

# **Pricing Access to U-space: A Cost-Recovery Framework for Drone Traffic Management Services**

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**Šárka Václavíková,  
Jakub Kraus, Adam  
Kleczatský, Peter  
Vittek**

**Czech Technical University in Prague,  
Faculty of Transportation Sciences,  
Department of Air Transport, Prague,  
Czech Republic**

The integration of unmanned aircraft systems into European airspace under the U-space regulatory framework raises unresolved questions about how shared infrastructure should be financed and how service charges should be designed. This paper proposes a structured, rule-based cost-recovery pricing methodology for U-space services, grounded in the EU regulatory framework and in economic theory on infrastructure pricing. The framework decomposes total charges into three layers: infrastructure costs, operational costs, and an operator-complexity weighting factor (Operator and Complexity Indicator, OACI). To test the framework, a synthetic traffic generator covering approximately 1,470,000 flights across five operator classes and four mission categories is used to evaluate a range of market-maturity scenarios. The results demonstrate robust cost recovery, a proportional distribution of fees across operator classes, and moderate sensitivity to calibration of the rate coefficient. The qualitative ordering of fee burdens remains stable across 125 rate-coefficient combinations.

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The methodology is presented as a structural template for regulators, Common Information Service Providers, and U-space Service Providers, intended to be populated with empirical cost and traffic data as European U-space deployment matures.

Keywords: U-space; drone pricing; UTM; infrastructure financing; cost recovery; airspace economics; unmanned traffic management.

The rapid development of unmanned aircraft systems (UAS) has created a need for new concepts to enable the safe and scalable integration of drones into the airspace. In Europe, this integration framework is commonly referred to as U-space, which comprises services designed to support large-scale drone operations, particularly in very low-level airspace (Barrado et al., 2020; EASA, 2024). U-space can be understood as the European implementation of the broader Unmanned Traffic Management (UTM) paradigm, which aims to provide digital, highly automated services that enable the safe coexistence of drone operations and manned aviation (Lieb and Volkert, 2020).

The concept of U-space has been developed primarily through the SESAR Joint Undertaking, which has played a central role in defining the architecture, operational procedures, and technological enablers required to integrate unmanned aviation into the broader air traffic management (ATM) ecosystem (SESAR JU, 2017). Beyond its general definition, U-space is best understood not merely as a regulatory label but as a service-oriented concept of operations built around structured airspace volumes, digitally delivered services, and progressive levels of operational support (Barrado et al., 2020). From this perspective, the object to be governed and, eventually, priced is not "airspace" in the abstract, but access to a managed, service-mediated operational environment. This interpretation is reinforced by research on U-space system architecture, which shows that real-time conflict resolution, threat management, and in-flight service provision require a modular yet technically substantial software and data backbone rather than a purely administrative layer (Capitán et al., 2021).

While the regulatory and operational aspects of U-space have been relatively well explored, its economic dimension remains considerably less developed (Decker and Chiambaretto, 2022). Questions concerning the financing of U-space infrastructure, the allocation of costs between system actors, and the design of charging mechanisms for drone operators remain largely unresolved.

At the same time, the emerging academic literature has begun to frame UTM and U-space explicitly as economic problems. Recent work has examined the institutional trade-offs of UTM governance in Europe and the United States, the case for variable user charging, the role of market design in allocating scarce access, and the incorporation of payment rules into airspace resource-allocation mechanisms (Decker and Chiambaretto, 2022; Merkert et al., 2021; Seuken et al., 2022; Li et al., 2022; Carramiana et al., 2025). Taken together, these studies suggest that U-space should not be analysed solely as a technical architecture, but as a regulated access system in which pricing, allocation, fairness, and cost recovery are structurally intertwined.

The regulatory framework established by Commission Implementing Regulation (EU) 2021/664 comprises a multi-actor ecosystem comprising the Common Information Service provider (CISP), U-space Service Providers (USSPs), and UAS operators (European Commission, 2021). However, the regulation does not prescribe a specific economic model for financing services or allocating costs among stakeholders. This absence constitutes a significant challenge for policymakers, infrastructure providers, and potential commercial actors. In particular, the coexistence of regulated infrastructure services, such as the CISP, with competitive commercial service providers (USSPs) creates a complex economic environment that differs substantially from traditional ATM structures (Decker and Chiambaretto, 2022).

The lack of empirical data further complicates the situation. Large-scale drone operations in controlled U-space environments have not yet materialised, which makes it difficult to estimate future traffic volumes or revenue streams (EUROCONTROL, 2022; U-ELCOM, 2025). Policymakers and researchers must therefore rely on scenario-based analysis, economic modelling, and conceptual frameworks to explore possible financing approaches for the emerging U-space ecosystem.

Addressing this challenge requires drawing on insights from multiple research domains. The economic literature on air traffic management financing provides important lessons regarding cost recovery, regulatory oversight, and infrastructure pricing (European Commission, 2019; EUROCONTROL, 2021). Research on digital network infrastructures and platform-based service ecosystems also offers useful perspectives for understanding the economic characteristics of distributed service architectures similar to those envisioned for U-space (Rochet and Tirole, 2003). In parallel, several research and innovation initiatives conducted under the SESAR Joint Undertaking have also explored the operational and technological foundations of U-space services. Projects such as CORUS, DACUS, and U-ELCOME have contributed significantly to the development of operational concepts, service architectures, and early deployment activities (CORUS, 2019; DACUS, 2022; U-ELCOME, 2025).

This paper addresses the lack of a clear financing framework for U-space services by proposing a structured cost-recovery methodology that accounts for the layered nature of service provision, infrastructure cost structures, and varying traffic development scenarios. Section 2 reviews relevant concepts from ATM financing and infrastructure economics and then examines the main findings of key SESAR research projects. Section 3 presents the methodology, including normative principles, the pricing architecture, the validation framework, and the synthetic traffic generator. Section 4 reports the results of applying the framework to the synthetic traffic corpus. Section 5 discusses implications, Section 6 discusses limitations, and Section 7 outlines directions for future work.

## Background

### Financing Air Traffic Management and Infrastructure Economics

The financing of ATM services has historically relied on cost-recovery principles combined with elements of economic regulation. In Europe, this framework has evolved within the context of the Single European Sky (SES) initiative and the EUROCONTROL route charges system, which aims to ensure that air navigation service providers (ANSPs) recover the costs of providing services while maintaining economic efficiency and fairness among airspace users (European Commission, 2019; EUROCONTROL, 2021).

Traditional ATM charging mechanisms are generally built on three key principles: cost recovery, transparency, and non-discrimination (European Commission, 2019). Airspace users, primarily airlines, pay charges based on factors such as aircraft weight and distance flown within controlled airspace, which serve as proxies for ATM infrastructure use and the complexity of service provision (EUROCONTROL, 2021). One of the defining characteristics of ATM financing is its high fixed-cost base. Air navigation infrastructure requires substantial investment and maintenance expenditure that is largely independent of the number of flights handled. Consequently, ATM services exhibit strong characteristics of natural monopolies, in which economies of scale make it inefficient to duplicate infrastructure (Baumol 1977).

Economic theory has developed several approaches to address pricing and cost allocation in such environments. Ramsey pricing aims to minimise welfare losses while ensuring that total revenue covers infrastructure costs. Under Ramsey pricing principles, prices are adjusted based on the elasticity of demand across user groups: users with less price-sensitive demand contribute a larger share of cost recovery, while users with more elastic demand are charged less to avoid discouraging usage (Ramsey, 1927; Boiteux, 1971).

Although theoretically efficient, its practical implementation requires detailed knowledge of demand elasticities, which may be difficult to estimate in emerging markets such as drone services. Nevertheless, the concept highlights an important principle: uniform cost allocation may not always produce economically efficient outcomes.

