocol's revenue grows, funding further infrastructure investment, which in turn supports higher traffic densities.

A portion of auction revenue is designated for public-infrastructure purposes: maintenance of emergency-reserve capacity, subsidized access for essential services, and investment in shared landing infrastructure. The allocation between operator revenue and public-infrastructure funding is a policy parameter negotiated with regulatory authorities.

5. Simulation Methodology and Results

We developed an agent-based reference simulator to evaluate LAPP's performance under controlled conditions. The simulator models a square airspace sector with aircraft spawning at random boundary points, selecting destinations uniformly within the sector, and executing the LAPP protocol (altitude selection, route planning, auction bidding, layer transitions). The simulator was iterated through multiple versions, with each version's design driven by empirical findings from the previous version.

Methodology note. During v0.4 development, a transition-timing bug was identified and corrected: layer transitions were being cancelled at waypoint arrival regardless of whether the altitude change had completed, effectively rendering the climb-rate parameter inert. All findings reported in this paper derive from the corrected v0.5 simulator. The reference simulator is publicly available and readers are encouraged to reproduce the experiments described here.

5.1 Optimal Lane Tolerance

Sweeping the lane tolerance parameter α from 1° to 22° at a traffic density of 60 aircraft and measuring steady-state conflict rate (conflicts per minute) and average detour ratio (path length / great-circle distance), we observe a U-shaped conflict curve with a minimum at $\alpha \approx 5$–7°. At tolerances above 7°, same-layer crossing conflicts increase as aircraft within a layer diverge in heading. At tolerances below 5°, conflict rates increase due to turn-point clustering: nearly all flights require turn points, and the geometric constraints of the eight-layer system concentrate these turn points in predictable locations.

Parameter	Finding	Implication
Lane tolerance	5–7° optimal	Spec recommendation for α
Tolerance < 5°	Conflicts increase (U-shape)	Turn-point clustering dominates
Tolerance > 7°	Conflicts increase	Same-layer crossing conflicts dominate
Auction vs FCFS	Higher allocative efficiency	Market directs slots to highest-value traffic
FCFS advantage	Sometimes lower raw conflicts	Conservative holding reduces density
Climb rate	No significant effect observed	Requires higher-fidelity simulation
Energy model	Sensitive to battery margin	Calibration must precede quantitative claims

Table 2: Summary of key simulation findings.

5.2 Auction vs. FCFS Allocation

Comparing auction-based and FCFS allocation modes at identical traffic densities, we find that the auction mechanism achieves superior allocative efficiency—defined as the proportion of contested slots awarded to the highest-priority bidder. Under auction allocation, efficiency typically exceeds 80%, compared to approximately 50% under FCFS (where slot assignment correlates with planning order rather than priority).

However, we observe that FCFS sometimes produces lower instantaneous conflict counts than auction allocation. This appears to result from FCFS's more conservative holding behavior: aircraft that lose slots under FCFS hold longer and attempt fewer alternatives, reducing airborne density. The auction mechanism, by actively displacing lower-priority holders, creates replanning cascades that can temporarily increase local density. This finding motivates the development of congestion caps (planned for future protocol versions) that would limit the number of active reservations per cell regardless of bid value.

5.3 Layer Transition Dynamics

The introduction of physical layer transitions reveals a new conflict category: vertical transition conflicts, in which aircraft climbing or descending between layers may encounter traffic in either the origin or destination layer during the maneuver. The LAPP conflict model correctly treats transitioning aircraft as present in both layers for separation purposes.

Quantifying the effect of climb rate on conflict frequency, however, proved beyond the fidelity of the present reference simulator. A preliminary sweep of climb rates from 50 to 600 ft/min at fixed traffic density and lane tolerance did not reveal a statistically significant relationship between climb rate and conflict frequency; the observed variation was within the noise band of the measurement. Additionally, the simplified energy model used by the reference simulator proved sensitive to battery-margin assumptions, limiting the reliability of energy-related findings. We conclude that climb-rate specifications and energy-feasibility analyses require migration to a higher-fidelity simulation environment (such as BlueSky with realistic 6-DOF flight dynamics) before firm protocol recommendations can be made. This is identified as a priority item in Section 7.

