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Regulatory Pathways for Inclusive Human Systems in Aviation: Embedding Ethics and Emerging Technologies into Global Oversight

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ABSTRACT

Aviation oversight is evolving in response to emerging technologies such as Artificial Intelligence (AI), Advanced Air Mobility (AAM), and digital-twin ecosystems. These innovations enhance safety and efficiency but also challenge the inclusivity, transparency, and ethical legitimacy of global regulatory systems. This paper explores how international authorities, including the International Civil Aviation Organization (ICAO), the European Union Aviation Safety Agency (EASA), and the Federal Aviation Administration (FAA), can embed inclusivity and ethics within the design and implementation of oversight mechanisms. Using the ICAO ADDIE framework (Analysis, Design, Development, Implementation, Evaluation), the study proposes a conceptual model for integrating inclusivity indicators, cultural intelligence, and AI-driven analytics into certification, training, and surveillance processes. Case vignettes demonstrate how inclusive governance can improve trust, fairness, and adaptability in areas such as community engagement and algorithmic transparency. The findings indicate that inclusivity should evolve from an aspirational value to an auditable regulatory requirement, supported by measurable indicators and interoperable data standards. By aligning the principles of the EASA AI Roadmap 2.0 and the proposed AI Code of Ethics with adaptive oversight practices, regulators can enhance both safety and social legitimacy. Ultimately, sustainable innovation in aviation depends not only on technological advancement but also on regulatory ecosystems that recognize diversity, foster dialogue, and institutionalize ethical accountability.

Keywords: Inclusive oversight, EASA AI Roadmap 2.0, Ethics in aviation, Anticipatory regulation, Cultural intelligence, Digital twins

INTRODUCTION

Aviation oversight is now facing rapid change due to digitalization, AI, and advanced air mobility, promising safer, more efficient, and more sustainable operations but challenging regulatory legitimacy (Demir, Moslem, & Duleba, 2024; Fang, 2024). As automation integrates into flight and maintenance, regulators must ensure technologies align with human performance, ethics, and societal standards (Hollnagel, 2014; Leveson, 2012). The shift to AI

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decision-support and unmanned systems transforms oversight from reactive certification to proactive system stewardship, requiring not just technical checks but fairness, transparency, and inclusivity (EASA, 2023; ICAO, 2023).

Historically, safety regulation evolved through reactive learning from accidents, with ICAO's SMS framework promoting systemic oversight over punitive measures (Reason, 1997; Harris, 2016; ICAO, 2023). EASA's AI Roadmap 2.0 and FAA policies stress explainability, traceability, and human oversight, yet often overlook social and cognitive diversity, risking socially brittle systems (EASA, 2022).

The rise of automation highlights the need to embed ethics and inclusivity, as algorithms can reproduce bias, and simulations may favor data-rich operators over smaller ones (Demir et al., 2024; Wild et al., 2025). Without inclusive governance, trust erodes, inequalities grow, and legitimacy weakens. As urban and regional AAM expand, regulators must incorporate social diversity and ethics into safety and environmental metrics (Fang, 2024; Jafari Roodbandi, Choobineh, & Nami, 2025).

This paper stresses that inclusivity is crucial for oversight, integrating human diversity into design, implementation, and evaluation, and fostering adaptive learning beyond mere enforcement. It explores how regulators such as ICAO, EASA, and FAA can embed measurable inclusivity, ethical AI governance, and culturally aware evaluation into their frameworks using the ICAO ADDIE model. The study develops an anticipatory oversight framework that turns inclusivity from an ethical ideal into a measurable regulatory requirement, viewing global aviation as a socio-technical system that values diversity as a source of resilience and legitimacy in automation. The research extends human-centered design by incorporating cultural intelligence and ethical-AI oversight into practice, drawing on adaptive governance, Safety-II, and systems ergonomics to treat inclusivity as a property of resilience. It supports a harmonized international approach to AI regulation with shared standards, advancing inclusivity as an auditable concept to guide future frameworks. The work contributes by conceptualizing inclusive oversight supported by AI and digital tools, adapting the ADDIE methodology to develop inclusivity indicators, and demonstrating its practical application through policy case vignettes. These efforts promote a shift from reactive compliance to proactive, evidence-based governance. The paper outlines the theoretical basis, presents the adapted methodology, and illustrates it with case studies, ending with policy discussions and future research suggestions for measurably embedding inclusivity across regulators.

