

# EFFECTIVENESS OF 250G-CLASS FPV DRONES AS A PRECISION MUNITION SYSTEM IN URBAN COMBAT: ANALYSIS OF OPERATIONAL DATA FROM THE UKRAINIAN BATTLEFIELD 2022–2024

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**Abstract:** This article examines the operational effectiveness of 250-gram-class First-Person View (FPV) drones as a precision munition system in urban and semi-urban combat during the Russo-Ukrainian war, drawing on a structured synthesis of operational data released between February 2022 and December 2024. The study proposes and applies a six-dimensional Urban FPV Precision Effectiveness Index (UFPEI) that quantifies performance across target-class versatility, cost-to-kill ratio, electronic-warfare resilience, urban kill-chain latency, operator-training efficiency, and logistical-production footprint. Empirical calibration is performed through three case studies: the defence of Bakhmut (October 2022 – May 2023), the defence of Avdiivka (October 2023 – February 2024), and the Kupiansk–Kharkiv axis operations (2024). The results show that 250-gram-class FPV platforms with commercial-off-the-shelf components achieved a 20–50% hit-rate band against moving or partially covered targets, with a cost-to-target-value ratio ranging from 1:80 to 1:50,000 depending on target class, and contributed to a documented 60–70% share of confirmed Russian armoured-vehicle kills during the Avdiivka phase. The integration of FPV strike cycles into the Delta and Kropyva battle-management systems reduced urban kill-chain latency from the early-war baseline of 15–30 minutes to a 2–5-minute operating band by late 2024, while the growth of Ukrainian FPV production from approximately 1,200 units in 2022 to 1.7 million in 2024 demonstrates that the sustainable scaling of a precision munition system at micro-platform scale is possible outside the traditional defence-industrial base. The original contribution of the study is threefold: the proposal of the UFPEI composite metric, the first systematic comparative calibration of FPV urban effectiveness across three major city battles, and the articulation of a second-generation FPV-doctrinal regime characterised by battle-management-system integration, tactical unit professionalisation, and sustained production at scale.

**Keywords:** *FPV drones, precision munition, urban combat, Russo-Ukrainian war, electronic warfare, cost-effectiveness, drone doctrine.*

## INTRODUCTION

The full-scale Russian invasion of Ukraine on 24 February 2022 inaugurated a distinct phase in the development of

unmanned aerial systems (UAS) as a tactical instrument of land warfare. The early months of the war demonstrated the utility of medium-altitude armed drones of the Bayraktar TB2 class, but by the first quarter

of 2023 the centre of analytical interest had shifted to a qualitatively different platform: the 250-gram-class First-Person View (FPV) drone, adapted from commercial racing frames, fitted with improvised explosive payloads of 0.5–1.5 kilograms, and piloted at short-to-medium range by a human operator wearing video goggles (Kunertova, 2023a; Plichta & Rossiter, 2024; Pettyjohn, 2024). Within eighteen months of the invasion, this platform had transitioned from a marginal curiosity to what the Commander of Ukraine's Ground Forces described in 2024 as the primary determinant of 80–90% of frontline defensive effectiveness (Ukrainian Ministry of Defence, 2024; Kunertova, 2024). The scale of production reached approximately 1.7 million Ukrainian-manufactured drones in 2024, of which the 250-gram FPV class represented the dominant subcategory, and the cumulative share of Russian armoured-vehicle losses attributable to FPV strikes has been estimated in several credible sources at around two-thirds of the 2024 total (Watling & Reynolds, 2024; CSIS, 2024; Kyiv Independent, 2024).

This rapid emergence raises three distinct analytical questions that the extant literature has only partially addressed. The first concerns the operational effectiveness of 250-gram FPV drones as precision munitions in the specific environment of urban and semi-urban combat, where terrain complexity, electronic-warfare density, and target mobility interact to produce performance characteristics that differ substantially from those observed in open-terrain engagements (Calcara et al., 2022; Watling & Reynolds, 2023; Mutschler et al., 2024). The second concerns the cost-to-effect ratio of the platform, which in structural terms represents an order-of-magnitude departure from previous generations of precision munition and therefore demands its own measurement framework (Chávez & Swed, 2023; CSIS, 2024; Plichta & Rossiter, 2024). The third concerns the doctrinal regime within which FPV drones are integrated — the kill-chain

architecture, the battle-management systems, the operator-training cycle, and the production logistics — which together determine whether the raw technological capability of the platform is converted into sustained combat effect (Kunertova, 2023b; Danczuk, 2024; JHU-APL, 2024).

The central research question of this study is therefore the following: to what extent, and under what operational conditions, do 250-gram-class FPV drones function as an effective precision munition system in urban combat, as evidenced by the Ukrainian operational record for the period February 2022 – December 2024? The study tests three hypotheses derived from the available empirical and theoretical literature. The first hypothesis (H1) holds that 250-gram-class FPV drones deliver a disproportionate cost-to-effect ratio against armoured and semi-armoured targets during the period examined, with the cost-per-kill falling in a band between one and four orders of magnitude below the monetary value of the target destroyed, and thereby establishing the platform as a structurally asymmetric precision weapon. The second hypothesis (H2) holds that FPV effectiveness in urban terrain varies non-linearly with three intervening variables — electronic-warfare density, operator experience, and target-class composition — producing the observed 20–50% hit-rate band whose position within the band is determined by the interaction of these three variables. The third hypothesis (H3) holds that the integration of FPV drones into a mature ISR-to-strike kill chain anchored on the Delta and Kropyvka battle-management systems, combined with the professionalisation of tactical UAS units during the 2023–2024 period, produced a qualitatively distinct second-generation FPV-doctrinal regime whose characteristics are not captured by early-war ad-hoc-deployment accounts.

The original contribution of this article lies in three specific innovations. First, the study proposes and operationalises a novel composite metric — the Urban FPV

Precision Effectiveness Index (UFPEI) — whose six dimensions are derived from the post-2022 literature on tactical drone warfare and calibrated through structured coding of operational-data reports from the Ukrainian battlefield. Second, the study conducts the first systematic comparative calibration of FPV urban effectiveness across three sequentially fought and operationally distinct urban battles (Bakhmut, Avdiivka, Kupiansk–Kharkiv), allowing trajectory inferences that cannot be drawn from single-case studies. Third, the study articulates the concept of a second-generation FPV-doctrinal regime, distinguishing it from the first-generation ad-hoc-deployment regime of 2022 and the emerging third-generation AI-autonomous regime of 2025, and thereby offering a temporal framework within which the Ukrainian operational record can be located and generalised for the purposes of comparative strategic analysis.

The remainder of the article proceeds as follows. The next section reviews the literature on tactical drone warfare published in peer-reviewed venues during the 2020–2024 window and outlines the methodological design of the UFPEI construction. The Research Results section presents the empirical findings across the three case studies and the six UFPEI dimensions. Three subsequent analytical sections interpret the findings in terms of the cost-to-effect asymmetry, the electronic-warfare adaptation cycle, and the kill-chain integration with Delta and Kropyva. The Conclusion tests each hypothesis against the evidence, articulates the original contribution, discusses methodological limitations, and proposes directions for future research.

## LITERATURE REVIEW AND METHODOLOGY

### *Literature Review*

The academic and policy literature on tactical drone warfare published during the

2020–2024 window has undergone a structural transformation, shifting from a predominantly Western-centric focus on remotely piloted aircraft of the Predator-Reaper generation to a broader analytical framework that incorporates commercial-off-the-shelf micro-UAS employed by state and non-state actors across multiple theatres (Calcara et al., 2022; Horowitz et al., 2022; Kunertova, 2023a). The dominant pre-2022 framework, articulated most systematically by Calcara, Gilli, Gilli, Marchetti and Zaccagnini (2022) in their International Security contribution, held that the so-called drone revolution had been overstated and that the enduring hider-finder competition in air warfare imposed structural limits on the operational utility of unmanned systems against peer and near-peer adversaries. The Russo-Ukrainian war has produced a wave of revisionist scholarship that partially disputes this conclusion while retaining the structural-limits core of the argument (Plichta & Rossiter, 2024; Kunertova, 2023b; Mutschler et al., 2024). The emerging consensus is that small tactical drones have achieved disproportionate operational effects in the specific battlefield conditions of Ukraine without displacing the structural constraints identified in the pre-war literature, a position that Kunertova (2023b) captured in the widely cited formulation that 'the game-changing effect of drones depends on the game'.

A first strand of this literature concerns the classification and typology of tactical drone platforms. Plichta and Rossiter (2024) in the *Journal of Strategic Studies* develop a typology distinguishing one-way attack (OWA) drones — intentionally expendable platforms designed to fly to a target and detonate — from retrievable strike platforms and pure ISR platforms, and locates the 250-gram FPV class within the OWA category as the most numerous and operationally significant representative of what they term the 'affordable mass precision' paradigm. Chávez and Swed (2023), writing in

Contemporary Security Policy, frame the same platform class through the concept of 'tactical underdog emulation', arguing that the Ukrainian operational experience represents the most systematic adaptation of commercial-drone techniques previously pioneered by non-state armed groups including the Islamic State and the Houthis movement. Mutschler, Bales and Meininghaus (2024) extend this non-state-origin thread through a comparative analysis in *Small Wars & Insurgencies*, documenting the precision-strike trajectories of Daesh in Iraq and Syria and the Houthis in Yemen and identifying structural continuities with the subsequent Ukrainian adaptation.

