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Analyzing Air Traffic Control Failures In Aviation Incidents And Accidents Through The HFACS Framework

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Abstract

Aviation safety depends heavily on precise interaction between pilots and Air Traffic Control (ATC), yet failures within that interaction remain a recurring contributing factor in civil aviation accidents and incidents. This study aims to identify and analyze patterns of ATC-related failure across a set of historically significant aviation accidents and incidents, and to derive implications for global aviation safety improvement. A qualitative literature review design was employed, drawing on official investigation reports, safety databases, and peer-reviewed journal articles concerning five representative events—Tenerife (1977), Zagreb (1976), Uberlingen (2002), Linate (2001), and Jakarta Halim (2016)—synthesized through directed content analysis guided by the Human Factors Analysis and Classification System (HFACS) and Reason's Swiss Cheese Model. The findings reveal that communication breakdowns, non-standard phraseology, controller work overload, limitations in surveillance technology, and weak inter-unit coordination constitute recurring causal patterns behind ATC-related accidents/incidents. The study concludes that enhancing aviation safety requires stricter phraseology standardization, strengthened Crew/Team Resource Management training for controllers, and sustained investment in surface radar and conflict-alert technologies.

Keywords: Air Traffic Control; Aviation Accident; Aviation Incident; Human Factors; Aviation Safety; Literature Review

INTRODUCTION

Civil aviation is among the safest modes of transportation when measured by the ratio of accidents per distance travelled; however, when an accident or incident does occur, its consequences are frequently catastrophic and involve substantial loss of life. One system component that plays a central role in maintaining that safety is Air Traffic Control (ATC), the service responsible for separating aircraft, providing navigational instructions, and ensuring the orderly flow of air traffic both on the ground and in the air. Although ATC is designed as one of the defense layers intended to prevent collisions and other unsafe occurrences, aviation history records a number of major accidents and incidents that originated from, or were exacerbated by, failures within the ATC system itself (Lyu, Song, & Du, 2019).

ATC-related failures can manifest in various forms, ranging from phraseology errors and radio miscommunication, excessive controller workload arising from traffic density, limitations in surface surveillance technology, to weak coordination between sectors or ATC units (Muecklich, Sikora, Paraskevas, & Padhra, 2023; Zhang, Chen, Liu, Ding, & Wu, 2021). The 2002 mid-air collision over Uberlingen, Germany, for instance, illustrates how a single controller managing two working positions simultaneously, combined with an ATC instruction that conflicted with a Traffic Collision Avoidance System (TCAS) resolution advisory, culminated in a fatal collision that killed 71 people. Similarly, the 2016 runway incursion incident at Halim Perdanakusuma Airport, Jakarta, originated from ambiguity in the clearance issued by ATC (Lyu et al., 2019).

These phenomena underscore that, despite continuing advances in aviation navigation and communication technology, human factors within ATC remain a significant vulnerability to aviation safety. Prior studies have highlighted the contribution of controller fatigue (Bongo & Seva, 2022; Zhang et al., 2021), failures in the application of standard phraseology (Yan, Boufous, & Molesworth, 2025), and limitations in organizational oversight (Lyu et al., 2019) as key determinants of ATC failure. However, most of these studies are quantitative in nature or rely on long-term statistical databases, and have therefore not extensively explored how such layered failure sequences (multiple failure layers) unfold contextually within specific accident or incident events.

Based on this gap, the present study aims to: (1) identify patterns of ATC-related failure across a set of civil aviation accidents and incidents that are historically and geographically representative; (2) analyze those patterns through the Human Factors Analysis and Classification System (HFACS) framework and Reason's (1990) Swiss Cheese Model; and (3) formulate practical implications for improving ATC safety governance going forward. Through a literature review approach, this research is expected to provide a contextual synthesis of existing documentary and scholarly evidence, while also serving as a reference for regulators, Air Navigation Service Providers (ANSPs), and aviation scholars.

RESEARCH METHODS

This study employs a qualitative literature review (studi pustaka) design, in which findings are constructed through systematic tracing, selection, and synthesis of secondary documents rather than through direct fieldwork or primary data collection. A literature review design was chosen because the purpose of this research is not statistical generalization but conceptual and analytic synthesis—that is, integrating patterns of findings already documented across independent, credible sources to reinforce or extend the existing theoretical framework of human factors in ATC.