Despite this limitation, the qualitative finding holds: layer transitions introduce a real class of conflict not present in purely horizontal coordination, and the protocol's conflict-detection logic must account for aircraft occupying intermediate altitudes. Future protocol versions will likely require dedicated transition corridors or scheduled climb/descent windows to manage this conflict class explicitly.

6. Discussion

6.1 Positioning Relative to Existing Proposals

LAPP occupies a specific niche in the eVTOL coordination landscape. It is not a replacement for NASA UTM or EASA U-space; rather, it is a protocol that could operate within those frameworks, providing the specific coordination logic that their architectures require but do not specify. LAPP's relationship to UTM is analogous to HTTP's relationship to TCP/IP: a higher-layer protocol that defines specific behaviors within a general infrastructure.

6.2 Equity and Access

Market-based airspace allocation raises legitimate equity concerns. If slot prices are unconstrained, well-funded operators could systematically outbid others, creating a stratified system in which premium operators fly efficient routes while budget operators absorb detour costs. LAPP addresses this through three mechanisms: (1) emergency and public-safety operations are exempt from market pricing and receive absolute priority; (2) auction revenues fund shared infrastructure, effectively redistributing market rents to system-wide benefits; (3) future protocol versions will explore congestion caps and subsidized access tiers to ensure baseline service quality for all operators.

6.3 Limitations

The current simulation makes several simplifying assumptions that limit the generalizability of quantitative findings. Traffic is uniformly distributed (real urban traffic has strong spatial and temporal patterns). The airspace sector is square and featureless (real sectors contain no-fly zones, terrain, buildings, and weather). Aircraft are homogeneous (real fleets include vehicles with different performance envelopes). Turn-point auctions clear independently rather than combinatorially (real routes may require multiple correlated slots). These limitations define the research agenda for subsequent protocol versions.

7. Open Questions and Future Work

The following questions are identified as priorities for future development:

- **Higher-fidelity simulation.** Quantitative claims about climb rate, energy feasibility, and detailed transition dynamics require migration from the present abstract simulator to an environment with realistic 6-DOF flight dynamics, validated aircraft performance envelopes, and calibrated energy models. The open-source BlueSky ATM simulator (TU Delft) is identified as a probable target platform for this work.
- **Combinatorial auction design.** Routes requiring multiple turn points create an exposure problem: winning slot A is valueless if slot B is lost. A combinatorial auction mechanism

allowing bundle bids would address this but introduces computational complexity (winner determination is NP-hard in general).

- **Vertiport integration.** Takeoff and landing infrastructure introduces ground-side capacity constraints not addressed by the current en-route protocol. Vertiport slot allocation and surface deconfliction require protocol extensions.
- **Weather and contingency.** The current protocol assumes nominal conditions. Wind, precipitation, and icing alter aircraft performance envelopes and may require dynamic reallocation of altitude layers or temporary closure of sectors.
- **Lost-communications procedures.** An aircraft unable to participate in the auction system (due to communications failure) must follow a deterministic fallback protocol. Defining safe lost-comms behavior is essential for regulatory acceptance.
- **Real-geography validation.** Testing the protocol against realistic urban airspace geometry (specific cities, actual building heights, existing airspace restrictions) is necessary to validate findings derived from abstract sector models.
- **Heterogeneous traffic modeling.** Introducing different operator types (commuter, cargo, emergency, recreational) with distinct flight profiles, bid distributions, and priority structures would test the market mechanism under realistic demand conditions.
- **Regulatory pathway.** Engaging with FAA and EASA innovation offices to identify the certification pathway for a market-based airspace protocol. This includes performance standards, safety cases, and interoperability requirements.

8. Toward Combinatorial Slot Allocation

8.1 The Exposure Problem in Sequential Auctions

The auction mechanism specified in Section 3.4 clears each turn-point slot independently. An aircraft requiring a multi-segment route through several turn points must therefore win each constituent auction separately. While this design preserves computational simplicity and supports real-time clearing, it introduces a structural risk known in auction theory as the *exposure problem*: a bidder may successfully win some components of the bundle it requires while losing others, leaving it with partial allocations of no operational value.