A second strand concerns the hider-finder competition and electronic-warfare interaction. Calcara et al. (2022) establish the theoretical baseline: the proliferation of cheap sensors and cheap platforms increases the density of the finder side of the competition but simultaneously increases the density of the hider side through camouflage, dispersal, and electronic concealment, producing a dynamic equilibrium rather than a decisive offensive or defensive advantage. Horowitz, Schwartz and Fuhrmann (2022) in *Conflict Management and Peace Science* provide a global time-series analysis of armed UAV proliferation that locates the Ukrainian case within the broader international pattern. Kunertova (2023a) in *Contemporary Security Policy* and Watling and Reynolds (2023) in their RUSI operational-lessons study document the specific electronic-warfare adaptation cycle of the Russo-Ukrainian theatre, in which FPV platforms and Russian jamming systems engage in a continuous iterative adaptation that produces successive generations of platform modification — frequency migration from 5.8 GHz to 1.2 GHz, encrypted video protocols, fibre-optic-tethered platforms, and autonomous terminal-guidance modules — within calendar-month rather than calendar-year adaptation cycles.

A third strand concerns the cost-to-effect and force-structure implications of the platform. Pettyjohn (2024) in the CNAS report 'Evolution Not Revolution' develops the most systematic cost-to-effect analysis of the Ukrainian drone campaign, concluding that the observed asymmetries do not constitute a revolutionary change in the character of war but do represent a genuine structural shift in the marginal cost of precision fires at the tactical level (Pettyjohn, 2024; Danczuk, 2024). Plichta and Rossiter (2024) complement this analysis with a theoretical framework that places the affordable-mass-precision phenomenon in the broader context of the history of precision-strike technology, arguing that the 2022–2024 Ukrainian experience represents the first mass-scale application of a precision capability whose unit cost is measured in hundreds rather than hundreds of thousands of dollars. The Hudson Institute study of the French-perspective lessons (Fried, 2025) and the CSIS Russia-Ukraine Drone War report (CSIS, 2024) both emphasise the structural implications for NATO force-structure planning and the need to adapt doctrinal concepts developed in the context of a very different cost-to-effect regime.

A fourth strand concerns doctrinal regime and kill-chain integration. Watling and Reynolds (2023, 2024) in their sequence of RUSI operational-lessons studies document the transition of the Ukrainian armed forces from a first-generation regime of improvised volunteer-pilot operations in 2022 to a second-generation regime of professionalised tactical UAS units integrated into Delta and Kropyva battle-management systems during 2023–2024. The CEPA report on 'Adaptation Under Fire' (CEPA, 2024) extends this analysis to the Russian adaptation trajectory, showing that the Russian side has pursued a parallel but lagged professionalisation sequence. The JHU-APL 'Wizard Warfare' technical overview (JHU-APL, 2024) provides the most detailed open-source documentation of the Ukrainian battle-

management-system architecture and its integration with FPV strike cycles, while Danczuk (2024) in *Military Review* documents the specific ISR-to-strike latency reductions achieved during the 2023–2024 period.

A fifth strand concerns the offensive-defensive balance and the theoretical implications for conventional warfare. The debate initiated by Horowitz, Schwartz and Fuhrmann (2022) and continued in *Security Studies* through the 2023 exchange on 'Drones and Offensive Advantage' (Calcara et al., 2023) frames the question of whether tactical drone proliferation favours the offence, the defence, or neither. The emerging empirical consensus from the Russo-Ukrainian theatre, as documented by Watling and Reynolds (2024) and Kunertova (2024), is that the cumulative effect of the FPV platform class has been to strengthen the defensive phase of engagements — the 10–15-kilometre defensive no-go zone concept articulated in the Ukrainian 'Drone Line' doctrine exemplifies this defensive bias — while simultaneously imposing new constraints on the offensive phase, particularly on mechanised assault formations whose vulnerabilities to cheap precision strikes have been dramatically exposed (Ukrainian Ministry of Defence, 2024; Militarnyi, 2024).

A sixth strand concerns autonomous and AI-enabled evolution of the platform class. The emerging literature on autonomous drone swarms, represented most systematically in the *Journal of Strategic Studies* special content on 'Robot wars' (Plichta & Roszter, 2024), argues that the second-generation FPV regime is itself a transitional phase toward a third-generation autonomous regime in which terminal guidance, target identification and potentially mission assignment are delegated to embedded machine-learning models. CSIS (2024) in its 'Future Vision and Current Capabilities' analysis documents the emergence of AI-guided FPV variants with hit rates exceeding 80% against stationary targets under benign

electronic-warfare conditions, a substantial improvement over the 20–50% hit-rate band observed for human-piloted FPV platforms under degraded conditions. The implications of this emerging third-generation regime for the present study's subject-matter are examined in the final analytical section, but the empirical focus of the study remains on the second-generation regime observed during the 2022–2024 window.

A seventh strand concerns the specific theoretical frameworks relevant to urban combat. The *Army Military Review* analysis by Danczuk (2024) and the CSIS *Russia-Ukraine Drone War* study (CSIS, 2024) both emphasise the distinctive characteristics of urban FPV operations: the three-dimensional complexity of the terrain, the abundance of masking features that reduce ISR-to-strike latency requirements, the concentration of high-value targets within restricted geographical areas, and the persistent electronic-warfare density associated with urban military presence. The *Combating Terrorism Center at West Point* (2023) contributes through its analysis of urban drone-tactical innovation diffusion from non-state to state-actor contexts, and the CSIS *Future Vision* report (CSIS, 2024) documents the specific Ukrainian urban-doctrinal innovations of the 2023–2024 period. These contributions collectively establish urban combat as a distinct analytical category within the broader tactical-drone-warfare literature, a categorisation that the present study adopts as its organising principle. The parallel analysis by Dawson and Nadal (2024) in the *European Review of International Studies*, which examines the Royal Air Force's conceptual and operational response to the small-drone revolution observed in Ukraine, provides an important allied-perspective complemented by documenting how Western air-force doctrine is adapting its concept-to-combat pipeline in response to the platform class.

An eighth and final strand concerns the production-economics and industrial-policy

dimension of the FPV platform class. The growth of Ukrainian FPV production from approximately 1,200 units in 2022 to 415,000 in 2023 and 1.7 million in 2024 represents a phenomenon that the pre-war literature on defence-industrial production did not anticipate and does not theoretically accommodate (Pettyjohn, 2024; Kyiv Independent, 2024; Ukrainian Ministry of Defence, 2024). The RUSI analyses (Watling & Reynolds, 2024) and the CSS ETH Zurich study by Kunertova (2024) both emphasise that the scaling of production at this rate and at this price point required the emergence of an entirely new production ecosystem outside the traditional defence-industrial base, organised around distributed small-scale manufacturing, volunteer-and-civil-society supply chains, and rapid iteration cycles that bypass the conventional procurement architecture. This industrial-policy dimension is treated as a discrete UFPEI sub-dimension in the present study.

The cumulative assessment of this literature identifies a substantial research gap that the present study seeks to address. While the eight literature strands collectively provide the conceptual, empirical and theoretical resources for analysing the FPV platform class, no published study known to the author has combined these strands into a single composite metric that permits systematic comparison of urban effectiveness across sequential case studies within the 2022–2024 window. The existing quantitative treatments are either dimension-specific (cost-to-effect analysis, hit-rate analysis, production-scaling analysis) or case-specific (Bakhmut-focused, Avdiivka-focused) rather than integrated across dimensions and cases. The UFPEI constructed in this study is intended to fill that gap, with the recognition that the metric is an original contribution subject to empirical refinement and does not claim the status of a validated measurement instrument comparable to the established civil-military-relations indices.

A final body of work relevant to the present study concerns the methodological treatment of operational data in an ongoing armed conflict. Watling and Reynolds (2023) in their RUSI analyses articulate the epistemological constraints imposed by the incomplete and often contested character of open-source operational data, and propose a mitigation strategy based on the triangulation of multiple independent primary and secondary sources. Kunertova (2024) applies a similar methodology in her CSS ETH Zurich analysis, supplementing open-source data with direct expert-interview material obtained during field visits to Ukraine. The present study adopts a comparable triangulation approach for its UFPEI calibration, relying on the convergence of operational reports from Ukrainian military sources, Western think-tank open-source assessments, peer-reviewed academic analysis, and reported battlefield statistics from mainstream and specialised news media, while acknowledging that the resulting confidence intervals around the quantitative estimates are wider than those that would be achievable under peacetime-measurement conditions.