Literature Search Strategy and Sources

The literature search was conducted across official accident-investigation repositories and academic databases, including SKYbrary Aviation Safety (jointly maintained by EUROCONTROL and ICAO), ICAO official documentation (including Annex 13 and the Global Runway Safety Action Plan), and indexed scientific databases such as ScienceDirect, MDPI, Taylor & Francis Online, and Google Scholar. Search terms combined keywords such as “air traffic control,” “human factors,” “HFACS,” “aviation accident,” “runway incursion,” and “controller fatigue.” Both English- and practice-oriented grey literature (official investigation reports) and peer-reviewed journal articles were included to ensure both factual accuracy and theoretical grounding.

Inclusion and Exclusion Criteria

Documents were included if they met the following criteria: (a) the source was an official accident/incident investigation report or a peer-reviewed article published in an indexed journal; (b) the content addressed an ATC-related element as a direct cause or contributing factor to an aviation accident or incident; (c) the case or study represented variation in the type of ATC failure examined (communication, workload, technology, or organizational coordination); and (d) for case material, the events spanned a diverse range of time periods and geographic regions to enhance the transferability of the synthesized findings. Sources lacking verifiable authorship, publication venue, or documentary backing (e.g., unmoderated forums, anonymous blogs) were excluded.

Based on these criteria, five illustrative cases were retained as the empirical anchor of the review: (1) the runway collision at Los Rodeos Airport, Tenerife (1977); (2) the mid-air collision over Zagreb (1976); (3) the mid-air collision over Uberlingen, Germany (2002); (4) the runway collision at Linate Airport, Milan (2001); and (5) the runway incursion incident at Halim Perdanakusuma Airport, Jakarta (2016). These cases function within the review as documented instances against which the broader literature on ATC human factors is triangulated, rather than as freshly collected field data.

Analytical Instrument and Framework

The analytical instrument used in this study is the Human Factors Analysis and Classification System (HFACS) framework developed by Wiegmann and Shappell (2003), which classifies causal factors into four hierarchical layers: (1) Unsafe Acts of Operators, such as phraseology errors or incorrect clearance issuance; (2) preconditions for unsafe acts, such as fatigue or loss of situational awareness; (3) unsafe supervision, such as assigning a single controller to two working positions

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simultaneously; and (4) organizational influences, such as communication-system maintenance policy or safety culture (see Figure 1). This framework is combined with Reason's (1990) Swiss Cheese Model, which conceptualizes an accident as the outcome of the alignment of multiple 'holes' across successive layers of system defense, including the defense layer that ATC is intended to provide.

Figure 1. The Four Levels of the HFACS Framework *(adapted from Wiegmann & Shappell, 2003)*

Data Extraction and Synthesis Technique

Data extraction was carried out through directed (deductive) content analysis, in which the narrative of each retrieved document was coded into ATC-relevant HFACS categories, followed by thematic clustering to identify recurring patterns across sources. The coding process was conducted manually and iteratively, comprising: (a) initial reading of all retrieved documents; (b) open coding to identify units of meaning related to ATC; (c) axial coding to group codes into HFACS categories; and (d) selective coding to formulate cross-source themes, which form the basis of the discussion in the following section. Where quantitative findings were reported in the underlying literature (e.g., the relative contribution of each HFACS layer), these figures were extracted and are presented descriptively in Figure 2 to support the qualitative synthesis.

Trustworthiness and Ethical Considerations

To maintain the trustworthiness of this literature-based study, the researcher applied Lincoln and Guba's four criteria: credibility (through source triangulation across official reports and peer-reviewed literature), transferability (through thick description of case context), dependability (through an audit trail of the coding process), and confirmability (through researcher reflexivity regarding potential interpretive bias). This study did not involve direct human subjects and therefore did not require individual ethical approval; nevertheless, academic ethical considerations were observed in representing events involving loss of life, avoiding blame-oriented judgment toward specific individuals and instead focusing on systemic analysis, consistent with the 'just culture' principle advocated in modern aviation safety investigation.

RESULTS AND DISCUSSION

Results: Characteristics of the Five Cases

Synthesis of the literature on the five cases reveals a fairly broad variation in the type of ATC failure involved, ranging from communication failures during the early era of the aviation industry to technology-coordination failures in the modern era. A summary of the characteristics of the five cases, as documented across official investigation reports and the supporting literature, is presented in Table 1.

