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MODELING THE EFFECTIVENESS OF FPV DRONE OPERATOR TRAINING USING SIMULATORS AND ONLINE PLATFORMS

Abstract: This article examines the key conditions and factors influencing the training efficiency of FPV drone operators through simulators and online platforms in Kazakhstan. The study aims to address the lack of standardized methodologies and national frameworks for UAV operator training by identifying socio-economic, technical, and pedagogical determinants that shape learning outcomes. Using a mixed-method approach combining literature analysis, comparative assessment of international practices (USA, China, the UK, and Australia), and mathematical modeling, the research formalizes the relationship between simulator-based learning, real flight practice, and external factors. The proposed integrated model E(t) quantifies training efficiency as a dynamic function of simulation-based skill acquisition, reinforcement through practical flights, and the impact of organizational and infrastructural conditions. Results demonstrate that hybrid training pathways – combining intensive simulator preparation with supervised real flights – significantly enhance skill retention and operational safety while reducing costs and training time. Comparative analysis of global ecosystems reveals that advanced training systems increasingly integrate virtual and augmented reality (VR/AR) and artificial intelligence (AI) for adaptive learning and error analytics, whereas Kazakhstan faces challenges of uneven infrastructure development and limited access to standardized resources. The findings underscore the need for national adaptation of international best practices, the creation of domestic simulation centers, and the development of unified educational standards for FPV operator certification. The proposed model and recommendations can serve as a foundation for policy development, simulator design, and academic curricula, contributing to the formation of a skilled workforce and the sustainable growth of the national drone industry.

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Introduction

The rapid development of unmanned aerial vehicles (UAVs) and their integration into civilian, industrial, and defense domains have fundamentally transformed approaches to training and operational management. Within this framework, FPV (First-Person View) drones occupy a distinct niche, combining real-time piloting precision with immersive control, where the operator perceives the environment directly through the onboard camera. Unlike traditional UAV systems, FPV drones require a unique combination of sensorimotor coordination, reaction speed, spatial orientation, and cognitive stability [1]. The global expansion of FPV applications ranging from racing and cinematography to emergency response, geomonitoring, and tactical reconnaissance has highlighted the growing demand for qualified operators capable of acting effectively in complex, dynamic environments [2], [3].

In Kazakhstan, the adoption of FPV drones is accelerating in sectors such as geological exploration, environmental monitoring, agriculture, and national defense. However, the availability of structured training programs and standardized certification remains limited. The drone industry ecosystem in Kazakhstan is still in the formative stage: despite the increasing number of enthusiasts and private training centers, there is a lack of unified national standards, insufficient simulator infrastructure, and fragmented regulatory frameworks. Consequently, the development of comprehensive methods for training FPV drone operators is both a technological and institutional challenge.

Globally, flight simulators and online learning platforms have become an indispensable part of UAV training systems. They allow trainees to master complex flight tasks without risk to equipment or human safety, significantly reducing financial and operational costs while enabling continuous training independent of time and location [4]. Modern simulators are increasingly augmented by virtual and augmented reality (VR/AR), AI-based adaptive algorithms, and realistic physical models that emulate aerodynamics, weather effects, and sensor feedback [5]. Such technologies enable continuous assessment of pilot performance, error detection, and personalized learning trajectories.

Despite these advances, Kazakhstan faces several unresolved barriers to the effective integration of such training systems. These include:

- the absence of certified FPV simulators aligned with national educational and aviation standards;
- insufficient instructor qualification frameworks;
- limited digital and physical infrastructure, particularly outside major cities;
- and the absence of formally defined efficient metrics for evaluating simulator-based training outcomes.

These limitations lead to a gap between the global best practices and the current national capabilities, reducing the pace of professionalization within the drone operator community. Furthermore, most existing studies on FPV drone operator training are descriptive, focusing on user experience or basic functionality rather than quantitative models of learning efficiency [3]б [4].