Two-part tariff pricing provides another relevant approach, commonly used in infrastructure networks and digital services (Baumol and Bradford 1970). Users pay a fixed access fee that helps cover infrastructure costs, along with a variable usage-based charge. Research on drone-specific pricing suggests that variable user charges may be more acceptable and potentially more efficient than flat registration-type levies, and that differentiated charging structures are better aligned with the heterogeneity of U-space use cases (Merkert et al., 2021).

The concept of long-run marginal cost pricing holds that efficient pricing occurs when users pay the marginal cost associated with their use of infrastructure. However, when fixed costs are high, as in ATM, marginal cost pricing alone cannot ensure cost recovery. This gives rise to the well-known marginal cost pricing dilemma, in which efficient usage pricing must be supplemented by mechanisms to recover fixed costs (Baumol and Bradford, 1970).

Congestion pricing provides a further dimension relevant to high-density drone operations. The fundamental principle is that users should face prices reflecting the external costs they impose on others, particularly when their activities contribute to congestion or reduced system performance (Pigou 1920; Vickrey 1969). Research on drone delivery density and parcel-delivery resource allocation suggests that once traffic grows, the key economic challenge is no longer merely whether digital infrastructure exists, but how scarce spatial and temporal capacity is to be allocated among interacting users (Doole et al., 2020; Li et al., 2022).

Market-design scholarship argues that drone traffic management should be understood as a mechanism-design problem requiring efficient, fair, simple, non-manipulable, and scalable allocation rules (Seuken et al., 2022; Carramiana et al., 2025; Hlavata et al., 2024).

Many modern infrastructure systems face economic challenges similar to those anticipated for U-space services: high fixed costs, relatively low marginal costs, and complex interactions among multiple categories of users (Baumol and Bradford, 1970). UTM in Europe is increasingly described as a distributed but highly coordinated ecosystem involving infrastructure-like functions, shared information layers, and competitive downstream service provision, rather than a simple extension of conventional ATM (Decker and Chiambaretto, 2022; Capitán et al., 2021).

#### SESAR Research Projects: CORUS, DACUS, and U-ELCOME

The conceptualisation and development of U-space in Europe has been largely driven by research and innovation activities conducted under the SESAR Joint Undertaking. Projects CORUS, DACUS, and U-ELCOME mark important stages in the transition from conceptual frameworks to future operational deployment (CORUS, 2019; DACUS, 2022; U-ELCOME, 2025).

The CORUS (Concept of Operations for European UTM Systems) project represents one of the earliest comprehensive efforts to define a European operational concept for unmanned traffic management. Conducted within the SESAR research programme, CORUS established a structured framework for the progressive integration of drone operations through a layered service architecture. This conceptual foundation was later articulated in the academic literature as a service-based concept of operations for opening low-altitude airspace to emerging operations (Barrado et al., 2020).

U-space, in that formulation, is not simply a legal framework but a structured operational environment composed of differentiated airspace volumes and service layers. This point is economically significant because it suggests that future charging models may need to distinguish not only among operators but also among airspace types, service intensity, and operational complexity.

From an economic perspective, the CORUS framework implicitly recognises that the cost structure of U-space services will evolve as the system matures. Early stages of deployment require relatively limited infrastructure, while higher levels of automation and traffic management introduce more sophisticated technological requirements. The project also emphasised a service-oriented architecture where different actors provide specialised services within an interconnected ecosystem. Drone operators interact primarily with USSPs, which in turn rely on shared information infrastructure provided by the CISP. Such architecture naturally points towards multi-level pricing structures, where cost allocation across layers plays a critical role in shaping market development and competition (Rochet and Tirole, 2003; Decker and Chiambaretto, 2022).

The DACUS (Demonstration of Airspace Integration of Unmanned Aircraft Systems in Controlled Airspace) project extended earlier conceptual work by focusing on the integration of drone operations within controlled airspace environments. The project highlighted the importance of operational scalability: as drone traffic increases, the demand for coordination services, conflict detection, and traffic information is expected to grow significantly. This suggests that the marginal cost of handling additional operations may remain relatively low once digital infrastructure is established, reinforcing the economic characteristics of high fixed costs and low marginal costs typical of digital platforms.

If infrastructure costs must be recovered through service charges, low traffic volumes during early deployment phases may result in high per-operation costs. Conversely, as traffic increases, average costs may decline significantly due to economies of scale (Baumol, 1977). This dynamic cost pattern is consistent with economic models of network industries, where initial investment barriers are often substantial but long-term operational costs remain relatively low.

The U-ELCOME (U-space European Common Deployment) project represents a significant step towards real-world implementation of U-space services across multiple European countries, shifting the discussion from abstract architecture to real implementation burdens (U-ELCOME, 2025). From a financing perspective, this deployment orientation is especially relevant: early U-space deployment in Europe has made visible the compliance, certification, coordination, and governance requirements associated with service provision, which are indispensable for any realistic pricing model. This practical dimension is reinforced by the first USSP certification in Europe, which demonstrates that U-space service provision already entails non-trivial institutional and technical readiness requirements (EASA 2025; EASA 2022). Economic studies of such ecosystems emphasise the importance of transparent and predictable pricing for core infrastructure services, as uncertainty in infrastructure costs can discourage private investment in downstream services (Decker and Chiambaretto, 2022; Rochet and Tirole, 2003).

## Research Gap

The reviewed SESAR projects collectively provide a comprehensive view of the technological and operational foundations of the European U-space ecosystem. Despite these significant contributions, the economic dimension of U-space service provision remains relatively underexplored. While the projects acknowledge the roles of different actors and the structure of service provision, they rarely address the specific mechanisms through which infrastructure and operational services should be financed.

At the same time, the broader literature on infrastructure pricing, network industries, and platform economics provides a range of theoretical frameworks that may inform the design of sustainable financing models. Concepts such as two-part tariffs, Ramsey pricing, and congestion pricing offer potential approaches to balancing cost recovery with market development. These economic principles have already been addressed, albeit in fragmented form, by emerging U-space and UTM literature. Institutional-economic work has examined the policy trade-offs of organising UTM markets and allocating roles between infrastructure-like and competitive activities (Decker and Chiambaretto, 2022). Pricing-oriented research suggests that variable user charging may be more acceptable and efficient than flat registration-type levies (Merkert et al. 2021). Market- and mechanism-design studies have argued that access to low-altitude airspace should not be governed by simple first-come, first-served rules but by allocation mechanisms that incorporate fairness, strategic behaviour, and congestion effects (Seuken et al., 2022; Li et al., 2022; Carramiana et al., 2025). Demand and airspace-structure studies have demonstrated that future U-space use is likely to be highly uneven across space and time, making differentiated charging and scarcity-sensitive allocation more plausible than uniform cost spreading (Doole et al., 2020; Morfin Veytia et al., 2023; Hlavata et al., 2024).

These approaches need to be systematically applied to the specific architecture of U-space services, particularly concerning the relationships between CIS providers, USSPs, and drone operators under different traffic conditions. The literature points toward a layered economic problem: first, how to identify the infrastructure-like cost base of U-space; second, how to allocate operational and congestion-related costs across heterogeneous use cases; and third, how to preserve fairness and market development while introducing access charges into an emerging ecosystem. This gap highlights the need for research that integrates operational insights from SESAR projects with economic theory on infrastructure pricing and digital platform ecosystems.