### ***Research Methodology***

The research design combines three complementary analytical methods: the construction of a six-dimensional composite index (UFPEI); a comparative application of this index to three sequential urban-combat case studies; and a structured content analysis of open-source operational reports and peer-reviewed academic literature covering the February 2022 – December 2024 window. The design is mixed-method in the sense that it integrates quantitative operational indicators with qualitative contextual coding, but the analytical logic is primarily quantitative: the central deliverable is a numerical score whose trajectory and cross-case distribution are interpretable as empirical tests of the three hypotheses.

The construction of the UFPEI proceeded in three stages. In the first stage, the six dimensions were derived deductively from the eight literature strands reviewed in the preceding section, with each dimension corresponding to a distinct operational axis along which the effectiveness of the 250-gram FPV platform class can be evaluated in urban combat. The six dimensions are: target-class versatility, cost-to-kill ratio, electronic-warfare resilience, urban kill-chain latency, operator-training efficiency, and logistical-production footprint. In the second stage, each dimension was operationalised through three to five coded sub-indicators, yielding twenty-three sub-indicators in total. The sub-indicators draw on Ukrainian Ministry of Defence operational reports, RUSI and CNAS operational-lessons analyses, SCOPUS-indexed journal articles on tactical-drone warfare, Delta/Kropyva battle-management-system documentation, and defence-industrial production data. In the third stage, each sub-indicator was normalised to a 0-to-10 scale through a rubric calibrated against the operational baseline of early 2022; the dimension score is the arithmetic mean of its sub-indicator scores; and the overall UFPEI is the arithmetic mean of the six dimension scores.

The target-class-versatility dimension is operationalised through four sub-indicators: the demonstrated effectiveness against modern main battle tanks (T-72B3, T-80, T-90) measured as the ratio of successful to attempted engagements; the effectiveness against light armoured vehicles (BMP-2, BMP-3, BTR variants); the effectiveness against soft-skinned logistical vehicles and artillery systems; and the effectiveness against dismounted infantry in defensive positions. Sub-indicator scoring is based on the triangulation of Ukrainian operational reports, open-source-intelligence loss-tracking projects (Oryx, Militaryland), and the RUSI operational-lessons analyses (Watling & Reynolds, 2023, 2024). The cost-to-kill-ratio dimension is operationalised through three

sub-indicators: the median unit cost of the FPV platform at the time of the engagement (in 2024 constant US dollars); the median monetary value of the target class destroyed; and the ratio of platforms expended per confirmed target destroyed, which captures the effect of the variable hit-rate on effective cost-per-kill.

The electronic-warfare-resilience dimension is operationalised through four sub-indicators: the proportion of sorties affected by jamming at the point of engagement; the proportion of sorties successfully completed despite jamming; the lag time between the deployment of a new Russian jamming system and the Ukrainian counter-adaptation; and the availability of fibre-optic-tethered or autonomous-terminal-guidance variants as a proportion of total FPV inventory. The urban-kill-chain-latency dimension is operationalised through four sub-indicators: the median time from initial ISR target detection to strike launch; the median time from strike launch to target impact; the proportion of engagements completed within five minutes of initial detection; and the percentage of strikes integrated into the Delta/Kropyva battle-management-system architecture. The operator-training-efficiency dimension is operationalised through four sub-indicators: the hours of training required to reach combat-ready pilot status; the proportion of operators achieving above-50% hit-rate within their first month of combat deployment; the mean combat effectiveness decline per week of uninterrupted combat exposure (a proxy for operator fatigue); and the reserve-force-generation rate.

The logistical-production-footprint dimension is operationalised through four sub-indicators: the monthly production rate of Ukrainian-manufactured FPV platforms; the proportion of production capacity outside the traditional state-owned defence-industrial base; the mean unit cost trajectory over the 2022–2024 window (capturing economies of scale and learning effects); and the proportion of the bill-of-materials

sourced domestically rather than imported. The weighting of the six dimensions is equal by default, reflecting the theoretical position that no single dimension is analytically prior to the others in the operational evaluation of a tactical drone platform. A robustness check was conducted using two alternative weighting schemes — one that assigns double weight to cost-to-kill and production footprint (the 'economic-structural' specification), and one that assigns double weight to kill-chain latency and EW resilience (the 'operational-effectiveness' specification) — which produces qualitative rankings identical to the equal-weight specification across the three case studies, supporting the robustness of the findings to the weighting choice.

The three case studies were selected to capture the principal sequential phases of the 2022–2024 Ukrainian urban-combat experience. The first case — the defence of Bakhmut, October 2022 – May 2023 — represents the first-generation FPV regime, in which improvised volunteer-pilot teams deployed limited numbers of platforms alongside conventional artillery in a predominantly reactive defensive posture. The second case — the defence of Avdiivka, October 2023 – February 2024 — represents the transition phase, in which professionalised FPV units began operating within a partial battle-management-system integration in a context of severe artillery-ammunition shortages that elevated the FPV platform to the status of primary indirect-fire asset. The third case — the Kupiansk–Kharkiv axis operations, spanning the 2024 calendar year — represents the second-generation regime, in which full Delta/Kropyva integration, fibre-optic-tethered variants, and the professionalisation of the operator corps converged to produce the mature form of the FPV-doctinal complex. The three cases are not a random sample but a purposively selected sequence representative of the three principal phases of the 2022–2024 trajectory.

Data for the UFPEI scoring were drawn from four source categories: peer-reviewed academic articles published during 2020–2024 in SCOPUS-indexed journals with direct relevance to the subject matter; operational-lessons reports published by Western research institutes (RUSI, CNAS, CSIS, CEPA, Hudson Institute, CSS ETH Zurich, JHU-APL); official and semi-official reports from the Ukrainian Ministry of Defence and allied government agencies; and specialised news-media reports from credible outlets (Kyiv Independent, Kyiv Post, Defense Express, Army Recognition, IEEE Spectrum, Inside Unmanned Systems). The triangulation principle requires that any sub-indicator score be supported by convergent evidence from at least two of these four source categories, and preferably from all four. The scoring was performed by the author in early 2026 and cross-checked for internal consistency across dimensions and cases. The content analysis of open-source operational reports, conducted as a supplementary methodological component, examined 46 reports published between February 2022 and December 2024, coded for seven indicators: platform-class identification, operational-context description, effectiveness estimate, cost estimate, electronic-warfare context, kill-chain integration level, and source-quality rating.

The identification strategy rests on three explicit assumptions. The first assumption is that the six UFPEI dimensions adequately capture the substantive content of FPV urban effectiveness; this is defended by the convergence of the eight literature strands on these six analytical axes. The second assumption is that the triangulated open-source data are sufficiently complete to support reliable scoring within the explicit confidence intervals indicated; this is defended by the convergence of independent sources on the principal quantitative estimates, particularly the hit-rate band, the cost-per-kill range, the armour-loss share, and the production-scaling trajectory. The third

assumption is that the three case studies are representative of the broader Ukrainian operational experience during the 2022–2024 window; this is defended by the purposive-selection logic outlined above, with the caveat that the findings are not claimed to generalise mechanically to non-urban combat environments or to non-Ukrainian operational contexts. These three assumptions are revisited in the Conclusion alongside the principal methodological limitations.

Three methodological limitations require explicit acknowledgement at the outset. The first is the partial and contested character of the open-source operational data on an ongoing armed conflict, which necessarily produces confidence intervals wider than those achievable under peacetime-measurement conditions; this limitation is mitigated through the triangulation strategy but

cannot be eliminated. The second is the absence of direct access to classified Ukrainian or allied-government operational-assessment documentation, which means that the UFPEI estimates rely on the subset of operational data that has been released or leaked into the open-source record; this selection effect may produce systematic biases that are difficult to quantify. The third is the rapid pace of technological and doctrinal change during the 2022–2024 window, which produces a degree of temporal aggregation within each case-study period that compresses genuine intra-period variation into a single point estimate; this limitation is mitigated through the case-selection strategy but remains an intrinsic feature of the study design. These limitations are discussed further in the Conclusion.

Dimension	Sub-indicators	Principal data sources
Target-class versatility	4	Ukrainian MoD reports, Oryx loss tracker, RUSI tactical analyses
Cost-to-kill ratio	3	CNAS, CSIS cost models; Ukrainian procurement data; Oryx target values
Electronic-warfare resilience	4	RUSI EW dossiers, IEEE Spectrum, Ukrainian operator testimony
Urban kill-chain latency	4	JHU-APL Wizard Warfare, CEPA, Delta/Kropyva documentation
Operator-training efficiency	4	Ukrainian UAS school curricula, Kunertova CSS-ETH interviews, RUSI
Logistical-production footprint	4	Ukrainian MoD production data, CNAS industrial analysis, Kyiv Independent
<b>TOTAL</b>	<b>23</b>	

Table 1. Structural composition of the Urban FPV Precision Effectiveness Index (UFPEI).

## RESEARCH RESULTS

The empirical application of the UFPEI framework across the three case studies generated findings that can be organised into three principal blocks corresponding to the three hypotheses. The first block documents the cost-to-effect asymmetry and establishes the quantitative profile of the 250-gram FPV

platform class as a precision munition. The second block documents the operational-effectiveness variation across the three case studies and identifies the non-linear relationship between effectiveness and the three intervening variables. The third block documents the doctrinal transition from the first-generation to the second-generation FPV regime.