METHODOLOGY

This study uses a conceptual, design-oriented approach that extends the ICAO ADDIE framework from training systems to regulatory oversight (ICAO, 2023). The ADDIE cycle (Analysis, Design, Development, Implementation, Evaluation) helps systematically incorporate inclusivity, ethics, and technology into oversight. Instead of analyzing a single dataset, the study synthesizes regulatory publications, AI policies, and human-factors literature to create a replicable framework guiding regulators in designing inclusive, anticipatory oversight (EASA, 2023; Leveson, 2012; Hollnagel, 2014). Based on systems ergonomics and adaptive governance, it sees regulation as a socio-technical ecosystem where human diversity and machine intelligence co-evolve. Oversight must learn, adapt, and recalibrate across various contexts, cultures, and cognitive styles (Ang & Van Dyne, 2008; Demir, Moslem, & Duleba, 2024). The goal is to develop a learning framework that makes inclusivity an auditable, improvable part of safety management, rather than a static set of rules (Leveson, 2012; Harris, 2016).

Although this paper is conceptual in nature, its development is informed by an analysis of three major reference domains:

1. **Regulatory documents**: including ICAO *Annex 19* (*Safety Management*, 4th ed., 2023), the *European Union Aviation Safety Agency (EASA) Artificial Intelligence Roadmap 2.0*, and the *Federal Aviation Administration (FAA)* human-centered certification policies (ICAO, 2023; EASA, 2023).
2. **Academic and policy literature**: peer-reviewed works on AI ethics, safety management, and cultural intelligence (Ang & Van Dyne, 2008; Hollnagel, 2014; Leveson, 2012; Demir et al., 2024).
3. **Illustrative case vignettes**: hypothetical yet plausible regulatory scenarios developed to test conceptual validity, including examples of AAM corridor design and AI-dispatch bias (Fang, 2024; Ziakkas, Plioutsias, & Pechlivanis, 2022).

This triangulation ensures that the framework is theoretically grounded, aligned with regulatory priorities, and oriented toward practical application.

Framework Application: ADDIE in Regulatory Oversight

The adapted ADDIE cycle guides the integration of inclusivity and ethics into regulatory systems (ICAO, 2023). The Analysis phase identifies oversight failure modes through safety reports, audits, and enforcement, focusing on bias, participation, and cultural issues (Harris, 2016; Reason, 1997). It maps inclusivity gaps impacting safety and legitimacy, leading to measurable indicators and protocols, such as monitoring equity in training and reporting accessibility (Hollnagel, 2014), aligned with standards (EASA, 2023). The Development stage builds infrastructure, such as AI analytics, dashboards, and VR/AR environments, for scenario testing (Demir et al., 2024; Wild et al., 2025). Digital twins visualize the impacts of policies and social outcomes (Fang, 2024). Inclusivity tools are integrated into workflows, including automation reviews, language assessments, and cultural literacy modules, with audits to ensure equitable feedback (EASA, 2023; Ang & Van Dyne, 2008; Reason, 1997). The Evaluation phase monitors indicator changes and outcomes through dashboards that display quantitative and qualitative data, supported by annual reports for regulatory learning and accountability (Hollnagel, 2014; ICAO, 2023; Leveson, 2012).

Table 1: Inclusivity-linked failure modes and regulatory levers.

System Level	Failure Mode (Inclusivity Gap)	Observable Signals / Evidence	Affected Populations	Regulatory Lever
Global / ICAO	Fragmented inclusivity criteria and uneven adoption across regions	Divergent audit findings; inconsistent terminology; non-aligned test practices	Multinational crews; small and emerging operators	SARPs addenda; harmonized glossaries; joint inclusivity test catalogs
Regional / EASA	Opaque automation logic and hidden bias in AI tools	Explainability gaps; disparate outcomes between cohorts	Non-native speakers; low-time crews	AI Roadmap AMCs; bias-testing protocols; conformity documentation
National / FAA / NAAs	Erosion of Just Culture and inequitable enforcement	Under-reporting; inconsistent remedial action	Front-line personnel; small ATOs	Policy notices; remedial enforcement guidance; channel audits
Operator / SMS	Exclusionary training or communication practices	Low participation; uneven training results	Minority crews; contractors	SMS inclusivity indicators; training oversight findings; corrective action plans
Community / Public	Legitimacy gaps during AAM deployment	Fairness complaints; local resistance	Noise-exposed or mobility-limited groups	Equity impact assessments; consultation requirements; transparency reporting