## Methodology

The methodology develops a rule-based financing framework that allocates the costs of a regulated service regime across heterogeneous users and operations. It does not seek to estimate a market-clearing price of airspace. Instead, it combines three analytical elements: a common cost base for infrastructure-like functions, a usage-sensitive allocation rule for operational costs, and a normative adjustment layer reflecting operator type and mission complexity. This is consistent with the literature that frames UTM as a problem of economic governance, institutional design, and access allocation rather than of purely technical coordination (Decker and Chiambaretto, 2022; Seuken et al., 2022).

The overarching methodological principle is that pricing must reflect the layered nature of U-space service provision. As established by Commission Implementing Regulation (EU) 2021/664, drone operations within designated U-space airspace are, at a minimum, subject to four mandatory services: network identification, geo-awareness, UAS flight authorisation, and traffic information (European Commission 2021). This regulatory baseline defines the minimum scope of cost recovery and directly shapes the structure of the proposed pricing architecture.

The methodology is structured around four interconnected components: (i) a normative and institutional foundation derived from the EU regulatory framework; (ii) a decomposition of the cost base; (iii) a pricing and allocation architecture; and (iv) a validation framework based on synthetic traffic generation. The framework is designed to be legally grounded, auditable, and adaptable to different airspace configurations and maturity levels of U-space deployment.

## Normative Principles

The methodology adopts four normative axioms that reflect both EU regulatory requirements and the operational principles established in the U-space concept-of-operations literature (Barrado et al., 2020).

The first principle is safety-first and performance-constrained pricing. Pricing must not incentivise operators to circumvent safety requirements. Instead, it must remain compatible with the operational and performance constraints derived from the Airspace Risk Assessment (ARA) conducted for each designated U-space zone. Safety is treated as a hard constraint on the pricing mechanism rather than a variable to be traded against short-run economic efficiency. This is consistent with both the U-space ConOps and the market-design literature, which treat minimum safety requirements as non-negotiable system constraints (Barrado et al., 2020; Seuken et al., 2022).

The second principle is regulated infrastructure with competitive downstream service provision. Where technically feasible, USSPs should compete on service packages, customer interfaces, and service-level conditions. By contrast, infrastructure-like layers, such as the Common Information Service, shared data publication, and common access rules, must be governed under non-discriminatory conditions. This reflects the broader economic question of how utility-like and competitive functions should be separated within UTM governance (Decker and Chiambaretto, 2022).

The third principle is equitable access with public-interest priority. Access to U-space must be available under reasonable conditions to a broad set of operators while allowing explicit prioritisation of emergency or public-interest missions where required. This is aligned with the UTM market-design literature, which explicitly recognises the need to balance efficiency, fairness, and mission priority under congestion and strategic behaviour (Seuken et al. 2022).

The fourth principle is proportionality of cost and complexity. Payments should be linked, as far as possible, to the complexity of the operation and the intensity of U-space service use. Operators and missions that place greater informational and coordination burdens on the system should not be charged at the same rate as those that impose lower service burdens. This principle is consistent with resource-allocation work in low-altitude urban airspace (Li et al. 2022).

### Pricing Architecture

The methodology distinguishes among three analytically distinct objects: the cost base (the annual costs that must be recovered), the allocation rule (how those costs are distributed across users and operations), and the policy weighting layer (how fairness and mission complexity modify that allocation). The annual charge assigned to flight  $i$  is defined as:

$$P_i = IC_i + OC_i$$

where  $IC_i$  is the flight-specific share of annual infrastructure costs, and  $OC_i$  is the flight-specific share of annual operational costs. The baseline charge is then adjusted through an Operator and Complexity Indicator (OACI):

$$P_{iadj} = P_i * OACI_i, \text{ where } OACI_i = OT_i * MT_i$$

$OT_i$  denotes the operator-type coefficient and  $MT_i$  the mission-type coefficient. This interpretation is methodologically important: Infrastructure Costs and Operational Costs are cost-recovery categories, whereas the OACI is not a separate fee category but a normative weighting factor that reflects policy choices concerning fairness, expected benefit from U-space, and mission complexity.

Two additional categories of charges are recognised but kept outside the scope of the present framework. The first is a scarcity or congestion charge, whose purpose is to influence demand and allocate scarce access during periods of heavy traffic.

This can be viewed as a fee that shapes demand rather than covers operational costs and therefore lies outside the baseline cost-recovery framework. The second is a premium charge for optional value-added services, which would typically arise in the contractual relationship between a USSP and a drone operator. Neither is included in the present baseline methodology, whose primary objective is transparent recovery of the costs of mandatory U-space functions.

### Operator and Complexity Indicators (OACI)

The Operator and Complexity Indicator is introduced to reflect two normative considerations not fully captured by raw flight metrics alone: the expected dependence of the operation on U-space services, and the fairness of distributing costs across heterogeneous users.

Mission complexity reflects the degree to which the operation relies on U-space. Simple VLOS operations can easily be flown without U-space, where U-space could actually become a burden. More advanced VLOS operations can already benefit from U-space, for example, through longer flights or flights around major obstacles, where awareness of other traffic is a safety asset. BVLOS flights are typical users of U-space services, which can further be divided into flights in simple environments (where high traffic volume is not expected) and flights in high-density environments, such as urban areas and delivery services.

Operator type is also fundamental, as it contributes to a fair distribution of payments based on expected benefits from U-space utilisation. A hobby operator does not require U-space for their activities. A professional operator owning a single drone and performing aerial work may utilise U-space, but only for a portion of their flight operations. A medium-sized operator with multiple drones will focus primarily on aerial work, but its scale suggests more flights and more advanced operations.

A specialised large company engaged in drone delivery can be considered the most intensive U-space user, as this business model becomes viable only at a certain volume and operating within U-space is an essential prerequisite. State authorities have a full spectrum of operations where U-space is utilised to varying degrees.

The OACI is defined as  $OACI_i = OT_i * MT_i$ . These coefficients are treated as normative expert parameters, not as empirically estimated behavioural constants. Their calibration must therefore be justified through regulatory consultation or expert elicitation, rather than presented as objective physical measurements.

### Infrastructure Costs (IC)

Infrastructure Costs represent the annualised cost of the utility-like layers of U-space. These include CISP data publication infrastructure (as required by Article 5 of Regulation 2021/664), shared information and interoperability infrastructure, regulatory oversight and certification-related system costs, and shared receiving or exchange infrastructure required for situational-awareness and traffic-information functions.

These costs are treated as predominantly fixed and only weakly sensitive to short-run traffic volume. In this respect, they resemble infrastructure sectors with high fixed costs and low marginal costs, which is consistent with both classic infrastructure economics and the economic framing of UTM governance (Baumol, 1977; Decker and Chiambaretto, 2022). The annual infrastructure cost base is  $IC_{tot} = C_{infra} + U_{infra}$ , where  $C_{infra}$  is the annualised infrastructure cost of the CISP and regulatory utility layer, and  $U_{infra}$  is the annualised shared infrastructure cost borne by the USSP layer. The flight-dependent infrastructure charge is then allocated as:

$$IC_i = \left( \frac{OACI_i}{\sum_j OACI_j} \right) * IC_{tot}$$

Infrastructure costs are thus distributed across the user base according to the relative policy weight of operator and mission type. The rationale is that infrastructure access is a system-wide enabling function, but one whose burden may reasonably be differentiated by the type of actor and operational complexity.

### Operational Costs (OC)

Operational Costs represent the annual cost of operating and maintaining the U-space service environment. These include CISP operating expenditure, USSP operating expenditure, maintenance of operational interfaces and data exchange, and recurrent costs associated with service execution and system availability. A key methodological distinction is made here between the nature of the cost and the allocation rule: some of these costs may be fixed or quasi-fixed in accounting terms, but they are allocated across flights using usage-sensitive variables. This reflects the fact that even where costs are not strictly marginal, a transparent allocation key may still be based on measured service use.