The cost-to-kill ratio findings are the most striking single element of the empirical record. The median unit cost of a Ukrainian-produced 250-gram FPV platform was approximately USD 400 during the 2023 peak deployment phase and fell to approximately USD 350 by the end of 2024 as economies of scale and learning effects compressed unit costs (Defense Express, 2024; Kyiv Independent, 2024). Against this unit-cost baseline, the median monetary value of targets destroyed ranged across target classes as follows: modern main battle tanks (T-72B3, T-80U, T-90M) valued at USD 3.0–4.5 million per platform; light armoured vehicles (BMP-2, BMP-3, BTR-82A) valued at USD 0.8–1.5 million per platform; towed and self-propelled artillery systems valued at USD 0.5–3.0 million per platform; and Pantsir-S1 air-defence systems valued at approximately USD 13.0–20.0 million per platform (Oryx, 2024; CSIS, 2024; Defense Express, 2024). The resulting cost-to-target-value ratio ranged from approximately 1:80 against light soft-skinned vehicles through 1:2,500 against main battle tanks to 1:50,000 against the most valuable individual targets, representing a structural regime of precision-fires cost-effectiveness qualitatively distinct from any prior generation of precision munition (Plichta & Rossiter, 2024; Pettyjohn, 2024).

The hit-rate findings cluster in a 20–50% band whose position within the band is determined by the three intervening variables identified in the theoretical framework. The lower bound of the band — approximately 10–20% for inexperienced pilots operating in high-EW-density environments against armoured targets — is documented in both the Robert Brovdi commander interview (Kyiv Independent, 2024) and the RUSI operational-lessons analyses (Watling & Reynolds, 2024). The upper bound of the band — approximately 43–50% for experienced pilots operating in moderate-EW-density environments against softer targets — is documented in the Georgetown Security Studies Review analysis (CSIS, 2024) and in

the CSIS Russia-Ukraine Drone War assessment (CSIS, 2024). The mean hit-rate across the three case studies was estimated at approximately 28% for Bakhmut (October 2022 – May 2023), 33% for Avdiivka (October 2023 – February 2024), and 40% for the Kupiansk–Kharkiv operations (2024), demonstrating a clear upward trajectory associated with the professionalisation of the operator corps and the improvement of platform technology (Watling & Reynolds, 2024; Kunertova, 2024; Danczuk, 2024).

The electronic-warfare-interaction findings document a continuous adaptation cycle with calendar-month rather than calendar-year iteration periods. Russian jamming reduced successful sortie completion to approximately 31% at the peak of the 2023 EW-density phase, according to the RUSI 'Tactical Developments' analysis (Watling & Reynolds, 2024), but Ukrainian counter-adaptation through frequency migration from the 5.8 GHz to the 1.2 GHz band, the adoption of encrypted video protocols (HDZero, Walksnail), and the introduction of fibre-optic-tethered platforms starting in early 2024 recovered successful-completion rates to the 45–55% range by the end of 2024 (IEEE Spectrum, 2024; IEEE Spectrum, 2024). The fibre-optic variants, while representing a minority of total FPV inventory (estimated at 5–15% by late 2024), provided an effectively unjammable capability at ranges of up to 20 kilometres and a corresponding qualitative shift in the EW-interaction equilibrium (IEEE Spectrum, 2024; Watling & Reynolds, 2024).

The target-class-versatility findings demonstrate effectiveness across the full spectrum of battlefield targets. A senior NATO official was quoted in 2024 to the effect that FPV drones costing less than USD 1,000 had destroyed approximately two-thirds of the Russian main-battle-tank losses of the preceding period, a statement corroborated by the Oryx open-source-intelligence loss-tracking project and by the RUSI 'Tactical Developments' analysis (Oryx, 2024;

Watling & Reynolds, 2024; CSIS, 2024). Against light armoured vehicles, FPV drones became the primary anti-armour asset of the Ukrainian armed forces during the 2023 artillery-ammunition shortage, with the CNAS 'Evolution Not Revolution' study estimating that FPV strikes accounted for approximately 40–60% of light-armour kills during the Avdiivka phase (Pettyjohn, 2024). Against dismounted infantry in defensive positions, the platform class demonstrated particular effectiveness at the squad-and-individual-soldier level, with the Bakhmut phase documented in open-source video evidence as the first systematic use of FPV platforms against infantry targets on a large scale (CSIS, 2024).

The production-scaling findings document a growth trajectory that the pre-war literature on defence-industrial production did not anticipate. Ukrainian FPV production grew from approximately 1,200 units in calendar year 2022 to approximately 415,000 units in calendar year 2023 and to approximately 1.7 million units in calendar year 2024, representing a compound annual growth rate in excess of 3,000% over the two-year window (Kyiv Independent, 2024; Ukrainian Ministry of Defence, 2024; Pettyjohn, 2024). By the end of 2024, approximately 96% of the Ukrainian armed forces' drone procurement was sourced from domestic Ukrainian suppliers, with production distributed across more than 80 independent manufacturers compared with only seven drone manufacturers in pre-war Ukraine (Kyiv Independent, 2024; CSIS, 2024). The structural implications of this scaling trajectory for force-structure planning and defence-industrial policy are examined in the third analytical section.

The battle-management-system-integration findings document a qualitative shift in the kill-chain architecture between the first and second case studies. During the Bakhmut phase, FPV strike cycles operated largely outside the Delta and Kropyvka battle-management-system architecture, with

target handover from ISR to strike assets occurring through informal radio communications, smartphone messaging, and voice-direction from officers (Watling & Reynolds, 2023; Danczuk, 2024). By the Avdiivka phase, partial integration of FPV strike cycles into Kropyvka had reduced the median ISR-to-strike latency from approximately 15–30 minutes to approximately 5–10 minutes, and by the Kupiansk–Kharkiv phase of 2024 full integration with Delta and the Vezha video-analysis platform reduced median latency to the 2–5-minute operating band, with specific high-priority targets engaged in under two minutes under favourable conditions (JHU-APL, 2024; CEPA, 2024; CSIS, 2024). The Vezha platform by late 2024 was reported to be classifying over 4,000 reconnaissance objects daily across Ukrainian tactical UAV feeds, indicating the scale at which automated target identification had begun to supplement human kill-chain processing (Defense Express, 2024).

The UFPEI composite scores across the three case studies confirm the trajectory inference. Bakhmut (October 2022 – May 2023) receives a composite UFPEI of 5.3 on the 0–10 scale, with dimension scores of 5.0 (target-class versatility), 7.5 (cost-to-kill ratio), 4.5 (EW resilience), 3.5 (kill-chain latency), 4.0 (operator-training efficiency), and 7.0 (production footprint). Avdiivka (October 2023 – February 2024) receives a composite UFPEI of 6.9, with dimension scores of 7.0, 8.5, 6.0, 6.0, 6.5, and 7.5 respectively. Kupiansk–Kharkiv (2024) receives a composite UFPEI of 8.1, with dimension scores of 8.5, 9.0, 7.5, 8.5, 7.5, and 7.5 respectively. The progression of composite scores from 5.3 through 6.9 to 8.1 indicates a 53% improvement in measured effectiveness over the 24-month window, driven primarily by kill-chain-latency and operator-training gains, with EW resilience and target-class versatility also contributing significantly. The cost-to-kill dimension was already near-saturation at the Bakhmut baseline and therefore contributes proportionally less to

the composite-score improvement, although the absolute cost-to-effect ratio continued to improve through the entire period.

The content analysis of the 46 open-source operational reports produced findings that corroborate the UFPEI scoring and provide additional contextual detail. Seventy-four per cent of the reports identified the 250-gram platform class as the operationally dominant FPV variant, with the remaining 26% describing larger platforms of the 500-gram to 3-kilogram class intended for heavier payloads. Sixty-three per cent of the reports provided cost estimates falling within the USD 300–500 range established

by triangulation, and a further 19% provided cost estimates within the USD 500–800 range corresponding to specialised or fibre-optic-tethered variants. Eighty-nine per cent of the reports identified electronic warfare as the principal operational constraint on FPV effectiveness, and 72% identified kill-chain integration as the principal determinant of between-unit variation in measured effectiveness (Watling & Reynolds, 2024; Kunertova, 2024; CSIS, 2024; CEPA, 2024). These content-analysis findings provide independent corroboration of the UFPEI dimensional structure.

Dimension	Bakhmut (Oct 2022 – May 2023)	Avdiivka (Oct 2023 – Feb 2024)	Kupiansk–Kharkiv (2024)	Δ Bakhmut → Kupiansk
Target-class versatility	5.0	7.0	8.5	+3.5
Cost-to-kill ratio	7.5	8.5	9.0	+1.5
Electronic-warfare resilience	4.5	6.0	7.5	+3.0
Urban kill-chain latency	3.5	6.0	8.5	+5.0
Operator-training efficiency	4.0	6.5	7.5	+3.5
Logistical-production footprint	7.0	7.5	7.5	+0.5
<b>COMPOSITE UFPEI</b>	<b>5.3</b>	<b>6.9</b>	<b>8.1</b>	<b>+2.8</b>
<i>Mean hit-rate (%)</i>	<i>28</i>	<i>33</i>	<i>40</i>	<i>+12</i>
<i>Median kill-chain latency (min)</i>	<i>20</i>	<i>7</i>	<i>3</i>	<i>-17</i>

Table 2. UFPEI dimension and composite scores across three Ukrainian urban-combat case studies, 2022–2024.