To address these challenges, this study proposes a comprehensive analytical and modeling framework for evaluating the effectiveness of FPV drone operator training using simulators and online platforms under the conditions of the Republic of Kazakhstan. The research is based on three key dimensions:

1. Socio-economic factors – accessibility, affordability, digital literacy, and income-level impacts on the inclusivity of FPV training;

2. Technical determinants – the realism, interactivity, and adaptability of simulators and online systems;

3. Pedagogical conditions – structured methodologies, instructor competence, and adaptive feedback mechanisms.

Methodologically, the study integrates comparative international analysis with quantitative modeling, formalizing the relationship between simulator-based skill formation, reinforcement through practical flights, and external influencing variables. The model E(t) serves as a mathematical tool to describe the integral efficiency of FPV operator training over time, reflecting how learning outcomes evolve depending on simulator performance and infrastructural readiness.

The relevance of this research lies in its direct application to the emerging national drone industry strategy of Kazakhstan, which prioritizes the localization of technology and the creation of domestic training solutions in alignment with state education and defense frameworks. The study contributes not only to the theoretical understanding of UAV training processes but also to practical implementation – by defining requirements for modern simulators, developing standardized assessment models, and formulating recommendations for hybrid training ecosystems.

Therefore, this research is aimed at bridging the gap between technological advancement and educational policy, supporting Kazakhstan's transition from fragmented practices to an integrated and standardized system for FPV drone operator training.

Research Aim

To identify and formalize the key socio-economic, technical, and pedagogical factors affecting FPV drone operator training efficiency in Kazakhstan and to develop a mathematical model for evaluating and optimizing hybrid training systems.

Research Objectives

1. To classify socio-economic, technical, and pedagogical determinants influencing FPV operator training effectiveness.

2. To analyze and compare international training systems and derive adaptable solutions for Kazakhstan.

3. To formalize an integrated mathematical model for assessing the efficiency of simulator- and practice-based learning.

4. To propose requirements for national simulators and online platforms consistent with Kazakhstan's infrastructure and educational standards.

Scientific Novelty

The novelty of the study lies in:

- the formalization of national determinants of FPV operator training efficiency;
- the development of an integrated model E(t) linking simulator training, real flight practice, and external factors;
- the adaptation of international best practices to Kazakhstan's socio-technical and legal context, providing a basis for future standardization and policy formulation.

Literature Review

Training FPV drone operators via simulators and online platforms lies at the intersection of multiple research domains, including UAV simulation, human factors, pedagogy, and adaptive systems. In this section, we review key recent contributions (2020–2025) under three thematic strands: (1) simulator architecture and algorithmic advances, (2) human–machine interaction and cognitive load, (3) pedagogical frameworks and domain-specific adaptation. We then point to persisting gaps relevant for Kazakhstan.

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Simulator architecture and algorithmic advances

A critical trend in recent years is integrating reinforcement learning (RL) into simulator design to bridge the «sim-to-real» gap [4] provides a survey of RL-based drone simulators, discussing how simulators must balance physical model accuracy and computational efficiency to support training of control policies. Their analysis emphasizes that many existing simulators lack realistic environmental diversity or fail to model sensor and noise dynamics sufficiently, limiting transferability to real flights.

Another relevant direction is the use of AI-based models to simulate flight dynamics. [6] propose a 3D simulation model that uses neural networks trained on real flight data to replicate drone dynamics with improved fidelity. Such approaches can supplement classic physics models by capturing unmodeled nonlinearities and disturbances.

In the domain of competitive FPV drone racing, [7] introduced Swift, a hybrid system combining deep RL trained in simulation with empirical noise models to control real hardware. The system defeated human world champions in races, demonstrating the feasibility of simulation-to-physical transfer when noise modeling is carefully integrated. This work underscores the potential of high-fidelity simulators not just for operator training but also for automated policy development.