No	Event / Year	Location	Aircraft Involved	Fatalities	ATC Failure Category (HFACS)
1	Tenerife, 27 March 1977	Los Rodeos Airport, Canary Islands, Spain	KLM Flight 4805 (B747) & Pan Am Flight 1736 (B747)	583	Unsafe Acts & Preconditions: radio miscommunication, ambiguous phraseology, overlapping (blocked) transmissions
2	Zagreb, 10 September 1976	Zagreb airspace, former Yugoslavia	British Airways (Trident Three) & Inex-Adria (DC-9)	176	Unsafe Supervision & Preconditions: controller work overload, inter-sector coordination failure
3	Uberlingen, 1 July 2002	Southern German airspace (controlled by Switzerland)	Bashkirian Airlines (Tu-154) & DHL (Boeing 757)	71	Organizational Influences & Unsafe Supervision: single controller working two positions, emergency telephone system offline, conflicting ATC instruction vs. TCAS
4	Linate, 8 October 2001	Linate Airport, Milan, Italy	SAS Flight 686 (MD-87) & Cessna Citation II	118	Organizational Influences & Preconditions: absence of Surface Movement Radar (SMR), dense fog, non-standard phraseology
5	Jakarta Halim, 4 April 2016	Halim Perdanakusuma Airport, Jakarta, Indonesia	Batik Air (B737-800) & TransNusa (ATR 42-600)	0 (incident)	Unsafe Acts & Preconditions: clearance ambiguity, ineffective monitoring, loss of situational awareness

Table 1. Summary of Characteristics of Five ATC-Related Aviation Accidents/Incidents

Discussion: Cross-Case Patterns

The results of the directed content analysis across the five cases reveal four recurring major themes: (a) communication failure and non-standard phraseology; (b) controller workload and supervisory limitations; (c) limitations in decision-support technology; and (d) organizational factors and safety culture. These four themes align with the four HFACS layers shown in Figure 1 and are interrelated as a chain of 'holes' within Reason's (1990) Swiss Cheese Model.

Communication failure and non-standard phraseology.

This theme is most prominent in the Tenerife case (1977), in which the captain of KLM 4805 transmitted the phrase 'we are now at takeoff,' which was interpreted differently by the controller and the Pan Am crew than originally intended, compounded by a blocked radio transmission caused by two aircraft transmitting simultaneously. A similar pattern, albeit in a different context, is identified in the Jakarta Halim incident (2016), where ambiguity in the clearance issued by ATC contributed to the runway incursion (Lyu et al., 2019). This finding is consistent with the research of Yan, Boufous, and Molesworth (2025), which shows that miscommunication during critical flight phases and variable situational awareness are significant contributors to runway incursions, and which emphasizes the importance of standard ICAO phraseology in reducing cross-linguistic ambiguity.

Controller workload and supervisory limitations.

This theme is prominent in the Zagreb (1976) and Uberlingen (2002) cases. In the Zagreb case, the controller responsible for a particular sector had to manage a traffic volume exceeding normal capacity without adequate coordination support from an adjacent sector, resulting in overlapping altitude instructions issued to two aircraft. In the Uberlingen case, a single controller was assigned to handle two working positions simultaneously late at night while the emergency telephone system was undergoing maintenance, preventing a timely warning from another ATC unit from being conveyed. This condition illustrates what Bongo and Seva (2022) describe as the inverse relationship between fatigue and controller situational awareness: the higher the workload and fatigue, the lower the controller's capacity to detect potential traffic conflicts at an early stage. The findings of Zhang, Chen, Liu, Ding, and Wu (2021) further reinforce this pattern by showing that the type of controller work and shift duration correlate significantly with objectively measured fatigue levels.

Limitations in decision-support technology.

In the Linate case (2001), the absence of Surface Movement Radar (SMR) at Linate Airport prevented the controller from visually or electronically verifying the position of the Cessna Citation that had mistakenly entered the active runway in dense fog, so that the take-off roll of SAS 686 could not be halted in time. In the Uberlingen case, the limitation was of a different nature—namely, a conflict between the verbal ATC instruction and the automated TCAS resolution advisory, in which one aircraft complied with the ATC instruction to descend while the other complied with the TCAS resolution advisory, also directing a descent, instead of one climbing and the other descending as the system was designed to ensure. This condition underscores the importance of procedural alignment between automated cockpit systems and human ATC instructions, an issue that continues to receive attention in the development of Short Term Conflict Alert (STCA) and other modern conflict-warning systems.

Organizational factors and safety culture.