Target class	Target value (USD)	FPV unit cost (USD)	Effective platforms per kill	Cost-to-value ratio
Soft-skinned logistical vehicle	20,000–50,000	350–400	2–3	1:50 – 1:80
Towed / SP artillery	500,000–3,000,000	350–400	2–4	1:600 – 1:2,100
Light armoured vehicle (BMP/BTR)	800,000–1,500,000	350–400	3–5	1:500 – 1:1,400
Main battle tank (T-72/T-80/T-90)	3,000,000–4,500,000	350–400	3–5	1:1,800 – 1:4,000
Pantsir-S1 air-defence system	13,000,000–20,000,000	350–400	4–8	1:5,000 – 1:50,000

Table 3. Cost-to-target-value ratios for 250-gram-class FPV engagements by target class, 2024.

### *The cost-to-effect asymmetry and the structural transformation of precision-fires economics*

The first analytical axis concerns the cost-to-effect asymmetry documented in the empirical record and its implications for the broader economics of precision-strike capability. The Ukrainian operational experience establishes a regime in which precision fires against high-value armoured targets are delivered at a unit cost that is structurally different from the precision-munitions economy that preceded the 2022 war. Prior to the war, the canonical precision-strike munitions employed by NATO and NATO-partner forces included the Javelin anti-tank missile (unit cost approximately USD 240,000 per round), the Hellfire AGM-114 (approximately USD 150,000 per round), and the Brimstone (approximately USD 175,000 per round) — all of them substantially cheaper than the targets they were designed to destroy, but all of them priced at an order-of-magnitude higher than the 250-gram FPV platform that has now been demonstrated to be capable of delivering comparable effect against similar target classes under the specific conditions of the Ukrainian battlefield (Plichta & Rossiter, 2024; Pettyjohn, 2024; Fried, 2025).

The magnitude of the cost asymmetry is not a marginal shift but a structural one. The ratio of target-to-munition cost for the Javelin system against a T-72B3 is approximately 12:1; for the Brimstone against the same target, approximately 17:1; for the 250-gram FPV platform against the same target, approximately 7,500:1 after adjustment for the hit-rate-compensating platform expenditure (Pettyjohn, 2024; CSIS, 2024). This two-order-of-magnitude improvement in the cost-to-target-value ratio does not, on its own, constitute a revolution in military affairs, but it does constitute a structural transformation of the marginal economics of precision fires at the tactical level, which in turn has implications for force-structure planning,

procurement policy, and doctrinal design that extend well beyond the specific Ukrainian context (Plichta & Rossiter, 2024; Kunertova, 2024; Calcara et al., 2022). The debate initiated by Calcara et al. (2022) on the structural limits of the drone revolution is partially sustained by the Ukrainian evidence — the FPV platform has not displaced the hider-finder competition, nor has it eliminated the role of conventional fires — but the specific argument that the cost-to-effect ratio of tactical drones would remain structurally bounded by the physics of the hider-finder equilibrium requires revision in light of the 1:2,500 and 1:50,000 ratios documented above.

A distinctive feature of the cost-to-effect transformation is its asymmetric incidence across different components of the target portfolio. Against the highest-value targets — main battle tanks, Pantsir-S1 air-defence systems, self-propelled artillery — the cost asymmetry is extreme and potentially decisive at the operational level, producing engagement economics in which even low hit-rates and high platform-expenditure rates yield positive cost-effect balances (Plichta & Rossiter, 2024; Oryx, 2024; Watling & Reynolds, 2024). Against mid-value targets — light armoured vehicles, logistical trucks, artillery pieces — the asymmetry is substantial but less extreme, and the cost-effect balance remains positive across the range of operational conditions observed (CSIS, 2024; Pettyjohn, 2024). Against low-value targets — individual infantry, soft-skinned civilian-pattern vehicles — the cost asymmetry narrows, and the operational rationale for FPV deployment shifts from cost-effectiveness to capability considerations such as precision, reach, and the substitution of FPV fires for scarce artillery ammunition (Pettyjohn, 2024; Danczuk, 2024).

The second implication of the cost-to-effect asymmetry concerns its interaction with production economics. A precision munition whose unit cost is measured in hundreds of dollars rather than hundreds of

thousands enables production at a scale and rate that is not accessible to conventional precision-munition lines, as evidenced by the growth of Ukrainian FPV production from approximately 1,200 units in 2022 to 1.7 million in 2024 (Kyiv Independent, 2024; Ukrainian Ministry of Defence, 2024). This scaling was achieved without the construction of new state-owned production facilities and without the long-lead-time capital investment that conventional munitions require, relying instead on the repurposing of commercial drone components, distributed small-scale assembly, and volunteer-and-civil-society supply chains (Pettyjohn, 2024; CSIS, 2024; Kunertova, 2024). The production-economics implication is that the cost-to-effect asymmetry at the unit level is compounded by an equivalent asymmetry at the system level, producing a total cost-of-capability that is qualitatively different from that of conventional precision-munition systems (Plichta & Rossiter, 2024; Chávez & Swed, 2023).

The third implication concerns the force-structure design question of whether the FPV cost-to-effect regime supports a substitution or a complementation logic vis-à-vis conventional fires. The Bakhmut and Avdiivka case studies provide evidence on both sides of this question. The Avdiivka phase, in particular, demonstrated the substitution capacity of FPV fires under conditions of acute artillery-ammunition shortage, with the platform class becoming the primary indirect-fire asset of Ukrainian defensive operations during the late 2023 – early 2024 period (Danczuk, 2024; Watling & Reynolds, 2024; Watling & Reynolds, 2024). However, the subsequent Kupiansk–Kharkiv phase demonstrated that restored conventional-fires availability did not displace FPV operations but rather enabled a complementation architecture in which FPV, artillery, and larger OWA drones combined to produce a layered precision-fires regime across multiple range bands (CSIS, 2024; Watling & Reynolds, 2024; CEPA, 2024). The

empirical conclusion is that the cost-to-effect asymmetry supports a complementation rather than a substitution logic under normal operational conditions but retains a substitution capacity under degraded-fires conditions, a dual-role capability that strengthens the strategic value of the platform class beyond what a single-logic interpretation would capture.

A fourth implication concerns the ethical and legal consequences of the cost-to-effect transformation. When the marginal cost of a precision-strike engagement falls from hundreds of thousands of dollars to hundreds of dollars, the economic disincentives against marginal-utility engagements correspondingly weaken, producing a potential shift in the pattern of force application toward higher-volume, lower-threshold operations (Mutschler et al., 2024; Plichta & Rossiter, 2024). The evidence from the Ukrainian experience suggests that this shift is partially observable in the use of FPV platforms for individual-infantry engagements that would not have been rational targets for the previous generation of precision munitions, although the full-scale character of the conflict and the associated intensity of the threat-environment makes it difficult to isolate the cost-driven component of the shift from the context-driven component (Kunertova, 2024; Danczuk, 2024). These implications are elaborated in the non-state-actor-proliferation literature (Chávez & Swed, 2023; Mutschler et al., 2024; Combating Terrorism Center, 2023) but their empirical validation in state-on-state conflict remains an open research question.

The fifth implication concerns the temporal and adaptive dimensions of the cost-to-effect regime. The observed compression of unit costs from approximately USD 400 in 2023 to approximately USD 350 by late 2024, combined with the scaling of production volumes from 415,000 to 1.7 million units over the same period, produces a learning-curve trajectory consistent with the classical Wright-curve industrial-learning

pattern observed in other mass-produced technological artefacts (Pettyjohn, 2024; CSIS, 2024). The absence of evidence for cost-scaling saturation within the 2022–2024 window suggests that the mature cost-effectiveness regime of the 250-gram FPV platform class has not yet been reached, and that further unit-cost compression and production-rate acceleration are probable in the near-term future (Kunertova, 2024; Kunertova, 2024). The strategic implication is that any force-structure analysis based on the 2024 snapshot of cost and production figures will underestimate the medium-term competitive pressure that the platform class exerts on conventional precision-fires acquisition.

### **ELECTRONIC-WARFARE ADAPTATION AND THE IDENTIFICATION OF A SECOND-GENERATION FPV REGIME**

The second analytical axis concerns the interaction between FPV platform effectiveness and the electronic-warfare environment of the Russo-Ukrainian battlefield, and the related emergence of what the present study identifies as a second-generation FPV-doctrinal regime during the 2023–2024 period. The theoretical baseline for this analysis is the hider-finder-competition framework developed by Calcara et al. (2022), which predicts that the proliferation of inexpensive sensing and strike platforms will produce an iterative hider-side countermeasure response whose effect is to maintain an equilibrium rather than to establish a decisive advantage for either side. The Ukrainian empirical record supports the theoretical prediction of iterative adaptation but modifies the equilibrium-maintenance implication in important respects, which the following analysis elaborates.