Each flight is described by three usage variables: flight duration  $T_i$  [min], flight path length  $D_i$  [km], and allocated occupancy volume  $AOV_i$  [ $m^3 \cdot min$ ]. The unweighted usage score of flight  $i$  is:

$$s_i = c_t * T_i + c_d * D_i + c_v * AOV_i$$

where  $c_t$ ,  $c_d$ , and  $c_v$  are the time, distance, and airspace-volume coefficients. The allocated operational volume is computed using a simplified containment model: the lateral buffer is  $w_i = 3V_i$  [m] (speed-proportional), and a fixed vertical buffer of 25m ( $h=50m$ ) is applied symmetrically above and below the nominal flight height, yielding  $AOV_i = D_i * w_i * h * T_i$ . The operational charge, adjusted for OACI weighting, is allocated as:

$$OC_{iadj} = \left( \frac{OACI_i * s_i}{\sum_j OACI_j * s_j} \right) * OC_{tot}$$

This formulation ensures that operational costs are distributed in proportion to measured resource usage, while still allowing normative differentiation across operator and mission classes. The three usage variables allow the formula to distinguish slow short flights from fast long ones, short long ones from fast short ones, and time-precise from imprecise.

## Validation Framework

The pricing architecture is validated across three complementary dimensions: cost recovery, distributional robustness, and parameter sensitivity. Cost recovery validation verifies whether total annual revenues equal the annual cost base by construction. The primary indicator is the cost recovery ratio  $CR = \frac{\text{total revenue}}{\text{total costs}}$ . A value of CR=1 indicates exact revenue neutrality. Cost allocation is demonstrated to be distributed across the user base in proportion to weighted airspace resource consumption rather than concentrated on a single category.

Distributional robustness examines how the burden of fees is distributed across operator and mission categories. The objective is not only to confirm revenue neutrality, but also to assess whether the resulting structure produces plausible outcomes across different classes of users. Key outputs include mean fee by operator class, mean fee by mission class, share of total payments by category, and distribution of fees within each category.

Parameter sensitivity is examined through two analyses. The first varies the three operational allocation coefficients ( $c_t$ ,  $c_d$ ,  $c_v$ ) across a  $5^3$ -factorial grid at full-scale traffic, evaluating how the shape of the fee distribution responds to shifts in the relative weight of the time, distance, and airspace volume billing dimensions.

The second varies the global traffic scaling factor  $\kappa$  across five levels  $\{0.2, 0.4, 0.6, 0.8, 1.0\}$ , corresponding to 20% to 100% of projected full-scale baseline traffic volume, quantifying how fee levels and distributional properties change as total flights range across market maturity scenarios. Together, these analyses characterise the pricing mechanism's sensitivity to its two principal sources of uncertainty: the calibration of rate parameters (within the discretion of the regulator or USSP) and the realised traffic volume (determined by market adoption). This stronger validation structure is consistent with the literature, indicating that UTM design must be evaluated not only for technical feasibility, but also for fairness, scalability, and differentiated operator impacts (Seuken et al., 2022).

#### Data Requirements, Inputs, and Known Gaps

The methodology explicitly distinguishes between parameters that are defined by the regulatory framework and those that must be empirically determined. Regulatory parameters are treated as fixed inputs; cost parameters are treated as variables to be estimated from operational data.

Three data pillars are required for full operationalisation. First, cost data (CAPEX/OPEX of the CISP and USSPs) must be obtained from accounting records, procurement data, and operational logs. The EASA certification of the first USSP demonstrates that compliance costs are substantial and multi-dimensional, encompassing safety, cybersecurity, operational readiness, and business continuity (EASA, 2025). Second, the coefficients for operator and mission types must be established through expert discussion at the state level to ensure transparency and uphold the principle of fairness. Third, realistic foreseeable traffic data needs to be set as a meaningful target to understand future pricing.

The methodology acknowledges that official European sources do not provide a unified cost catalogue for U-space services, a gap widely noted in the policy literature (Decker and Chiambareto, 2022). Consequently, the pricing formulas presented in this paper are structural rather than numerical: they define the computation logic and identify the parameters that implementers must populate from empirical data. All one-off capital expenditures must be transformed into annual equivalents before entering the revenue-neutrality logic, using a regulator-defined depreciation period and discount rate.

For the purpose of illustrating the framework, demonstrative input data are used as shown in Tables 1 and 2. These should be understood explicitly as illustrative calibration inputs, not as final market estimates. Input data is complemented by randomly generated flight trajectories distributed by these parameters, with average flight speed ranging from 10 m/s to 50 m/s (normal distribution dependent on mission type) and flight distance ranging from 0.1 km to 200 km (truncated normal distribution dependent on operator and mission type).

Table 1. OACI coefficients and illustrative traffic volume inputs

| Operator type             | OT  | Mission type      | MT  |
|---------------------------|-----|-------------------|-----|
| Hobby                     | 0.1 | VLOS simple       | 0.1 |
| Small business (ad hoc)   | 0.5 | VLOS long-term    | 0.5 |
| Medium business           | 1.0 | BVLOS non-complex | 1.0 |
| Large business (delivery) | 1.2 | BVLOS complex     | 1.5 |
| State                     | 1.0 | -                 | -   |

Table 2. Illustrative traffic volume inputs by operator type

| Operator type             | Operators | Drones/operator | Flights/operator/yr | Total flights/yr |
|---------------------------|-----------|-----------------|---------------------|------------------|
| Hobby                     | 10,000    | 1               | 25                  | 250,000          |
| Small business            | 300       | 1               | 300                 | 90,000           |
| Medium business           | 50        | 6               | 2,000               | 100,000          |
| Large business (delivery) | 5         | 100             | 200,000             | 1,000,000        |
| State                     | 2         | 100             | 15,000              | 30,000           |
| Total                     | -         | -               | -                   | 1,470,000        |

## Synthetic Traffic Generator

Because mature empirical U-space traffic data are not yet available, the validation uses a synthetic traffic corpus. The simulation space is structured as a two-dimensional grid of operator type ( $OT_1$ – $OT_5$ ) and mission type ( $MT_1$ – $MT_4$ ). The number of flights assigned to each operator-mission cell is determined by the product of the baseline annual flight volume  $N_{0(OT)}$ , the mission allocation coefficient  $\alpha_{(OT, MT)}$ , and the global scaling factor  $\kappa$ :  $N_{(OT, MT, \kappa)} = N_{0(OT)} * \alpha_{(OT, MT)} * \kappa$ . This formulation allows the total traffic volume to be modulated continuously, enabling sensitivity analysis across market maturity scenarios ranging from early adoption ( $\kappa = 0.2$ ) to full-scale deployment ( $\kappa = 1.0$ ). The use of synthetic traffic is justified by the current lack of mature empirical data while still allowing systematic examination of fee distributions under varied density conditions (Doole et al., 2020).

For each flight, two primary physical parameters are sampled stochastically. Flight path length  $D_i$  [km] is drawn from a truncated normal distribution bounded to mission- and operator-specific intervals; minimum path lengths range from 0.1 km for short-range micro-drone operations to 2.0 km for medium-range missions, while maximum values reach up to 200 km for complex long-range operations by enterprise operators. Cruising airspeed  $V_i$  [m/s] is sampled from a normal distribution with analogously derived moments and enforced through rejection sampling, ensuring that the resulting distribution strictly respects the physical envelope of the drone class. Mission-dependent speed bounds range from 1–10 m/s for micro-drone operations to 20–50 m/s for medium- and long-range missions. The choice of standard deviation equal to range/4 ensures that approximately 95% of untruncated draws fall within the defined bounds, so truncation and rejection effects remain modest across all categories.