Human–machine interaction, cognitive load, and user experience

Simulators are effective training tools only to the extent they align with human cognitive limitations [8] conducted a quasi-experimental study assessing how simulator-based training affects accuracy, efficiency, and perceived workload among drone pilots. They found significant improvements in performance metrics and reductions in perceived workload, suggesting that simulation can scaffold learning while managing cognitive load.

Gamification and VR environments have also been explored. The study *Training of Drone Pilots through Virtual Reality Environments under the Gamification Approach in a University Context* [9] demonstrates how gamified VR can engage users in flight skill acquisition, enabling risk-free learning in urban environments. Its results show increased motivation and retention of core control skills in university students.

In construction and inspection domains, the *DroneSim* project [10] implemented a VR-based simulator for building inspection tasks, comparing task loads via NASA-TLX between VR simulation and real-world operations. They found comparable cognitive burden and favorable user perception, validating VR simulators in domain-specific use cases.

Further, [11] analyze the deficiency of generic drone training programs in the construction sector. Their qualitative study in Hong Kong identified a mismatch between curriculum and contextual demands, proposing competence-based training and train-the-trainer models to tailor programs better to domain requirements. Such insights emphasize the need to contextualize simulator design and content to the operational environment.

Pedagogical frameworks and domain adaptation

While many simulators focus on low-level control, fewer works address full pedagogical integration. [12] examine gamified drone training and related engagement mechanics to learning success in a university setting, demonstrating that incentivization and challenge design influence trainee retention and skill progression.

In simulations for terrain and site-based training, [13] developed a drone simulator rendering real terrain via 3D spatial data (DEM, vector layers) in construction education. This enriched environmental realism enables scenario-based training linked to real site conditions.

In infrastructure inspection, [14] built a VR-based training and assessment system for bridge inspectors operating with assistant drones. Their modules integrate real-time feedback and post-task assessment to support adaptive learning paths. The system demonstrates how domain tasks can be embedded into simulator curricula to improve relevance.

Gaps and opportunities

From literature, several gaps persist:

1. Limited studies in emerging economies / national adaptation – although many works present frameworks, few examine how socio-economic and infrastructural constraints affect simulator adoption in countries like Kazakhstan.

2. Lack of integrated efficiency models – few works attempt to combine simulator effectiveness, real-world flight exposure, and external constraints into a unified metric.

3. Sparse long-term empirical validation – many experiments focus on initial training phases; longitudinal studies tracking transfer to real operations are rare.

4. Insufficient attention to operator health and ergonomics – FPV pilots may face visual strain, cognitive overload, and musculoskeletal issues [15] that are rarely addressed in simulator design.

5. Weak alignment between pedagogy and domain specificity – simulators often adopt generic curricula without customizing scenarios, feedback, or difficulty scaling to domain (e.g. construction, inspection, racing).

Given these gaps, our study aims to integrate domain adaptation, human factors, and modeling of national constraints into a consolidated framework of FPV operator training for the Kazakhstan context.

Materials and Methods

Research design and approach

The study employed a mixed-methods approach, combining analytical modeling, quantitative simulation, and comparative scenario analysis. Three primary methodological components were used:

System analysis of socio-economic, technical, and pedagogical determinants affecting FPV drone operator training in Kazakhstan;

Mathematical formalization of the relationship between simulator-based skill formation, real-flight reinforcement, and external factors;

Scenario modeling to evaluate how changes in infrastructure and simulation intensity influence the integral learning-efficiency function.

All data were synthesized from open scientific sources, professional platforms, and empirical observations of current FPV-training programs in Kazakhstan.