The electronic-warfare interaction during the 2022–2024 window can be decomposed into a sequence of adaptation cycles. The first cycle (early 2022 – mid-2023) saw the

initial deployment of commercial-off-the-shelf FPV platforms operating on the widely-available 5.8 GHz frequency band, producing substantial early effectiveness gains that were progressively degraded by the scaling of Russian Shipovnik-Aero, Silok, and Pole-21 jamming systems across the front line (Watling & Reynolds, 2023; Kunertova, 2023b; IEEE Spectrum, 2024). The second cycle (mid-2023 – mid-2024) saw the Ukrainian migration from 5.8 GHz to 1.2 GHz as the dominant FPV-operating band, combined with the adoption of encrypted video protocols (HDZero, Walksnail) that increased resistance to analogue-signal jamming, and the introduction of higher-power video transmitters (up to 5 watts) that extended operational range and penetration of electromagnetic-interference environments (IEEE Spectrum, 2024; IEEE Spectrum, 2024). The third cycle (early 2024 – end-2024) saw the introduction of fibre-optic-tethered platforms as an unjammable minority-share variant and the emergence of autonomous terminal-guidance modules employing machine-learning-based target recognition that reduced platform dependence on the real-time radio-frequency control link (IEEE Spectrum, 2024; CSIS, 2024; IEEE Spectrum, 2024).

The adaptation-cycle structure produced a quantitatively documentable fluctuation in FPV effectiveness. During the jamming-intensive 2023 phase, the Watling and Reynolds (2024) RUSI analysis estimated that approximately 31% of sorties were lost to electronic warfare, with an additional 20–30% lost to non-EW failure modes including battery depletion, navigation error, operator error, and terminal-guidance failure. By late 2024, the Ukrainian counter-adaptation recovered successful-sortie-completion rates to the 45–55% band, with the adaptation principally attributable to frequency migration, protocol encryption, and the partial deployment of fibre-optic-tethered variants (IEEE Spectrum, 2024; IEEE Spectrum, 2024; CSIS, 2024). The net result over the

24-month window was an adaptation cycle operating on a calendar-month rather than calendar-year periodicity, with each cycle producing a partial recovery of pre-adaptation effectiveness levels but never a full restoration to the pre-countermeasure baseline (Kunertova, 2024; Watling & Reynolds, 2024).

The continuous adaptation pattern produced a structural consequence that the hider-finder-equilibrium framework predicts but does not fully capture: the increasing technological complexity of the platform class over the adaptation cycle. The 250-gram FPV platform that dominated the 2024 operational environment was not the same platform that dominated the 2022 operational environment, even though both shared the same mass class, operator-interface architecture, and basic tactical role. The 2024 platform incorporated encrypted video protocols, variable-frequency-band operation, fibre-optic tethering options, and autonomous terminal-guidance modules that collectively represented a substantial increment in technological sophistication over the early-war baseline (Watling & Reynolds, 2024; CSIS, 2024; IEEE Spectrum, 2024). This technological evolution, while maintained within the 250-gram mass class for operational and logistical reasons, produced a *de facto* platform-generation transition that the literature has not yet adequately theorised.

The second-generation FPV regime as identified in the present study is distinguished from the first-generation regime along six operational axes that correspond to the six UFPEI dimensions. In the target-class-versatility dimension, the second-generation regime extends effective engagement capacity across the full target portfolio, including main battle tanks and heavily-protected air-defence systems, where the first-generation regime was primarily limited to lighter vehicles and infantry. In the cost-to-kill-ratio dimension, the second-generation regime maintains the cost asymmetry while

substantially improving hit rates, producing a compound improvement in effective cost-per-kill. In the EW-resilience dimension, the second-generation regime incorporates the adaptations described above that were largely absent in the first-generation platforms. In the kill-chain-latency dimension, the second-generation regime operates within the 2–5-minute band enabled by Delta/Kropyva integration. In the operator-training-efficiency dimension, the second-generation regime benefits from standardised training pipelines, while the first-generation regime relied on volunteer self-training. In the logistical-production-footprint dimension, the second-generation regime has achieved the 1.7-million-unit annual production scale, while the first-generation regime operated at a 1,200-unit annual baseline (Pettyjohn, 2024; Watling & Reynolds, 2024; Kunertova, 2024; CSIS, 2024; CEPA, 2024).

The emergence of the second-generation regime across the three case studies is empirically captured in the UFPEI composite-score progression from 5.3 at Bakhmut through 6.9 at Avdiivka to 8.1 at Kupiansk–Kharkiv. The trajectory is not linear but concave, with the largest single-case improvement occurring between the first and second case studies, and a smaller incremental improvement occurring between the second and third. This concavity suggests that the transition between the two regimes was largely completed during the 2023 phase, with the 2024 phase representing the maturation of an already-established regime rather than the inauguration of a new one (Watling & Reynolds, 2024; CEPA, 2024; Kunertova, 2024). A third-generation regime based on autonomous terminal guidance and swarm-coordination capabilities is emerging at the margin of the 2024 operational record but is not yet dominant within the observed window; its characterisation lies outside the scope of the present study and is treated as a direction for future

research (CSIS, 2024; Plichta & Rossiter, 2024; Combating Terrorism Center, 2023).

The second-generation-regime concept has implications beyond the Ukrainian case. If the platform generation transition identified here represents a structural phase rather than a context-specific Ukrainian phenomenon, then it provides a template for analogous transitions in other operational contexts where tactical-drone warfare is now emerging — including the Israeli-Hamas conflict in Gaza, the Myanmar civil war, and the Sahel-region conflicts where non-state armed groups are adopting commercial-drone techniques (Mutschler et al., 2024; Chávez & Swed, 2023; Combating Terrorism Center, 2023). The empirical verification of the generational-transition concept across multiple operational contexts is a natural extension of the present research agenda and is discussed in the Conclusion as a direction for future work. The present study's contribution to this broader research programme is the articulation of the generational-transition concept itself and the provision of a quantitative framework (the UFPEI) within which the transition can be measured and compared across contexts.

A final consideration in this analytical axis concerns the inherent limits of the second-generation regime. The RUSI 'Tactical Developments' analysis (Watling & Reynolds, 2024) and the War on the Rocks soldier-testimony analysis (Watling & Reynolds, 2024) both emphasise that the 250-gram FPV platform class, even in its mature second-generation form, retains structural limitations that the triumphalist interpretations of the Ukrainian experience have sometimes obscured. These limitations include the weather dependence of the platform (performance degrades substantially in high wind, precipitation, and fog conditions), the short operational endurance (typically 10–20 minutes at combat payloads), the operator-fatigue constraints that limit sortie-rates per pilot to approximately 6–10 per combat shift, the payload limitations that

constrain effectiveness against heavily-protected targets such as modern main battle tanks with explosive-reactive armour, and the inherent vulnerability of the human-operator element to counter-battery and counter-ISR fires (Watling & Reynolds, 2024; Kunertova, 2024; Watling & Reynolds, 2024; Danczuk, 2024). These limitations do not invalidate the second-generation-regime concept but establish the boundary conditions within which it operates and the specific friction points at which the third-generation autonomous regime is expected to emerge.

### **KILL-CHAIN INTEGRATION, DELTA-KROPYVA, AND THE DOCTRINAL ARCHITECTURE OF SECOND-GENERATION FPV WARFARE**

The third analytical axis examines the doctrinal architecture within which the second-generation FPV regime operates, with particular attention to the integration of FPV strike cycles into the Delta and Kropyva battle-management systems and the consequent transformation of the kill-chain from an ad-hoc improvised structure into a formalised operational architecture. The analysis proceeds in four stages: the characterisation of the pre-integration first-generation kill-chain, the documentation of the integration process during 2023–2024, the identification of the operational effects produced by integration, and the articulation of the resulting doctrinal-architectural framework that the present study identifies as the mature second-generation regime.

The first-generation kill-chain as observed during the 2022 phase and the early Bakhmut phase operated through an essentially improvised architecture in which ISR assets (primarily Mavic reconnaissance quadcopters and similar commercial platforms), strike assets (early-generation FPV platforms operated by volunteer-pilot teams), and command-and-control elements

(infantry-regiment and battalion headquarters) were connected through informal radio communications, smartphone messaging applications (primarily Signal and Telegram), and voice-direction from mid-ranking officers (Watling & Reynolds, 2023; Danczuk, 2024; JHU-APL, 2024). The resulting architecture produced median ISR-to-strike latencies in the 15–30-minute range under favourable conditions and substantially longer latencies when unit-level coordination required reference to higher-echelon command elements (Danczuk, 2024; Danczuk, 2024; Watling & Reynolds, 2024). The first-generation kill-chain therefore delivered the cost-to-effect asymmetry documented in the previous analytical section but did so at a tempo that was inadequate against moving targets or highly mobile target classes, producing a structural ceiling on first-generation effectiveness against precisely those target categories that the platform was most valuable against.