From the sampled values, three derived attributes are computed for each flight record: flight duration  $T_i = \frac{D_i}{V_i}$ ; lateral buffer width  $w_i = 3V_i$  (speed-proportional containment zone); and  $AOV_i = D_i * w_i * 50 * T_i$  [ $m^3 \cdot min$ ]. Each synthetic flight record, therefore, contains the tuple  $\{OT_i, MT_i, D_i, V_i, T_i, AOV_i\}$ , providing a self-consistent and fully auditable description of the operation sufficient for fee computation under the pricing architecture. The simulation is implemented in MATLAB.

## Results

This section presents the results of applying the pricing architecture to the synthetic traffic corpus. The analysis proceeds in four stages: benchmark rate estimation, the baseline fee schedule, sensitivity analysis over rate coefficients, and sensitivity analysis over traffic volume. Graphical summaries accompany each analytical stage.

### Benchmark Rate Estimation

Before fees can be computed, the three rate coefficients governing the relative weight of time, distance, and airspace volume in the operational cost formula must be calibrated. The principle adopted is inverse-mean normalisation: each coefficient is set to the reciprocal of the fleet-wide mean of its billing dimension, ensuring that no single axis numerically dominates the fee distribution by virtue of its physical scale alone.

The three benchmark rates are then defined as:

$$r_t = \frac{1}{\text{mean}(T)}, r_d = \frac{1}{\text{mean}(D)}, r_v = \frac{1}{\text{mean}(AOV)}$$

Applied to the full baseline traffic corpus ( $\kappa = 1.0$ , 1,470,000 flights), this procedure yields the benchmark values  $r_t = 0.788 \text{min}^{-1}$ ,  $r_d = 0.030 \text{km}^{-1}$ ,  $r_v = 6.43 * 10^{-7} \text{m}^{-3} * \text{min}$ . These values confirm that the three billing dimensions span several orders of magnitude in absolute terms, underscoring the necessity of explicit rate calibration: without normalisation, the AOV term would numerically dominate the usage score across the entire fleet and effectively collapse the fee structure to a single-axis charge.

## Baseline Fee Schedule

Using the benchmark rates, the raw fee for each flight is computed as the proportional share of total annual costs (CAPEX + OPEX = EUR 2,743,200) allocated in proportion to the flight's weighted usage score, where the weight combines the operator type coefficient OT and the mission type coefficient MT. Two post-processing steps are applied to make the resulting schedule operationally practicable. First, all fees are rounded to the nearest multiple of EUR 0.05, eliminating sub-cent precision that would be operationally meaningless. Second, a minimum fee floor of EUR 0.10 is enforced for every flight, reflecting the principle that even the simplest operation consumes some regulatory and system resources and should contribute a non-trivial amount to cost recovery. If the combined effect of rounding and floor application causes total revenue to deviate from total cost by more than half a rounding step, a pro-rata correction is distributed among all flights whose fee exceeds the minimum, ensuring exact cost recovery while preserving the relative fee ordering.

The resulting baseline fee distribution is right-skewed, with the majority of flights clustered near the minimum fee, while a smaller number of complex long-range operations (MT3 and MT4 missions by OT4 enterprise operators) attract substantially higher fees commensurate with their disproportionate use of airspace resources and the higher OACI multipliers applied to them (see Figure 1).

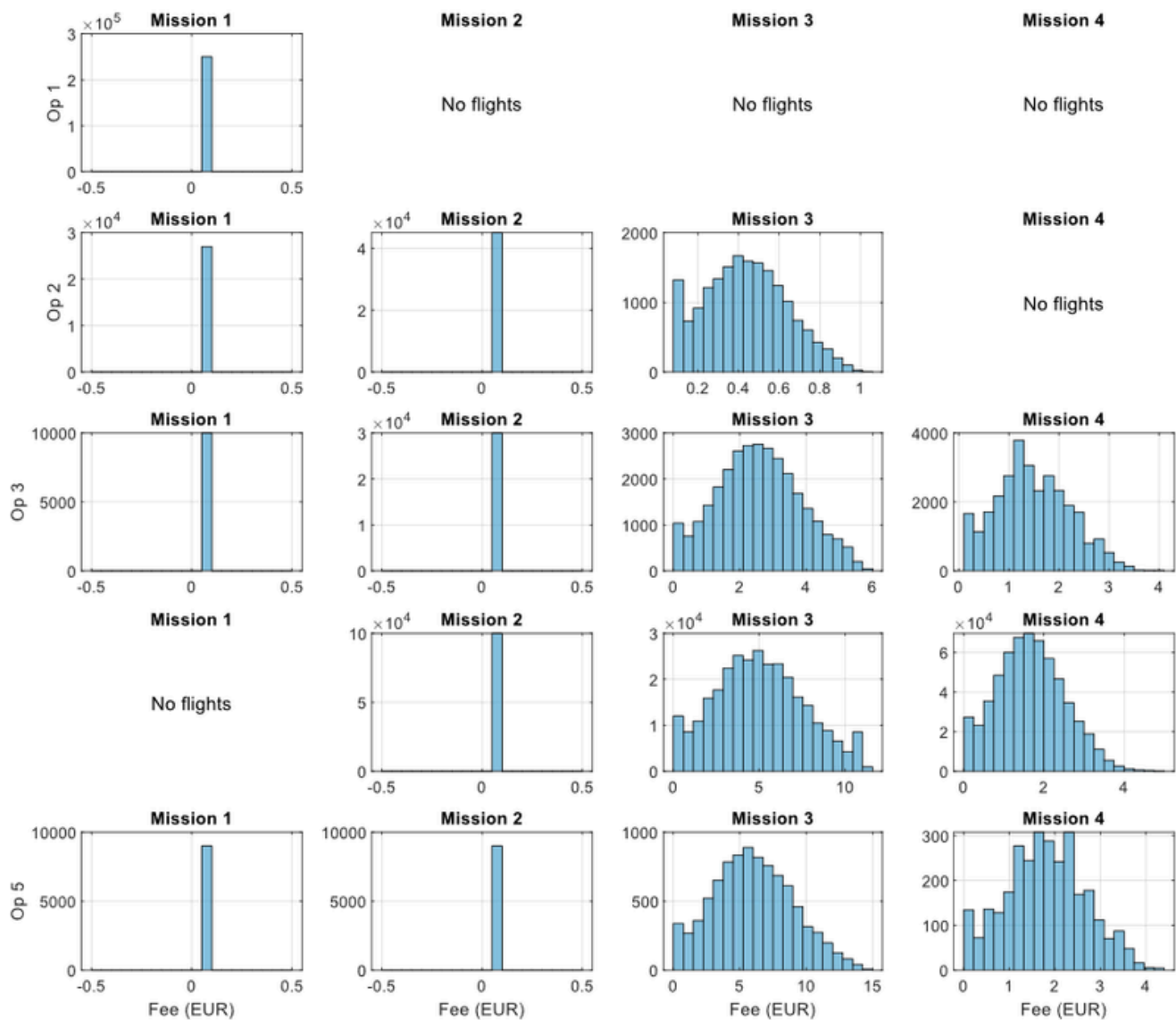


Figure 1. Baseline fee distribution by operator and mission category

### Average Fee by Operator Type

Figure 2 decomposes the average per-flight fee by operator type, averaged across all mission categories weighted by the number of flights in each operator-mission cell. The bar chart directly illustrates the effect of the OACI weighting scheme on the practical fee burden experienced by each operator class.

Hobby operators ( $OT1 = 0.1$ ) face an average fee near the minimum floor of EUR 0.10, reflecting that their operations are predominantly simple VLOS flights with a low mission complexity coefficient and minimal airspace resource consumption.