ADDIE-Aligned Evaluation Framework

To operationalize the cycle, the study defines an evaluation matrix (Table 2) that maps inclusivity objectives to measurable outcomes. This draws on methods in safety management system evaluation (ICAO, 2023; Reason, 1997) and systems-theoretic assurance frameworks (Leveson, 2012) while incorporating principles from Safety-II and adaptive governance (Hollnagel, 2014). The matrix links inclusivity indicators to the five phases of the ADDIE model, connecting regulatory objectives to data sources such as safety-reporting databases, training audits, and AI explainability logs (EASA, 2023; Demir, Moslem, & Duleba, 2024). Combining quantitative metrics with feedback loops, the framework offers regulators a reference model for designing or auditing inclusive oversight systems that evolve through continuous learning (Ang & Van Dyne, 2008; Harris, 2016).

Table 2: ADDIE-aligned evaluation framework for decision-making in inclusive oversight.

ADDIE Phase	Regulatory Objective	Key Activities	Data Sources / Tools	Evaluation Metrics
Analysis	Identify inclusivity failure modes	Text mining of safety reports; qualitative coding of training audits	Safety databases, SMS records, stakeholder interviews	Frequency of inclusivity-linked findings; risk-weighted occurrence ratios
Design	Create measurable inclusivity indicators and protocols	Define observables; draft Acceptable Means of Compliance (AMCs)	ICAO and EASA guidance materials; focus group validation	Indicator reliability; inter-rater consistency
Development	Build digital and analytical infrastructure	Develop dashboards, digital twins, and VR training tools	Data visualization software; simulator environments	Usability scores; participation equity indices
Implementation	Embed inclusivity mechanisms in oversight	Integrate indicators into certification, licensing, and audit checklists	Certification records; training syllabi	Adoption rate; inspector training completion; audit traceability
Evaluation	Assess performance and sustain learning	Conduct trend analysis, peer review, and cross-agency comparison	Inclusivity dashboards; stakeholder feedback surveys	Improvement in inclusivity scores; stakeholder trust index; transparency cadence

Validation and Limitations

The framework was validated conceptually by comparing it with regulatory roadmaps such as EASA's AI Roadmap 2.0 and ICAO Annex 19, demonstrating internal coherence and face validity aligned with systems thinking and safety principles by Leveson and Reason. Empirical testing is needed to confirm scalability through pilot applications, such as digital-twin simulations and field trials within EASA or national authorities, to validate inclusivity indicators and their integration into certification and audit systems. Limitations include reliance on secondary data and a lack of statistical analysis; these can be addressed by future research using mixed-methods validation to combine quantitative and qualitative data. Despite constraints, the approach offers a robust conceptual scaffold for integrating inclusivity into aviation oversight, providing regulators with a stepwise, adaptable, and harmonizable process aligned with safety and performance goals. By adapting the ADDIE methodology to regulatory design, this study presents a structured, flexible process to transform inclusivity and ethics from principles into operational requirements, supporting anticipatory governance and laying a foundation for policy applications and case vignettes.

Analysis

The adapted ADDIE framework helps regulators operationalize inclusivity, ethics, and new technologies in aviation oversight. Using two simulation-based vignettes based on design-science and systems-ergonomics principles (Hollnagel, 2014; Leveson, 2012), the study shows how inclusivity indicators guide decision-making, influence regulatory levers, and boost public legitimacy, as seen in EASA's AI Roadmap 2.0 (2023) and ICAO Annex 19 (2023). These vignettes show how inclusive oversight turns regulation into a proactive, learning system aligned with Safety-II and adaptive governance (Reason, 1997; Ang & Van Dyne, 2008; Harris, 2016).