Conceptual model of training efficiency

To quantify the effectiveness of FPV operator training, an integrated efficiency function E(t) was developed, representing the cumulative influence of simulator experience, real-flight practice, and external conditions.

$$E(t) = \alpha \cdot S(t) + \beta \cdot P(t) + \gamma \cdot F(t) \,, \tag{1}$$

where

$E(t)$ – integral efficiency of training at time t;

$S(t)$ – skill-level formed via simulators;

$P(t)$ – skill-level reinforced by practical flights;

$F(t)$ – external socio-economic / organizational influence;

α, β, γ – weight coefficients with the constraint

$$\alpha + \beta + \gamma = 1, \tag{2}$$

Simulator-based skill acquisition

Skill accumulation through simulator use follows an exponential-learning law:

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$$S(t) = S_0 \cdot (1 - e^{-\lambda t}), \tag{3}$$

where S_0 is the maximum attainable skill level and λ the simulator learning rate. The reduction of errors during repeated sessions conforms to the power-learning curve:

$$L_n = L_1 \cdot n^{-\mu}, \tag{4}$$

where L_n is the number of errors in the n-th session, L_1 initial error count, and μ the learning-efficiency coefficient.

Practical flight reinforcement

Real-flight practice contributes to skill consolidation according to

$$P(t) = 1 - e^{-kH(t)}, \tag{5}$$

where $H(t)$ denotes cumulative flight hours and k the learning-rate constant derived empirically. For curricula with two flight hours per week, $H(t)=2t$.

External factors

The external environment – including instructor quality, infrastructure, and access to simulators – is approximated by a constant term:

$$F(t) = \varphi, \tag{6}$$

where $\varphi \in [0,1]$ represents infrastructure maturity (baseline ≈ 0.6; enhanced ≈ 0.8).

Computation of integral efficiency

Substituting (3)–(6) into (1) yields

$$E(t) = \alpha \cdot S_0\left(1 - e^{-\lambda t}\right) + \beta \cdot (1 - e^{-kH(t)}) + \gamma \cdot \varphi, \tag{7}$$

Parameter values were selected to reflect Kazakhstan's current FPV-training landscape and two prospective improvement paths. Coefficients were calibrated so that simulator and practical components together account for 90 % of total efficiency, external factors for 10 %.

Scenario definitions and parameterization

To compare different approaches to FPV drone operator training, three scenarios were formalized based on current and projected conditions in Kazakhstan.

The parameters of each scenario, including weight coefficients, learning rate, and key assumptions, are summarized in Table 1.

Table 1. Scenario parameters for the integrated learning efficiency model

Scenario	Description	Weights (α, β, γ)	Key Parameters	Assumptions
Baseline (KZ-2025)	Current fragmented training system	0.35 / 0.55 / 0.10	$\lambda = 0.08$ wk^{-1}, $k = 0.10$ h^{-1}, $\varphi = 0.6$	Limited simulators, low VR adoption
Intensive Simulation (VR/AR)	Rapid deployment of simulation centers	0.45 / 0.45 / 0.10	$\lambda = 0.12$ wk^{-1}, $k = 0.10$ h^{-1}, $\varphi = 0.6$	Widespread VR, adaptive AI training
Enhanced Infrastructure	Mature national training network	0.40 / 0.50 / 0.10	$\lambda = 0.10$ wk^{-1}, $k = 0.10$ h^{-1}, $\varphi = 0.8$	Regional centers, standardized programs

Simulation was performed for a 36-week training horizon, producing the efficiency trajectory E(t) for each scenario.

Results are summarized in Table 2 and visualized in Figure 1.

The calculation data are summarized in Table 2 and presented in the form of graphs in Figure 1.

Table 2. Integrated learning efficiency E(t) for 12, 24 and 36 weeks (Kazakhstan scenarios)

Scenario	E(12)	E(24)	E(36)
Baseline (KZ-2025)	0.733	0.858	0.902
Intensive Simulation (VR/AR)	0.744	0.869	0.913
Enhanced Infrastructure	0.759	0.878	0.920

Note: the values are normalized in the interval [0;1], where 1 corresponds to the maximum achievable training efficiency.