Small commercial operators (OT2 = 0.5) pay a modest average fee of approximately EUR 0.45, consistent with a mixed portfolio of VLOS and basic BVLOS missions. Professional operators (OT3 = 1.0) face a substantially higher average of approximately EUR 4.40, driven by their significant share of medium-range BVLOS operations. Enterprise operators (OT4 = 1.2) carry the highest average fee at approximately EUR 8.80, reflecting that 60% of their flights are complex BVLOS operations with the highest mission coefficient (MT = 1.5) and the largest AOV values in the fleet. State operators (OT5 = 1.0) occupy an intermediate position at approximately EUR 7.20, as their mixed portfolio includes both simple and demanding missions. The monotonic increase from OT1 to OT4 confirms that the pricing architecture achieves its proportionality objective: operators that derive greater benefit from U-space infrastructure and impose greater demands on it contribute proportionally more to cost recovery.

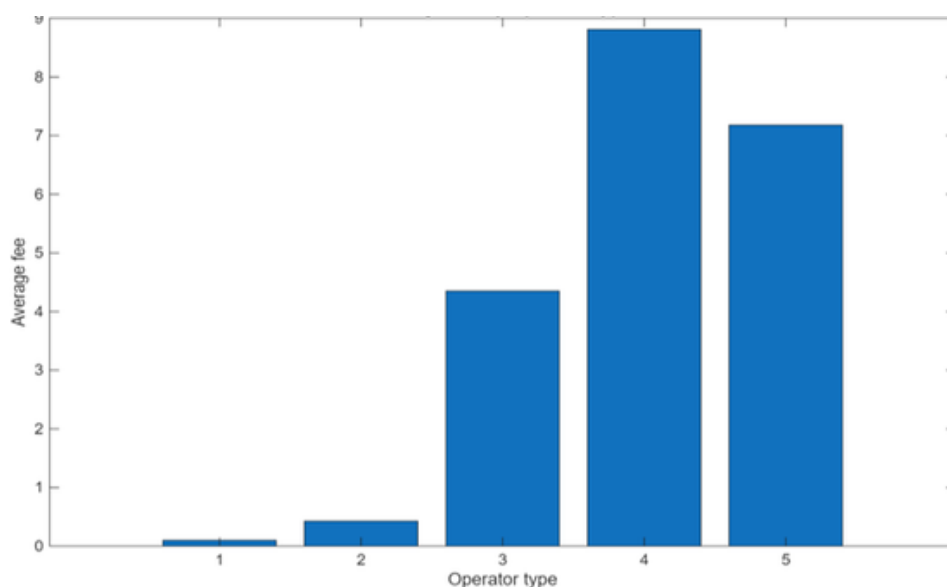


Figure 2. Average fee per flight by operator type (OT1-OT5) at full-scale baseline traffic ( $\kappa = 1.0$ ) and benchmark rate coefficients

## Revenue Concentration

The degree of revenue concentration inherent in the baseline fee schedule is illustrated in Figure 3. The curve plots the cumulative share of total revenue against the cumulative share of flights, ordered from the lowest to the highest fee.

The pronounced convexity of the curve confirms a strongly unequal distribution: approximately 10% of flights (primarily complex BVLOS operations by enterprise operators) account for roughly 40% of total revenue, while the majority of flights (simple VLOS and short commercial operations) contribute comparatively little individually.

This concentration pattern is a structural consequence of the OACI weighting scheme combined with the AOV billing dimension: high-speed, long-range flights occupy disproportionately large airspace volumes and carry high OT x MT multipliers, placing them far above the fleet median on the weighted usage score. The pattern is consistent with the Pareto-like cost allocation observed in analogous network infrastructure pricing models and suggests that the fee schedule is well-calibrated to recover a large portion of costs from the segment of operators that most intensively uses the U-space infrastructure.

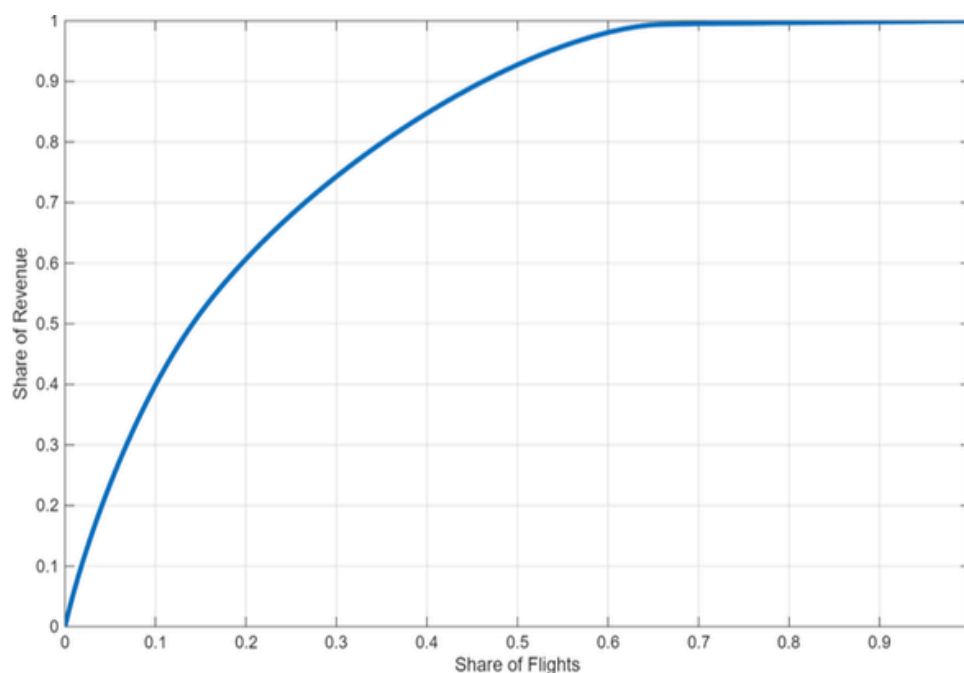


Figure 3. Revenue concentration curve. The x-axis shows the cumulative share of flights (ordered from lowest to highest fee); the y-axis shows the corresponding cumulative share of total revenue

## Sensitivity Analysis: Rate Coefficient Variation

The benchmark rates derived in Section 3.5 represent one particular calibration of the fee formula, grounded in the inverse-mean normalisation principle. In practice, a regulator or USSP may wish to place greater emphasis on one billing dimension. For instance, penalising long-duration loiter more heavily, or reflecting a policy preference for distance-based charges familiar from conventional ATM charging. To quantify the fee schedule's sensitivity to these choices, a full factorial grid search is conducted across the three rate parameters.

The time rate  $r_t$  is varied across five levels:  $\{0.0, 0.3, 0.6, 0.9, 1.2\} \text{ min}^{-1}$ . The distance rate  $r_d$  is varied across five levels:  $\{0.0, 0.012, 0.024, 0.036, 0.048\} \text{ km}^{-1}$ . The AOV rate  $r_v$  is varied across five levels:  $\{3.0, 5.0, 7.0, 9.0, 11.0\} \times 10^{-7} \text{ m}^{-3} \cdot \text{min}$ . This produces  $5^3 = 125$  combinations, each evaluated on the fixed baseline traffic corpus at  $\kappa = 1.0$ .

For each combination, four output metrics are recorded: total revenue, the index and value of the maximum per-flight fee, and the median fee across all flights. Because total cost recovery is enforced by construction within the fee computation procedure, total revenue remains stable across rate combinations at EUR 2,743,200. The substantive variation therefore, manifests in the shape of the fee distribution: combinations with a high time rate and low AOV rate compress the fee range (pulling high-AOV enterprise flights toward the median), while high AOV rate settings amplify fee dispersion, concentrating cost recovery on the small fraction of complex, high-volume operations.