At the organizational level, all five cases show that individual controller or pilot failures rarely stand alone, but are preceded by weaknesses at the policy and organizational-oversight level, such as the decision to schedule emergency telephone-system maintenance during a busy period (Uberlingen), delayed investment in surface radar despite prior recommendations (Linate), or the absence of standardized procedures for managing radio-frequency congestion at high-traffic-volume airports (Tenerife). This pattern is consistent with the findings of Lyu, Song, and Du (2019), who, through HFACS-Bayesian Network modeling of 142 ATC-related accidents/incidents during the 1980–2019 period, found that unsafe acts contributed the most to ATC performance degradation (79.4%), followed by unsafe supervision (56.9%), while preconditions for unsafe acts contributed the least (40.3%), as illustrated in Figure 2. The convergence between this qualitative literature synthesis and the quantitative, large-database findings strengthens the argument that unsafe acts at the sharp end are in fact rooted in systemic weaknesses at the blunt end of the organization, as underscored by the core premise of the Swiss Cheese Model (Reason, 1990).

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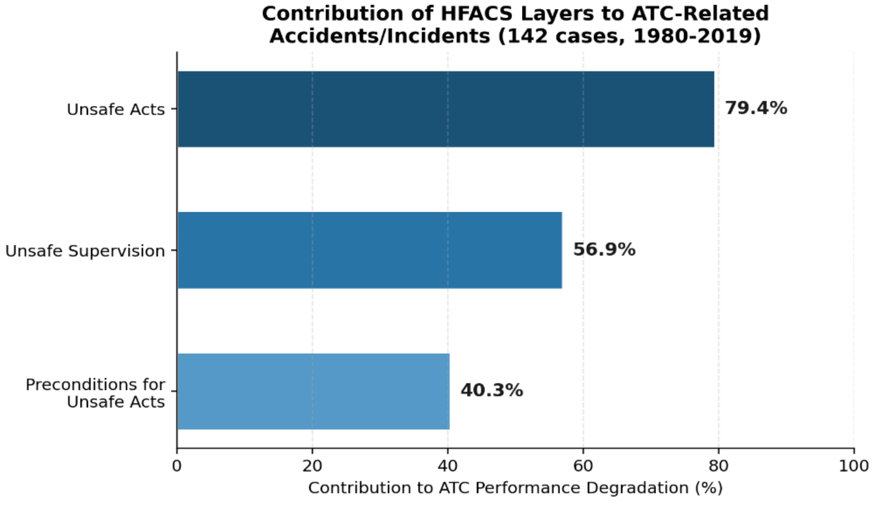

Figure 2. Contribution of HFACS Layers to ATC-Related Accidents/Incidents (Source: Lyu, Song, & Du, 2019)

Overall, the findings of this study are consistent with the initial proposition that ATC-related failures are multicausal and layered in nature, rather than attributable to a single point of failure. Each case demonstrates that individual controller or pilot errors are, in essence, the 'tip of the iceberg' of a series of latent conditions that existed well before the event occurred, consistent with the findings of Muecklich, Sikora, Paraskevas, and Padhra (2023) in the context of aviation ground operations, which show that procedural non-compliance and lack of situational awareness consistently emerge as the principal causal and contributing factors across multiple aviation subsystems, including ATC. The implication is that effective mitigation cannot focus solely on retraining individual controllers, but must extend to improvements in standard procedures, investment in surveillance technology, and the strengthening of organizational safety culture as a whole.

CONCLUSIONS

This study answers the question of how patterns of Air Traffic Control-related failure contribute to civil aviation accidents and incidents by demonstrating that such failures are multicausal and layered in nature, involving an interaction between communication failure and non-standard phraseology, controller workload and fatigue, limitations in decision-support technology, and weaknesses at the policy and organizational safety-culture level, as consistently illustrated across the five cases examined—Tenerife, Zagreb, Uberlingen, Linate, and Jakarta Halim. Individual controller or pilot errors that appear, on the surface, as the direct cause of an event are in fact rooted in latent conditions at the organizational level, meaning that efforts to improve ATC-related aviation safety must extend to systemic improvement rather than merely corrective action directed at individuals. Going forward, strengthening cross-linguistic phraseology standardization, implementing evidence-based controller fatigue and workload management, accelerating the adoption of surface surveillance technology and conflict-alert systems at high-risk airports worldwide, and cultivating a safety culture oriented toward systemic learning rather than individual blame-seeking (just culture) constitute strategic steps that aviation regulators, Air Navigation Service Providers, and airlines worldwide should prioritize in order to prevent the recurrence of similar failure patterns in the future.

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