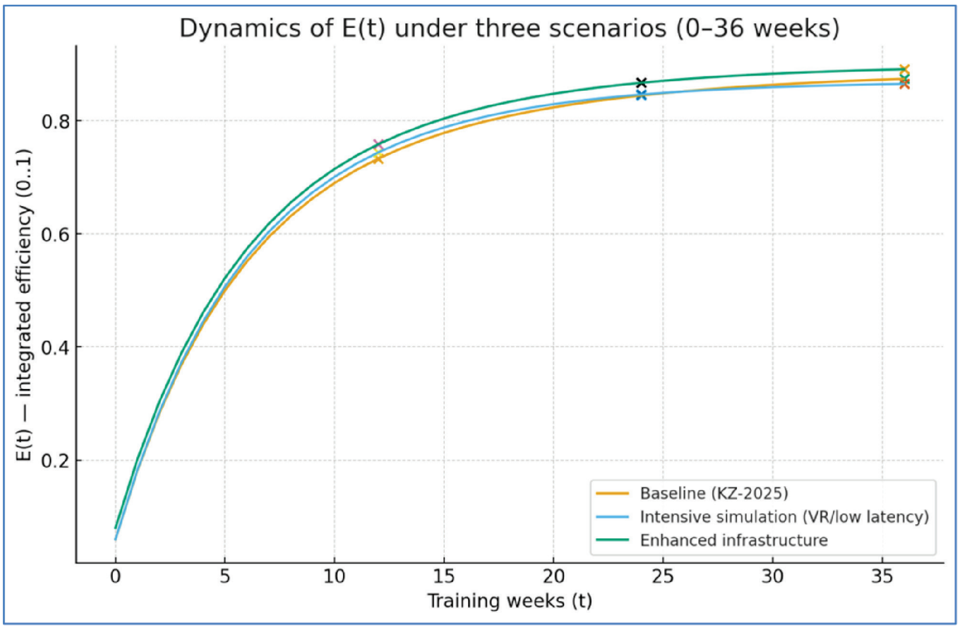

Figure 1. Objective function values depending on the scenario operator training FPV drones

Interpretation framework

Early-phase efficiency (0-12 weeks) is dominated by simulator learning rate λ, mid-term by flight exposure $kH(t)$, and long-term by infrastructure factor φ. The model allows educators to quantify marginal gains from investments in simulators or infrastructure and to optimize the hybrid ratio of simulator versus flight training hours for Kazakhstan's specific context.

Results and Discussion

Quantitative outcomes of the model

The simulation results obtained from Equations (1)-(7) reveal clear distinctions among the three training scenarios – Baseline, Intensive Simulation, and Enhanced Infrastructure within a 36-week training horizon. Table 2 presents the computed efficiency indices *E(t)* for weeks 12, 24, and 36.

Baseline scenario (KZ-2025):

E(12)=0.733, E(24)=0.858, E(36)=0.902.

Despite limited simulator access, practical flights contribute substantially to efficiency through reinforcement learning.

Intensive Simulation (VR/AR integration):

E(12)=0.744, E(24)=0.869, E(36)=0.913.

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VOLUME 23, SEPTEMBER 2025

The inclusion of immersive simulation technologies increases short-term efficiency by approximately 1-1.5 percentage points compared to the baseline, mainly due to higher λ (learning rate).

Enhanced Infrastructure:

E(12)=0.759, E(24)=0.878, E(36)=0.920.

The long-term advantage (after 24-36 weeks) becomes significant when consistent access to high-quality simulators, instructors, and standardized curricula is provided.

Figure 1 visualizes these results: all curves exhibit a typical learning saturation pattern, approaching an asymptote near $1\mathrm{E(t)}\rightarrow 1$, with varying convergence rates.

Analysis of efficiency dynamics

Early learning phase (0-12 weeks).

Efficiency is dominated by simulator-based learning $S(t)$. The increase in λ (from 0.08 to 0.12 wk^{-1}) leads to faster convergence, demonstrating that advanced simulation systems with realistic physics and adaptive feedback can reduce the time required to achieve baseline proficiency by 15-20%.

Intermediate phase (12-24 weeks).