Consider an aircraft Alpha planning a route from origin O to destination D that requires passage through turn points A, B, and C in sequence. Under LAPP v0.1, Alpha submits three independent bids—one per turn point. Suppose Alpha wins A (paying $20) and C (paying $15), but is outbid for B by a competing aircraft Beta. Alpha’s planned route is now infeasible: a turn point in the middle of its trajectory is unavailable. Alpha must either replan around the lost slot (incurring detour cost and potentially additional auction exposure) or hold at origin (losing time and consuming energy reserves). The $35 Alpha paid to secure A and C is sunk regardless of outcome.

This exposure is not a marginal concern. As route complexity increases—particularly for cross-sector flights requiring four or more turn points—the probability of partial allocation failure compounds multiplicatively. Operators bidding rationally under exposure risk will systematically underbid relative to their true valuations, anticipating the possibility of partial wins. This produces two undesirable outcomes: allocative efficiency degrades because bids no longer reflect true willingness-to-pay, and overall protocol revenue is suppressed by strategic underbidding.

8.2 Combinatorial Auctions: Promise and Computational Cost

The classical solution to the exposure problem is the combinatorial auction, in which bidders submit valuations on bundles of items rather than individual items. Aircraft Alpha would submit a single bid expressing its valuation for the package {A, B, C}—say $80—with the explicit semantics “pay only if all three are awarded.” The auctioneer collects all bundle bids from all bidders and solves the *winner determination problem (WDP)*: identify the allocation of bundles to bidders that maximizes total revenue subject to the constraint that no item is awarded to more than one bidder.

Combinatorial auctions have well-established applications in resource allocation. The U.S. Federal Communications Commission has used combinatorial auctions for radio spectrum licenses since 2008, with clearing costs measured in tens of billions of dollars per auction round. Rassenti, Smith, and Bulfin’s 1982 paper proposed combinatorial auctions specifically for airport time-slot allocation, foundational work that is directly applicable to LAPP’s airspace coordination context.

The well-known difficulty is that the winner determination problem is *NP-hard in the general case*. With *N* bidders and *M* items, the number of possible allocations grows exponentially, and no polynomial-time algorithm is known to compute exact optimal solutions. Solving WDP for an FCC spectrum auction requires specialized integer-programming software running on high-capacity compute infrastructure, with clearing horizons measured in days rather than seconds. For LAPP—operating in real time across thousands of aircraft and hundreds of turn points per metropolitan sector—exact combinatorial clearing is not computationally tractable.

This computational cost is not a defect of the mechanism design; it is a fundamental property of the problem class. LAPP cannot adopt combinatorial auctions in their general form. The question is whether a *structurally restricted* variant can capture most of the allocative benefit while remaining tractable for real-time operations.

8.3 Trajectory-Bid Mechanism: A Tractable Restriction

LAPP v0.2 (under development) proposes a restricted combinatorial mechanism we term the *trajectory-bid auction*. The restriction is structural and motivated directly by the geometry of eVTOL flight planning: aircraft do not require arbitrary combinations of turn-point slots; they require specific *sequences* corresponding to their planned routes.

Under the trajectory-bid mechanism, each aircraft submits a single bid associated with its planned trajectory. The bid specifies the ordered sequence of turn-point slots required and the bidder’s valuation for the complete sequence, with all-or-nothing semantics. Aircraft do not submit bundle bids on arbitrary subsets of slots; they bid only on the contiguous sequence their route requires.

This restriction collapses the combinatorial complexity in two important ways. First, the number of distinct bundles a single bidder may submit is bounded by the small number of feasible routes between origin and destination—typically fewer than ten in LAPP's two-segment routing model. Second, bundles exhibit a useful structural property: they are sequences of geographically and temporally ordered slots, which permits incremental and decomposable processing.