The results demonstrate that the fee structure is moderately sensitive to the choice of rate coefficients, but that the qualitative ordering of operator-mission categories is robust across all 125 combinations: enterprise operators performing complex BVLOS missions consistently attract the highest fees, while leisure VLOS operations remain at or near the minimum floor.

This robustness is a desirable property of the pricing architecture, confirming that the relative fairness of the charge distribution does not depend critically on the precise calibration of individual rate parameters within the explored range. Figure 4 presents heatmaps of the maximum and median fee across 25 rate-coefficient combinations ( $r_t \times r_d$ ) for selected AOV rate levels, illustrating how fee dispersion responds to changes in the time and distance rate parameters at fixed airspace-volume weighting. Figure 5 visualises the full three-dimensional pricing space, confirming that cost recovery remains stable at the break-even threshold across all combinations.

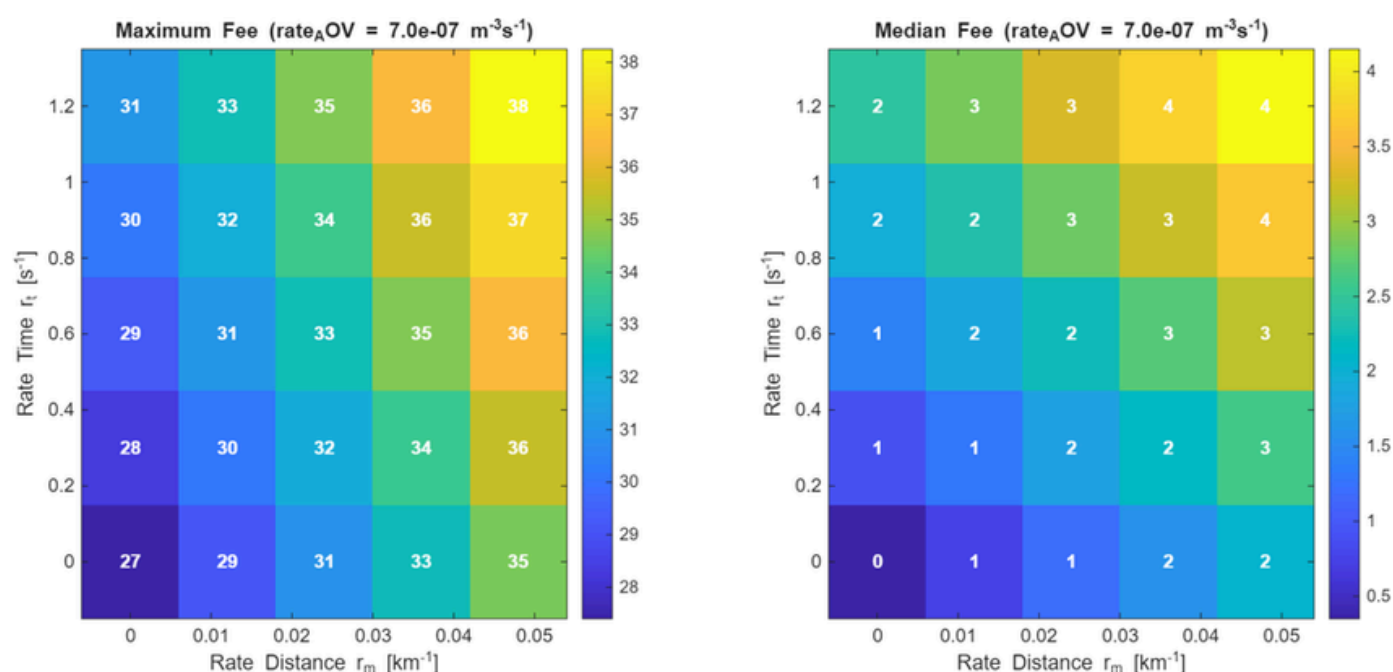


Figure 4. Heatmap of maximum fee and median fee across rate coefficient combinations for selected AOV rate levels for full traffic kappa = 1,0 and CR = 1

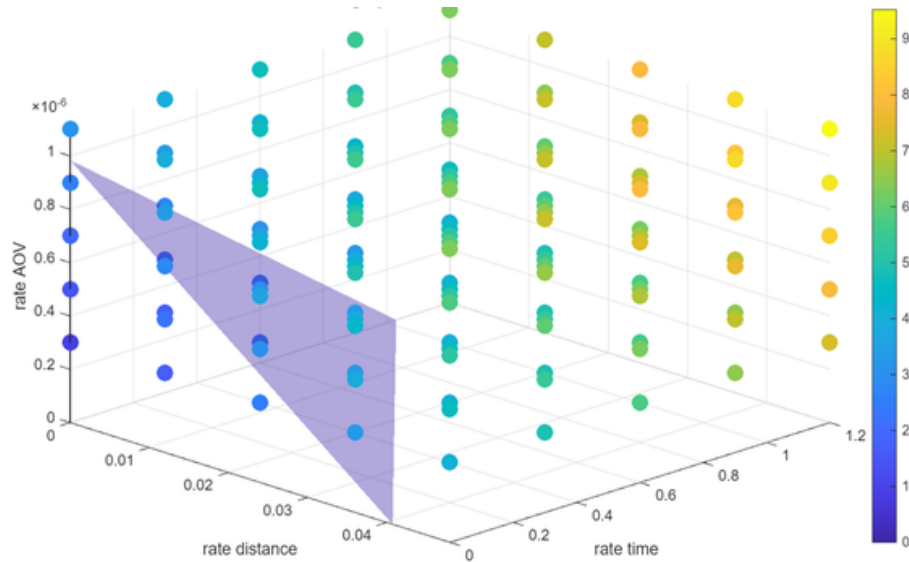


Figure 5. Three-dimensional pricing space with break-even plane. Each point represents one of the 125 rate combinations; colour indicates total revenue (EUR). The semi-transparent plane marks the break-even threshold at EUR 2,743,200

#### Sensitivity Analysis: Traffic Volume Variation

The second sensitivity analysis addresses the dependence of the fee schedule on overall traffic volume, which is the primary uncertainty in any near-term U-space economic model. The global scaling factor kappa is varied across five discrete levels {0.2, 0.4, 0.6, 0.8, 1.0}, corresponding to 20%, 40%, 60%, 80%, and 100% of the projected full-scale baseline traffic volume.

Because CAPEX and OPEX are largely fixed and independent of traffic volume, a reduction in traffic volume does not reduce total required revenue but instead forces the same aggregate cost to be spread across a smaller number of operations, mechanically increasing the average per-flight fee. At kappa = 0.2, the system operates with approximately 294,000 flights, and average fees are approximately five times higher than at full scale. This inverse relationship between traffic volume and average fee level has direct implications for market development: excessively high per-flight charges at low traffic density may deter early adoption, creating a demand suppression dynamic that further delays the transition to higher traffic volumes and lower fees.

The minimum fee floor partially mitigates this effect by limiting how high fees can rise for low-complexity operations, shifting residual cost recovery toward higher-complexity flights. At  $\kappa = 0.2$ , the floor is binding for a substantially larger fraction of flights than at  $\kappa = 1.0$ , and the maximum fee, borne by the most complex enterprise operations, rises sharply. This pattern suggests that early-phase U-space pricing may effectively function as a cross-subsidy from enterprise and public-safety operators toward lower-complexity users, which may be consistent with market development objectives but merits explicit regulatory scrutiny.

Figure 6 illustrates how the fee distribution shifts across kappa levels, confirming the inverse relationship between traffic volume and per-flight cost and the increasing binding effect of the minimum fee floor at low density.