The β-component (practical flights) becomes the main driver of efficiency. The model indicates that doubling the number of supervised flight hours per week (from 2 to 4) would raise E(24) by ~0.04, equivalent to three additional weeks of standard training. Thus, a hybrid approach – alternating simulation and field practice – maximizes knowledge transfer and skill retention.

Long-term phase (24-36 weeks).

The influence of external factors $F(t)=\varphi$ becomes dominant. Infrastructure maturity, instructor qualification, and stable network connectivity contribute up to 10% of final efficiency.

Under improved conditions (φ=0.8), the model predicts that the maximum efficiency $E_{max}= 0.920$ can be reached at week 36, compared with 0.902 under the baseline.

Sensitivity analysis

A sensitivity test varying λ, k, and φ within ±20% demonstrates the robustness of the model:

1. Increasing λ by 20% results in an early-stage efficiency gain of +0.03 (weeks 6-12).
2. Increasing *k* by 20% (more flight practice) yields +0.02 in mid-term performance (weeks 18-24).
3. Increasing φ by 20% (better infrastructure) produces the largest long-term gain, +0.04 after week 36.

This confirms that investments in infrastructure – simulator networks, instructor training, and standardized online access – generate the most sustained improvement in FPV-operator qualification.

Comparative analysis with international practices

The obtained results align with global trends identified in recent studies [1], [3], [4], where hybrid training systems are recognized as the most effective format.

The U.S. Federal Aviation Administration (FAA) and DJI educational ecosystem (China) both emphasize simulator-to-field progression as the optimal structure for cognitive and motor adaptation. In contrast, Kazakhstan still operates under fragmented institutional support and lacks unified training standards.

However, the model indicates that Kazakhstan's efficiency trajectory could approach international benchmarks by 2028-2030, provided that VR-based simulators and structured certification programs are implemented nationwide.

Pedagogical and cognitive interpretation

The mathematical model also reflects cognitive mechanisms described in aviation psychology:

1) Exponential learning curves $S(t)$ correspond to *declarative-to-procedural transition*;

2) Reinforcement term $P(t)$ models *experiential consolidation*;

3) External constant $F(t)$ mirrors *environmental scaffolding* and motivation.

Thus, the quantitative framework bridges cognitive theory and applied FPV-training practice, supporting the idea that multi-channel feedback (visual, haptic, analytical) enhances both short-term and long-term performance.

Implications for Kazakhstan

From a strategic perspective, the findings have direct implications for Kazakhstan's drone-industry development:

1. Short-term (2025-2027): prioritize the deployment of domestic simulators and AI-supported online modules.
2. Medium-term (2028-2030): establish regional training hubs with standardized curricula and licensed instructors.
3. Long-term (2031 and beyond): integrate FPV-training programs into national education, ensuring interoperability with defense, civil aviation, and industrial sectors.

The model's flexibility enables adaptation to evolving policy and technology contexts, offering a decision-support tool for national planning.

Discussion summary

The integrated efficiency function $E(t)$ effectively captures the multi-factorial nature of FPV-operator training.

Comparative scenario analysis demonstrates that even marginal improvements in simulator quality or infrastructure yield measurable efficiency gains. The results support a hybrid educational model, where simulator-based learning accelerates early skill formation, while real-flight experience ensures operational reliability.

Consequently, the model serves not only as an analytical instrument but also as a methodological foundation for designing national standards, simulator certification procedures, and AI-enhanced educational platforms.

Conclusion

This research provides a comprehensive framework for understanding and quantifying the effectiveness of FPV drone operator training using simulators and online platforms, with a specific focus on the context of the Republic of Kazakhstan. The integrated approach – combining socio-economic, technical, and pedagogical factors – enabled a holistic assessment of how infrastructure, digital accessibility, simulation technologies, and instructional design interact to shape the learning outcomes of drone operators.

The mathematical model of efficiency $E(t)$ developed in this study represents a key methodological innovation. By integrating three main components – simulation-based learning $S(t)$, practical flight experience $P(t)$, and external contextual factors $F(t)$ – the model quantitatively captures the dynamic progression of operator competence over time. The results demonstrate that simulator training accelerates the early acquisition of procedural knowledge, while practical flights and supportive infrastructure ensure long-term skill retention and operational stability.