Case 1: Anticipatory Oversight in a Greek AAM Corridor

IGreece launches a pilot AAM corridor between Crete and Santorini to test sustainable air-taxi services for seasonal tourism. Initial delays due to concerns over noise, visual intrusion, and access were mitigated by the Hellenic Civil Aviation Authority (HCAA) and EASA through an inclusive oversight framework aligned with anticipatory governance principles. AI sentiment analysis of social media and feedback revealed three inclusivity issues: remote resident exclusion, digital access inequality, and unclear fare fairness. Regulators used participation indicators, such as trust surveys, and a digital twin to simulate routes and social data to assess societal impacts. Multilingual and hybrid participation methods improved accessibility. Ongoing evaluation with the twins' dashboard refined processes and increased public trust by 32%, reducing approval time by four months. Transparency through the twin fostered fairness and accountability, strengthening legitimacy. The inclusivity dashboard built trust among regulators across Europe, exemplifying AI-assisted governance's potential to shorten approval cycles, improve transparency, and identify social friction early.

Case 2: AI Dispatch Bias and Post-Certification Oversight

A European operator introduces an AI-assisted dispatch system trained on flight, weather, and scheduling data to optimize efficiency and reduce delays (Demir, Moslem, & Duleba, 2024; Fang, 2024). Post-market surveillance under EASA's AI Roadmap found an anomaly: the system issued more "go" recommendations for crews with fewer flight hours in marginal conditions, increasing operational risk (EASA, 2023; Zacharias, Schütte, & Schaefer, 2023). This reflected a data-driven bias in which historical correlations are misinterpreted as causal (Leveson, 2012; Hollnagel, 2014). It underscored the need for explainable AI (XAI) and ongoing monitoring to support safety and fairness (Zacharias et al., 2023; ICAO, 2023). The NAA, supported by EASA, used the ADDIE cycle to address this. Analysis revealed bias favoring low-hour crews on less-congested routes. Regulators and the operator developed bias-detection metrics reflecting fairness, with a retraining protocol supported by an XAI interface visualizing the model's reasoning. Inspectors practiced VR review and documentation of overrides. A dual-control process paired AI proposals with human rationales for traceability, leading to quarterly audits that improved fairness. Within six months, AI "go" recommendations balanced across experience levels, confirming bias mitigation. Transparency tools helped trace logic, and the override mechanism increased accountability. Audits resulted in fewer operator appeals and more reports of marginal conditions, boosting trust. The NAA incorporated these metrics into broader AI standards, influencing EASA's ethical AI guidelines. The case demonstrated that fairness, transparency, and continuous learning are measurable, auditable outcomes of inclusive regulation.

Cross-Case Insights

Both vignettes demonstrate that inclusive oversight enhances legitimacy and efficiency. The AAM corridor emphasizes early community involvement and transparent digital modeling to prevent conflicts. The AI-dispatch case highlights explainable oversight and inclusivity metrics that correct biases after certification (EASA, 2023; ICAO, 2023; Zacharias, Schütte, & Schaefer, 2023). Inclusivity indicators detect weak signals before safety or trust issues emerge (Leveson, 2012; Hollnagel, 2014). These are improved through periodic reporting, comparison, and interpretation, promoting transparency and cross-agency learning (Reason, 1997; Ang & Van Dyne, 2008). The trust index and bias-parity score support adaptive improvements (Harris, 2016; Hollnagel, 2014). Digital twin platforms offer ethical testing environments for regulators (Tao & Zhang, 2021; Plioutsias, Ziakkas, & Pechlivanis, 2023). Oversight shifts from compliance to iterative design, with inclusivity as a key metric (Leveson, 2012; Hollnagel, 2014). The ADDIE framework confirms this method (EASA, 2023; ICAO, 2023). Inclusivity signals vulnerabilities and complements safety indicators, fostering resilience aligned with Safety-II principles (Reason, 1997; Hollnagel, 2014). Transparency improves compliance, and fair data governance reduces underreporting (Ang & Van Dyne, 2008; Demir, Moslem, & Duleba, 2024). Regulators can embed inclusivity into auditable processes without sacrificing safety or efficiency (EASA, 2023; Leveson, 2012). Incorporating data ethics, community engagement, and human–machine collaboration within the ADDIE cycle enhances oversight, making it rigorous and socially legitimate, and encouraging proactive learning regulation (Harris, 2016; Plioutsias, Ziakkas, & Pechlivanis, 2023).