The integration of FPV strike cycles into the Delta and Kropyva battle-management systems during the 2023–2024 period represented the operational response to this first-generation-regime ceiling. Delta is a situational-awareness and common-operating-picture platform developed by the Ukrainian Ministry of Defence's Innovation Centre that integrates ISR, fires, and movement data into a unified interface accessible to command elements at multiple echelons (JHU-APL, 2024; JHU-APL, 2024; CSIS, 2024). Kropyva is a tactical battle-management system originally developed for artillery fire-control that has been extended to integrate UAS operations, and by 2024 had reportedly become the most widely deployed Ukrainian battlefield-management platform with a user base numbering in the hundreds of thousands (CEPA, 2024; JHU-APL, 2024). The two systems complement rather than duplicate each other, with Delta providing the strategic-and-operational layer and Kropyva providing the tactical-and-unit layer, and by 2024 the Ukrainian Ministry of

Defence had demonstrated integration of both systems with NATO interoperability frameworks through the TIDE Sprint and CWIX exercises (CEPA, 2024; Defense Express, 2024).

The integration produced a measurable transformation in kill-chain-latency performance. The Avdiivka phase saw partial integration of FPV strike cycles into Kropyva, reducing median ISR-to-strike latency from the first-generation 15–30-minute baseline to approximately 5–10 minutes for well-integrated units (Danczuk, 2024; CEPA, 2024; Watling & Reynolds, 2024). The Kupiansk–Kharkiv phase of 2024 saw full integration of FPV strike cycles into both Delta and Kropyva, further reducing median latency to the 2–5-minute operating band with specific high-priority targets engaged in under two minutes under favourable conditions (JHU-APL, 2024; CSIS, 2024; CEPA, 2024). The Vezha video-analysis platform, which by late 2024 was reported to be processing feeds from hundreds of UAVs and classifying over 4,000 reconnaissance objects daily, represented a further evolution in which automated target identification began to supplement human kill-chain processing and to reduce the latency contribution of the target-identification and target-handover phases of the kill chain (Defense Express, 2024; CSIS, 2024).

The operational effects of the kill-chain-integration transformation are observable at three distinct levels of analysis. At the tactical level, the reduction of median latency from 15–30 minutes to 2–5 minutes shifts the effective target set from stationary or slowly-moving targets to the full spectrum of battlefield targets including manoeuvring mechanised formations, reducing the adversary's capacity to exploit temporal gaps in the kill-chain through mobility. At the operational level, the reduction enables the sustained implementation of the 10–15-kilometre defensive no-go-zone concept articulated in the Ukrainian 'Drone Line' doctrine and maintained across continuous frontline

sectors rather than only at specific engagement points (Ukrainian Ministry of Defence, 2024; Militarnyi, 2024; CEPA, 2024). At the strategic level, the combination of tactical-level latency reduction and operational-level area-denial sustainment enables the substitution of a distributed precision-fires regime for the concentrated conventional-fires regime that the Ukrainian armed forces could not sustain under the artillery-ammunition shortages of 2023–2024 (Danczuk, 2024; Plichta & Rossiter, 2024; CSIS, 2024).

The doctrinal-architectural framework that emerges from the integration process is characterised by five distinctive features that together define the mature second-generation FPV regime. The first feature is the formalisation of the tactical-UAS unit as an independent combat element organised at the company or battalion level, rather than as a subordinate component of an infantry or artillery formation; the establishment of the separate Unmanned Systems Forces branch within the Ukrainian armed forces in June 2024 institutionalised this arrangement at the service-branch level (Ukrainian Ministry of Defence, 2024; Kyiv Independent, 2024; Kunertova, 2024). The second feature is the integration of ISR, strike, and electronic-warfare functions within the tactical-UAS unit, producing a self-contained kill-chain capacity at the battalion level that does not require external echelon coordination for routine engagements (JHU-APL, 2024; Watling & Reynolds, 2024; CEPA, 2024). The third feature is the standardisation of operator-training pipelines through specialised training centres, replacing the volunteer-self-training pattern of the first-generation regime with a formalised qualification architecture (Kunertova, 2024; CSIS, 2024; Kunertova, 2024).

The fourth feature is the integration of the distributed commercial-production ecosystem with the tactical-use-case feedback loop, enabling rapid iteration of platform designs in response to operational lessons and electronic-warfare countermeasures. The

observed calendar-month adaptation cycle during the 2023–2024 window — frequency migration from 5.8 GHz to 1.2 GHz, protocol-encryption adoption, fibre-optic-tethering introduction — was possible only because the production ecosystem and the user-operator community were connected through tight feedback loops that the traditional defence-industrial base does not support (Pettyjohn, 2024; CSIS, 2024; Plichta & Rossiter, 2024; Kunertova, 2024). The fifth feature is the emerging integration of the Ukrainian second-generation FPV architecture with NATO interoperability frameworks and allied operational concepts, which by late 2024 had produced export inquiries for the Delta platform itself and had established the Ukrainian doctrinal architecture as a reference point for NATO-wide tactical-UAS doctrinal development (CEPA, 2024; JHU-APL, 2024; CEPA, 2024; Fried, 2025).

The five-feature doctrinal-architectural framework characterising the second-generation regime has implications that extend beyond the specific Ukrainian operational context. The framework represents a template for the integration of commercial-drone capabilities into a professional-military kill-chain architecture, and as such provides a reference point for NATO and NATO-partner militaries seeking to adapt their force structures in response to the demonstrated effectiveness of the platform class (Plichta & Rossiter, 2024; Pettyjohn, 2024; Fried, 2025). The framework also provides a template, in inverted and adversarial form, for the proliferation of FPV-drone tactics to non-state armed groups including terrorist organisations, and the Combating Terrorism Center at West Point has already documented the beginning of this proliferation in Syrian, Iraqi, and Sahel contexts (Combating Terrorism Center, 2023; Chávez & Swed, 2023; Mutschler et al., 2024). The dual-use character of the doctrinal-architectural framework — its applicability to both conventional-military and non-state-actor

contexts — represents one of the more important secondary findings of the present study and is discussed further in the Conclusion.

A final consideration in this analytical axis concerns the interaction between the second-generation regime and the emerging third-generation autonomous regime. The trajectory from first- through second- to third-generation FPV warfare, as captured in the present study's analytical framework, is not a simple linear progression but a concave curve with diminishing marginal returns along the human-operator axis and increasing marginal returns along the autonomous-system axis (CSIS, 2024; Plichta & Rossiter, 2024; JHU-APL, 2024). The 2024 operational record contains early evidence of the third-generation transition: AI-guided FPV variants with reported hit rates of 80% against stationary targets under benign EW conditions, autonomous-terminal-guidance modules that operate for the final 500–1,000 metres of flight without human-operator input, and swarm-coordination experiments that connect multiple FPV platforms into coordinated engagement complexes (CSIS, 2024; CSIS, 2024; Plichta & Rossiter, 2024). The full characterisation of the third-generation regime is beyond the scope of the present study, but its emergence at the margin of the 2024 operational record establishes the temporal boundary within which the second-generation findings of the present study should be interpreted.

## CONCLUSION

This study has examined the operational effectiveness of 250-gram-class First-Person View drones as a precision munition system in urban combat, drawing on a structured synthesis of operational data from the Ukrainian battlefield during the February 2022 – December 2024 window. The study constructed and applied a novel six-dimensional composite metric — the Urban FPV Precision Effectiveness Index — and

calibrated the metric through three sequential case studies (Bakhmut, Avdiivka, Kupiansk–Kharkiv) and a structured content analysis of 46 open-source operational reports. The findings support the three research hypotheses to varying degrees of confirmation, as elaborated below.

The first hypothesis, which held that 250-gram-class FPV drones deliver a disproportionate cost-to-effect ratio against armoured and semi-armoured targets falling in a band between one and four orders of magnitude below the monetary value of the target destroyed, is strongly confirmed by the empirical record. The documented cost-to-target-value ratios across the target portfolio range from approximately 1:80 against soft-skinned vehicles through 1:2,500 against main battle tanks to 1:50,000 against the most valuable individual targets such as Pantsir-S1 air-defence systems. These ratios represent a two-to-three-order-of-magnitude improvement over the cost-to-target-value ratios achievable with conventional precision-munition systems of the Javelin, Hellfire and Brimstone classes, establishing the 250-gram FPV platform as a structurally asymmetric precision weapon in the sense specified by the hypothesis (Plichta & Rossiter, 2024; Pettyjohn, 2024; Chávez & Swed, 2023). The confirmation is robust across the three case studies and across the full range of target classes documented in the operational record.

The second hypothesis, which held that FPV effectiveness in urban terrain varies non-linearly with three intervening variables — electronic-warfare density, operator experience, and target-class composition — producing the observed 20–50% hit-rate band whose position within the band is determined by the interaction of these three variables, is also confirmed by the empirical record, albeit with partial specification of the non-linearity. The observed 20–50% hit-rate band, with case-specific means of 28% (Bakhmut), 33% (Avdiivka) and 40% (Kupiansk–Kharkiv), corresponds to the variation

predicted by the hypothesis and is principally driven by the reduction of electronic-warfare effectiveness (through counter-adaptation), the increase of operator experience (through professionalisation and standardised training), and the evolution of target-class composition (through the shift from armoured-vehicle targets at Bakhmut toward a broader portfolio at Kupiansk–Kharkiv). The non-linearity of the interaction is empirically confirmed, but the specific functional form of the interaction — which would require larger-sample quantitative analysis to identify precisely — remains a direction for future research.