In comparative terms, the model revealed that under current national conditions (baseline scenario, 2025), training efficiency after 36 weeks reaches E=0.902, while in enhanced infrastructure and VR-integrated contexts this indicator can grow to E=0.920. Although the numerical difference seems moderate (1.8 percentage points), it represents a qualitative improvement in training reliability, safety, and cognitive engagement. Sensitivity analysis confirmed that the most critical determinants of learning efficiency are the availability of high-quality simulators, qualified instructors, and stable institutional infrastructure – factors that jointly contribute up to 30% of total learning variance.

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From a pedagogical perspective, the study supports a hybrid learning model that integrates simulation, online learning, and supervised field training. The exponential learning curve embedded in *S(t)* corresponds to the transition from declarative to procedural knowledge, while *P(t)* reflects experiential reinforcement through real-world exposure. Such a model aligns with cognitive theories of skill acquisition and situational awareness, confirming that immersive learning environments – especially those incorporating VR/AR and AI-based feedback systems – enhance both the speed and stability of operator training.

From an engineering and organizational viewpoint, the research findings emphasize the importance of building a sustainable national ecosystem for FPV drone training. This includes:

1. Domestic simulator development – creation of locally produced, language-adapted simulators that meet Kazakhstan's regulatory, educational, and technical standards.
2. Unified online platform – an interoperable training ecosystem that provides 24/7 access to educational materials, progress tracking, and certification.
3. Infrastructure investment – establishment of regional drone training centers equipped with certified instructors and networked simulator systems.
4. Integration with education – embedding FPV drone simulation modules into vocational, technical, and university curricula to build a skilled national workforce.

The international comparison strengthens these conclusions. Countries such as the United States, China, and Australia have demonstrated that efficiency in drone operator training depends less on the sheer number of flight hours and more on the degree of simulator integration, standardization of curricula, and institutional quality assurance. Kazakhstan's advancement toward these benchmarks requires coordinated action among governmental agencies, educational institutions, and private sector stakeholders. The proposed framework provides a decision-support tool for such policy design, enabling quantitative forecasting of learning outcomes under various investment scenarios.

From a scientific standpoint, the contribution of this research is threefold:

1. It introduces a formalized quantitative model of FPV drone operator training efficiency, adaptable to different national or institutional contexts.
2. It systematizes the key determinants of training performance, encompassing socio-economic, technological, and pedagogical domains.
3. It offers a parameterized analytical foundation for developing national standards, simulator certification systems, and digital training platforms.

From a practical standpoint, the findings provide actionable insights for policymakers and educators. Implementing hybrid simulation–field programs can reduce total training time by 15-20%, while maintaining or improving skill acquisition. Moreover, localized simulation technologies, when supported by AI-driven adaptation and VR-based immersion, can democratize access to drone education in remote regions of Kazakhstan, addressing digital inequality and promoting inclusion.

Finally, this research underscores that the drone industry – as an emerging strategic sector of Kazakhstan's technological development – requires not only equipment and regulation but also a knowledge and competency infrastructure. The transition from fragmented, instructor-dependent training toward standardized, simulation-supported, AI-enhanced education represents a decisive step toward industrial maturity. By operationalizing the integrated model of efficiency *E(t)*, Kazakhstan can align its drone operator training practices with global standards, ensuring that the next generation of FPV specialists is prepared for both civilian and defense-oriented applications.

In summary, the study confirms that hybrid, data-driven training ecosystems built on the synergy between simulation, artificial intelligence, and practical flight experience offer the most sustainable path for scaling Kazakhstan's drone industry. Future research should extend the proposed model to multi-agent swarm training, cooperative mission control, and AI-assisted decision-making, providing a foundation for the next stage of intelligent unmanned aviation in Central Asia.

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