DISCUSSION

This study confirms future aviation oversight depends on balancing innovation with ethical inclusivity, integrating inclusivity into certification, surveillance, and safety through a framework linking ethical AI governance and cultural intelligence for transparent oversight. These findings are crucial for regulation, international harmonization, and transitioning to anticipatory oversight, especially as traditional models focus on post-incident investigations, which are less effective for complex AI risks. The new framework emphasizes real-time, anticipatory oversight using feedback from digital twins, AI analytics, and community platforms to improve assumptions and early detection, with inclusivity serving as a resilience indicator. Embedding ethics involves trade-offs like transparency versus data protection, which can delay certification; therefore, regulators need transparent frameworks like ADDIE to evaluate ethical goals. Measuring inclusivity is challenging; combining quantitative metrics with qualitative methods in a hybrid approach and emphasizing developmental indicators fosters trust. International standards are vital; differences hinder cross-border recognition, so ICAO could create a Joint Inclusivity Annex with shared indicators and data standards. Aligning agencies' policies, such as EASA's emphasis on explainability and the FAA's focus on usability, within ICAO's SARPs would improve coherence without reducing regional autonomy. Cross-agency collaboration and shared training can enhance interoperability and trust, despite operational and institutional barriers like capacity constraints and data governance challenges. Embedding inclusivity also requires cultural and procedural shifts supported by leadership, with long-term benefits including increased legitimacy, efficiency, and social license. Incorporating cultural intelligence (CQ) into oversight enhances understanding of biases and supports human–machine collaboration, fostering resilience and cross-cultural learning. An inclusive, anticipatory oversight model reflects modern ethics, shifting regulators from enforcers to facilitators of collective sense-making, emphasizing transparency, accountability, and trust-building across sectors. Overall, inclusivity is both an ethical obligation and a strategic necessity, and harmonized indicators across ICAO, EASA, and FAA will promote a proactive, resilient, and trusted aviation system embodying societal diversity.

CONCLUSION

The evolution of aviation oversight toward inclusivity and anticipatory governance signifies a cultural shift in global safety. As AI, AAM, and digital twin technologies increase complexity, traditional regulation is insufficient (EASA, 2023; Hollnagel, 2014; Leveson, 2012). Inclusivity must be measurable, auditable for oversight to stay legitimate and trusted (ICAO, 2023; Reason, 1997). An adapted ADDIE framework helps regulators embed inclusivity into certification, training, and surveillance, promoting continuous learning. By identifying failure modes, creating indicators, and institutionalizing dashboards, the system addresses ethical and cultural aspects (Hollnagel, 2014; Plioutsias, Ziakkas, & Pechlivanis, 2023). This approach shifts oversight from reactive to anticipatory, learning from human diversity, data, and context (Leveson, 2012; Ang & Van Dyne, 2008). Regulation is viewed as a socio-technical ecosystem where human, cultural, and technological factors co-evolve. Inclusivity acts as a stabilizing design load, increasing resilience against failures (Harris, 2016; Hollnagel, 2014). Digital tools such as AI analytics, VR/AR training, and digital twins help visualize social impacts before decisions are made (Tao & Zhang, 2021; Plioutsias et al., 2023) and embody anticipatory oversight through transparency, fairness, and learning (EASA, 2023; ICAO, 2023). Establishing a Joint Inclusivity Annex among ICAO, EASA, and FAA could harmonize standards, streamline compliance, and foster safety learning (ICAO, 2023; Leveson, 2012). Training should include cultural intelligence, ethical AI auditing, and inclusive communication. Inclusivity indicators, such as language accessibility and participation equity, should be added to safety metrics (Hollnagel, 2014; Reason, 1997). Economically, inclusive oversight reduces rework, litigation, and investigation costs by enabling fairer, more predictable systems. Better decision algorithms and documentation can shorten approval cycles and build trust, reinforcing aviation's social license (Zacharias, Schütte, & Schaefer, 2023; Plioutsias et al., 2023). Philosophically, accountability shifts from control to dialogue, gaining legitimacy through openness and collective learning. Participatory, evidence-based decisions blend technology with humanistic purpose, aligning with societal expectations for transparency and justice (Reason, 1997; Leveson, 2012). This enhances aviation's legitimacy in the digital age. Limitations include its conceptual nature and need for practical testing to assess scalability (EASA, 2023; ICAO, 2023). Future research should pilot the model in digital-twin or sandbox environments, combining metrics and stakeholder insights to improve predictability, ethics, and usability (Leveson, 2012; Hollnagel, 2014). Collaboration among academia, regulators, and industry is key. Making inclusivity a measurable oversight component helps global aviation become more adaptive and equitable, relying on systems designed to learn with and for the people they serve (Reason, 1997; Leveson, 2012).

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