The third hypothesis, which held that the integration of FPV drones into a mature ISR-to-strike kill chain anchored on Delta and Kropyva, combined with the professionalisation of tactical UAS units, produced a qualitatively distinct second-generation FPV-doctrinal regime, is confirmed by the empirical record and by the UFPEI composite-score progression from 5.3 at Bakhmut through 6.9 at Avdiivka to 8.1 at Kupiansk–Kharkiv. The five-feature doctrinal-architectural framework articulated in the third analytical section — tactical-UAS-unit formalisation, integrated ISR-strike-EW capacity at battalion level, standardised operator-training pipelines, commercial-production-ecosystem-with-user-feedback integration, and NATO-interoperability integration — constitutes a qualitatively distinct doctrinal regime that was not observable in the first-generation phase and that provides the architectural substrate for the observed effectiveness improvements. The confirmation is robust across the case studies, though the relative contributions of the five features to the overall regime-level effect require further empirical decomposition that is beyond the scope of the present study.

The principal original contribution of this article is threefold. First, the study proposes and operationalises the Urban FPV Precision Effectiveness Index as a novel composite metric integrating six operational

dimensions into a single effectiveness score that permits systematic comparison across case studies and time-points. The UFPEI is designed to be adaptable to operational contexts outside the specific Ukrainian case and to be extensible through additional sub-indicators as the evidence base matures. Second, the study provides the first systematic comparative calibration of FPV urban effectiveness across three sequentially fought and operationally distinct urban battles, allowing the identification of the concave-trajectory pattern of effectiveness improvement and the associated decomposition of regime-level gains into dimension-level contributions. Third, the study articulates the concept of a second-generation FPV-doctrinal regime and specifies its five architectural features, providing a conceptual framework within which the observed Ukrainian operational record can be located and from which comparative extensions to other operational contexts can be developed.

The study has three explicit methodological limitations that constrain the interpretation of its findings. The first is the partial and contested character of the open-source operational data on an ongoing armed conflict, which necessarily produces confidence intervals around the quantitative estimates wider than those achievable under peacetime-measurement conditions. The triangulation strategy employed in the study mitigates but does not eliminate this limitation, and the specific quantitative estimates should therefore be interpreted as reliable-order-of-magnitude values rather than as precise point estimates. The second limitation is the absence of direct access to classified Ukrainian or allied-government operational-assessment documentation, which means that the UFPEI estimates rely on the subset of operational data that has been released or leaked into the open-source record; this selection effect may produce systematic biases in directions that are difficult to quantify *ex ante*. The third limitation is the rapid pace of technological and doctrinal

change during the 2022–2024 window, which produces a degree of temporal aggregation within each case-study period that compresses genuine intra-period variation into a single point estimate.

Three directions for future research emerge from the study. The first is the empirical extension of the UFPEI framework to non-Ukrainian operational contexts, including the Israel-Hamas conflict in Gaza, the Myanmar civil war, the Sahel-region conflicts, and any future large-scale state-on-state conflict involving tactical-drone warfare. Such extension would allow verification or refutation of the generational-transition concept articulated in the present study and would provide comparative context for the Ukrainian findings. The second direction is the larger-sample quantitative analysis of the three-intervening-variable interaction identified in hypothesis H2, which would require access to disaggregated hit-rate data at the sortie-level or mission-level rather than the case-study-aggregate level employed in the present study; such analysis could identify the specific functional form of the non-linear interaction and produce predictive models of FPV effectiveness under alternative operational conditions. The third direction is the systematic characterisation of the emerging third-generation autonomous FPV regime and its relationship to the second-generation regime, which would require dedicated research on the autonomous-terminal-guidance modules, swarm-coordination experiments, and AI-assisted-target-identification systems that are beginning to supplement human-operator-based FPV warfare at the margin of the 2024 operational record.

The study's findings have implications for military doctrine, force-structure planning, and arms-control policy that extend beyond the strictly academic interest of the Ukrainian case. For NATO and NATO-partner military planners, the findings support the conclusion that the 250-gram FPV platform class represents a structural rather

than a transient shift in the economics of tactical precision fires, and that force-structure adaptations to integrate the platform class into existing doctrinal architectures are both operationally warranted and economically feasible. For the smaller NATO states and for non-aligned states with limited defence budgets, the findings support the conclusion that the platform class offers a qualitatively distinct opportunity for the development of asymmetric deterrent and defensive capabilities at costs compatible with constrained budgetary environments. For the arms-control and international-humanitarian-law community, the findings establish the platform class as a reality on the modern battlefield that requires dedicated normative and regulatory attention, including through the potential extension of existing conventions on indiscriminate-effects weapons, the establishment of export-control protocols for dual-use components, and the development of counter-drone frameworks compatible with international-humanitarian-law principles (Mutschler et al., 2024; Plichta & Rossiter, 2024; Combating Terrorism Center, 2023).

The Ukrainian experience of 2022–2024 demonstrates that a precision munition system can be constructed at micro-platform scale from commercial-off-the-shelf components, scaled to production volumes in the millions of units per year, integrated into a professional-military kill-chain architecture, and employed effectively across the full spectrum of urban-combat target classes. The UFPEI composite-score progression from 5.3 through 6.9 to 8.1 across the three case studies captures the trajectory of this transformation in a single quantitative measure, and the five-feature doctrinal-architectural framework identified in the study specifies the organisational conditions under which the transformation has been achieved. The present study has sought to document, measure, and conceptualise this transformation within the limits of open-source evidence and within the recognition that the

empirical record is still emerging. The continuation of this research programme — through the extension of the UFPEI framework to additional operational contexts, the refinement of the quantitative estimates through larger-sample analyses, and the

systematic characterisation of the emerging third-generation regime — will be necessary to convert the present study's preliminary findings into a mature theoretical framework for the analysis of tactical-drone warfare in the post-Ukrainian era.

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# EFIKASNOST FPV DRONOVA KLASSE 250g KAO PRECIZNOG MUNICIJSKOG SUSTAVA U URBANOJ BORBI: ANALIZA OPERATIVNIH PODATAKA IZ UKRAJINSKOG RATIŠTA 2022–2024

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**Sažetak:** Članak analizira operativnu efikasnost FPV (First-Person View) dronova klase 250 grama kao preciznog municijskog sustava u urbanoj i poluurbanjoj borbi tokom Rusko-ukrajinskog rata, oslanjajući se na strukturiranu sintezu operativnih podataka objavljenih između februara 2022. i decembra 2024. godine. Studija predlaže i primjenjuje novi šestodimenzionalni kompozitni indeks — Urban FPV Precision Effectiveness Index (UFPEI) — koji kvantificira performanse duž šest operativnih osovina: višenamjenskost prema klasama ciljeva, omjer troška po uništenom cilju, otpornost na elektronsko ratovanje, latentnost urbanog lanca ciljanja, efikasnost obuke operatera i logističko-proizvodni otisak. Empirijska kalibracija provodi se kroz tri studije slučaja: odbrana Bahmuta (oktobar 2022. – maj 2023.), odbrana Avdijivke (oktobar 2023. – februar 2024.) i operacije na osi Kupjansk–Harkiv (2024.). Nalazi pokazuju da su platforme klase 250 grama s komercijalnim komponentama postigle stopu pogodaka u rasponu od 20 do 50% prema pokretnim ili djelomično zaklonjenim ciljevima, s omjerom troška prema vrijednosti cilja u rasponu od 1:80 do 1:50.000 ovisno o klasi cilja, i doprinijele dokumentiranom udjelu od 60–70% potvrđenih gubitaka ruskih oklopnih vozila tokom faze Avdijivke. Integracija FPV ciklusa napada u sisteme za upravljanje borbom Delta i Kropiva smanjila je latentnost urbanog lanca ciljanja s ranoratih 15–30 minuta na 2–5 minuta do kraja 2024. godine, dok rast ukrajinske FPV proizvodnje s približno 1.200 jedinica u 2022. na 1.7 miliona u 2024. pokazuje da je održivo skaliranje preciznog municijskog sustava na mikroplatformi moguće izvan tradicionalne odbrambeno-industrijske baze. Originalni doprinos studije je trostruki: predlaganje UFPEI kompozitnog mjerila, prva sistematska komparativna kalibracija urbane FPV efikasnosti kroz tri velike bitke za gradove, i artikulacija drugoeneracijskog FPV doktrinarnog režima karakteriziranog integracijom sistema za upravljanje borbom, profesionalizacijom taktičkih jedinica i održivom proizvodnjom u masovnoj razmjeri.

**Ključne riječi:** *FPV dronovi, precizna municija, urbana borba, Rusko-ukrajinski rat, elektronsko ratovanje, troškovna efikasnost, doktrina dronova.*