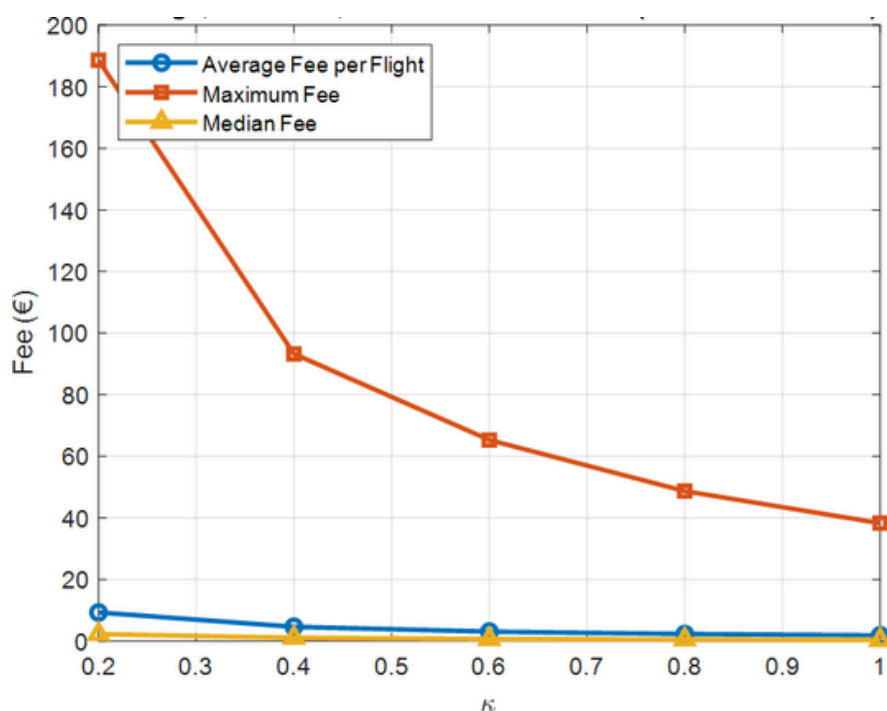


Figure 6. Effect of traffic volume scaling ( $\kappa$ ) on the per-flight fee distribution; higher  $\kappa$  values shift the distribution toward lower fees as fixed costs are spread across a larger number of operations. The minimum fee floor is binding for a larger share of flights at lower  $\kappa$  levels

## Discussion

The proposed framework demonstrates that cost recovery for U-space services is achievable with a small number of auditable parameters, and that the proportionality objective of the OACI weighting scheme produces stable, plausible fee distributions across operator and mission classes. The right-skewed distribution and revenue concentration on enterprise operators are structural outcomes of the framework rather than artefacts of specific calibration choices, and are consistent with Pareto-like cost allocation patterns observed in analogous network infrastructure pricing models.

From a market development perspective, the early-phase pricing challenge identified in the traffic volume sensitivity analysis deserves particular attention. If full cost recovery is required from the outset, per-flight fees at low traffic density may be prohibitively high for many potential users, suppressing the adoption that would lower fees over time. This suggests a case for phased cost recovery, with public support or targeted subsidies during early deployment, that mirrors approaches used in the introduction of conventional ATM infrastructure. The framework is readily adapted to test such scenarios by modifying the cost recovery ratio CR.

The cross-subsidy pattern observed at low kappa levels, where enterprise and public-safety operators effectively subsidise lower-complexity users through a concentrated fee burden, warrants explicit regulatory scrutiny. Whether such cross-subsidies are desirable depends on market development objectives and distributional equity considerations that lie beyond the scope of a purely technical pricing analysis. The framework makes these trade-offs visible and auditable, which is itself a contribution to evidence-based regulatory design.

The robustness of the qualitative fee ordering across all 125 rate-coefficient combinations is a particularly valuable property of the architecture. Regulators and service providers need not determine precise rate coefficients to be confident that enterprise BVLOS operators will bear the largest fee burden relative to hobby VLOS operators. This robustness also means that the framework can accommodate different policy preferences without destabilising the fundamental proportionality of the charge distribution.

A comparison with the broader UTM governance literature reveals that the framework is consistent with the institutional trade-offs identified by Decker and Chiambareto (2022), who highlight the importance of separating infrastructure-like from competitive functions, and with the market-design principles articulated by Seuken et al. (2022), who emphasise fairness, scalability, and non-manipulability. The present framework operationalises these principles within the specific regulatory architecture of EU 2021/664, providing a concrete link between abstract governance considerations and practical tariff design.

### **Limitations and Future Work**

The proposed framework should be understood as a conceptual and computational pricing methodology, not as a market-calibrated tariff proposal. Several limitations must be acknowledged explicitly.

First, the model does not incorporate a separate scarcity charge for congestion management. The literature strongly suggests that high-density UTM environments may require explicit access-allocation mechanisms beyond simple cost recovery (Seuken et al., 2022; Carramiana et al., 2025). Urban low-altitude airspace design and traffic-density effects are highly sensitive to allocation rules and demand concentration (Doole et al., 2020; Barrado et al., 2020).

Integrating congestion-sensitive pricing into this framework, potentially through a separate demand-management layer, is an important direction for future work for next steps in U-space deployments.

Second, the OACI parameters are normative and expert-based rather than empirically estimated. Their calibration requires transparent regulatory consultation and will be subject to political trade-offs concerning fairness and market development that cannot be resolved through technical analysis alone. Future work should develop structured elicitation methodologies and test the sensitivity of fee distributions to plausible ranges of OACI coefficients.

Third, the traffic generator relies on synthetic distributions rather than observed operational data. This is acceptable for exploratory and structural analysis, but future work should replace demonstration inputs with empirical traffic and cost data as European deployment matures. The first generation of operational U-space deployments should generate cost and traffic data that can be used to calibrate the framework parameters empirically.

Fourth, the framework does not yet address the dynamic evolution of costs and traffic over time. As U-space deployments scale and technology matures, both CAPEX and OPEX profiles are likely to change substantially. A dynamic pricing model that accounts for economies of scale, technology learning curves, and evolving regulatory requirements would be a natural extension of the present static framework.

Fifth, the framework does not address cross-border issues. As U-space deployments expand across multiple member states, questions of mutual recognition, cross-border cost allocation, and regulatory harmonisation will arise. The EU regulatory framework provides a basis for harmonisation, but the economic design of cross-border pricing arrangements remains unexplored.

## Conclusion

This paper has proposed a structured cost-recovery pricing methodology for U-space services, grounded in the EU regulatory framework established by Commission Implementing Regulation (EU) 2021/664 and informed by economic theory on infrastructure pricing, ATM financing, and digital platform economics. The framework decomposes total charges into infrastructure costs, operational costs, and an operator-complexity adjustment layer, and provides explicit cost allocation formulas for each component.

The validation using a synthetic traffic corpus of approximately 1,470,000 flights demonstrates that cost recovery is achievable, that the fee distribution is proportional to airspace resource consumption and mission complexity, and that the qualitative ordering of operator classes is robust across 125 rate-coefficient combinations. The traffic volume sensitivity analysis identifies the early-phase pricing challenge as a key market development concern and demonstrates how the minimum fee floor functions as a partial mitigation mechanism.

The methodology is explicitly structural rather than empirical: it defines the computation logic and identifies the parameters that implementers must populate from operational data. It is intended as a template for regulators, CISPs, and USSPs to adapt as European U-space deployment generates empirical cost and traffic data over the coming years. As the European drone market matures and U-space services scale from early pilots to operational deployment, the economic design of access charges will become an increasingly important determinant of market structure, innovation incentives, and the equitable distribution of costs across the diverse community of drone operators. The present framework provides a principled foundation for that design process.

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