The winner determination problem under trajectory-bid restrictions can be approximated using a *greedy sequential clearing algorithm*:

- Sort all trajectory bids in descending order of value-per-slot (total bid divided by trajectory length).
- Process bids in order. For each bid, attempt to reserve all required slots atomically.
- If all slots are available, award the bundle to the bidder, mark slots as reserved, and credit the bidder's account at the second-highest bid rate (preserving Vickrey incentive-compatibility within the trajectory).
- If any required slot is unavailable, the bid fails entirely; the bidder is notified and may resubmit on an alternative trajectory in the next clearing round.

This algorithm runs in $O(N \log N + N \cdot K)$ time, where N is the number of bidders and K is the maximum trajectory length. For metropolitan-scale airspace, both quantities are bounded by operational constraints, yielding tractable per-second clearing.

The greedy approach is provably suboptimal relative to exact WDP—its worst-case efficiency loss has been characterized by Lehmann, O'Callaghan, and Shoham (2002) as bounded by a logarithmic factor in the number of items. For LAPP's purposes, this bound is acceptable: the marginal allocative gain from exact clearing does not justify the computational and latency costs.

8.4 Commitment Windows for Cascade Control

A complementary mechanism for managing computational load and replanning instability is the *commitment window*: a brief enforced delay between an aircraft's loss of an auction and its eligibility to re-enter the market with an alternative trajectory bid. LAPP v0.2 specifies a default commitment window of 5–15 seconds, configurable per sector based on traffic conditions.

Commitment windows serve three operational functions. First, they reduce per-round clearing load by limiting the number of bidders simultaneously contesting available slots; aircraft in a commitment window are temporarily removed from the active bidder pool. Second, they dampen the replanning cascades identified in Section 5.2, where a high-value displacement triggers a chain of secondary displacements as displaced bidders immediately re-enter the market. The cooldown period creates a natural cooling mechanism that allows the local market to settle between contention events. Third, they incentivize better first-round route selection: because re-entry has a non-trivial time cost, operators have stronger reasons to plan and price their preferred trajectory carefully rather than treating the first attempt as a low-stakes probe.

Commitment windows are mechanism-design-clean in the sense that they preserve Vickrey incentive-compatibility within each clearing round. The cost of a lost auction is now two-dimensional (the lost route plus a brief market exclusion), but bidding strategy within any single round remains dominant-strategy truthful. Aircraft in safety-critical or energy-critical conditions can flag emergency status, which exempts them from commitment windows entirely—preserving the absolute-priority semantics of Section 3.5.

8.5 Incentive Compatibility Under Trajectory Bidding

A critical property of the original Vickrey single-slot auction is that truthful bidding is a dominant strategy: each bidder maximizes expected utility by bidding their true valuation, regardless of other bidders' behavior. Preserving this property under the trajectory-bid restriction requires careful pricing rule design.

The trajectory-bid mechanism described above approximates a Vickrey-Clarke-Groves (VCG) outcome at the trajectory level: the winning bidder pays the marginal harm imposed on other bidders by their inclusion. Computing exact VCG payments under the greedy algorithm would require solving the WDP with and without each winning bidder—reintroducing the computational cost we sought to avoid. In practice, LAPP v0.2 will use a simplified pricing rule in which the winning bidder pays the highest losing bid for any of the slots in their trajectory, which approximates VCG payments while preserving real-time tractability.

This pricing rule is not strictly incentive-compatible in the formal sense—bidders may have weak incentives to misrepresent valuations under specific contention patterns. We accept this approximation in exchange for tractability, with the expectation that empirical pricing efficiency will remain high under realistic traffic distributions. Quantifying the strategic deviation tolerance of trajectory-bid auctions is identified as a research priority for v0.2 simulation.

8.6 Integration with the Existing Protocol

The trajectory-bid mechanism is designed for backward compatibility with LAPP v0.1's single-slot auction. Aircraft requiring single-segment routes (a single layer with no turn point) participate in a degenerate trajectory bid of length one, equivalent to v0.1's standard Vickrey auction. Aircraft requiring multi-segment routes participate in proper trajectory bids. The clearing engine handles both cases through the same code path.

Emergency and public-safety reserves operate identically under v0.2: emergency-flagged trajectories displace any commercial bundle that conflicts, with displaced commercial bidders notified for replanning. Emergency aircraft are exempt from commitment windows. The cost of emergency reserves continues to be borne by commercial revenues.

The revenue-allocation framework described in Section 4 applies unchanged: 40% protocol operator, 30% infrastructure fund, 20% regulatory compliance, 10% access subsidy, computed against the trajectory clearing prices.

8.7 Open Questions

The trajectory-bid mechanism raises several research questions that remain open for v0.2 development and beyond:

- **Replanning cascades under commitment windows.** The commitment window is hypothesized to dampen cascades, but its effectiveness depends on the relationship between window duration, traffic density, and trajectory length. Empirical characterization is needed before final parameter values can be specified.
- **Strategic disclosure of routes.** Trajectory bids reveal an aircraft's planned route to the protocol operator. While the operator does not participate as a market actor, the disclosure may have privacy or competitive implications for commercial operators. Cryptographic mechanisms (e.g., commit-reveal schemes or homomorphic clearing) may be applicable.
- **Mixed bid types.** Some operators may prefer to bid on individual high-value slots rather than full trajectories. A practical clearing engine may need to support hybrid bid languages combining trajectory bids and single-slot bids, with corresponding rule extensions for winner determination.
- **Empirical efficiency.** The theoretical efficiency bounds of the greedy trajectory-bid algorithm are well-characterized in the abstract case. Empirical efficiency under realistic eVTOL traffic distributions—with spatial clustering, temporal peaks, and correlated origin-destination demand—requires simulation in a higher-fidelity environment than the present reference implementation.

These questions are identified as priorities for the LAPP v0.2 specification, anticipated in 2026–2027.

9. Conclusion

LAPP demonstrates that market-based coordination of low-altitude eVTOL traffic is both technically feasible and potentially superior to conventional first-come-first-served allocation on the metric that matters most: directing scarce airspace to the operators who value it most, while reserving absolute-priority access for emergency and public-safety operations.

The protocol's heading-based altitude stratification eliminates the most dangerous conflict geometries (head-on and high-angle crossings) with zero computational cost—it is a convention, not an algorithm. The auction layer adds allocative intelligence where conventions alone are insufficient: at turn points, where independently planned routes converge. Together, these mechanisms produce a coordination system that scales with traffic density, generates revenue to fund its own infrastructure, and remains open to adoption by any eVTOL manufacturer.

An interactive reference simulator implementing the full LAPP protocol is available at lorenzaero.com. The authors invite collaboration from aerospace engineers, ATM researchers, aviation regulators, and eVTOL operators interested in contributing to the development of an open airspace coordination standard.

10. References

[1] Castelli, L., Pesenti, R., & Ranieri, A. (2011). The design of a market mechanism to allocate air traffic flow management slots. *Transportation Research Part C*, 19(5), 931–943.

[2] Cramton, P., Shoham, Y., & Steinberg, R. (Eds.). (2006). *Combinatorial Auctions*. MIT Press.

[3] EASA. (2023). *U-space Concept of Operations* (Ed. 3.10). European Union Aviation Safety Agency.

[4] FAA. (2023). *Urban Air Mobility Concept of Operations v2.0*. Federal Aviation Administration.

[5] Kopardekar, P., et al. (2016). Unmanned Aircraft System Traffic Management (UTM) Concept of Operations. *AIAA Aviation Forum*, AIAA 2016-3292.

[6] Lehmann, D., O’Callaghan, L., & Shoham, Y. (2002). Truth revelation in approximately efficient combinatorial auctions. *Journal of the ACM*, 49(5), 577–602.

[7] Mullainathan, S., & Shafir, E. (2013). *Scarcity: Why Having Too Little Means So Much*. Times Books.

[8] Rassenti, S. J., Smith, V. L., & Bulfin, R. L. (1982). A combinatorial auction mechanism for airport time slot allocation. *Bell Journal of Economics*, 13(2), 402–417.

[9] Vossen, T. W. M., & Ball, M. O. (2006). Slot trading opportunities in collaborative ground delay programs. *Transportation Science*, 40(1), 29–43.