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# Assessing Mid-Air Collision Risk Between Commercial Aircraft and Small Uncrewed Aircraft Systems: A Functional Resonance Analysis Approach

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Abstract: Unauthorized use of small drones is becoming a serious threat, raising new safety concerns in commercial aviation. Although collisions between drones and aircraft are still rare, near misses indicate potential risks of serious accidents. This study uses the Functional Resonance Analysis Method to assess systemic hazards from drone encounters in controlled airspace. Voluntary pilot safety reports and previous research on collision techniques and pilot responses were reviewed. The initial risk assessment was rated high, underscoring the need for targeted mitigation strategies. Recommended measures include stricter regulations, geofencing, training, improved reporting, and advanced detect-and-avoid systems. These actions could significantly lower the risk and enhance overall safety management. This study demonstrates that the Functional Resonance Analysis Method can be an effective tool for airline operators to help identify emerging hazards and proactively incorporate mitigation measures into safety systems.

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## Introduction

Collisions involving the unauthorized use of small uncrewed aircraft systems (sUAS), commonly known as drones, increasingly threaten commercial air carriers in the United States (Kumar & Chaudhary, 2024). While these systems serve various purposes in recreation, agriculture, construction, media, and emergency response, their presence in shared airspace significantly elevates the risk of conflicts with crewed aircraft (Franke et al., 2022; Kumar & Chaudhary, 2024). As sUAS become more prevalent, commercial airline safety management systems (SMS) mandated under 14 C.F.R. Part 5 (2024) must evolve to adopt proactive, data-informed risk management strategies, even with sparse industry data.

This study employs the Functional Resonance Analysis Method (FRAM) to help evaluate the risk of mid-air collisions between sUAS and Part 121 aircraft. Data for this study were obtained from the Federal Aviation Administration's (FAA) Near Mid-Air Collision System and the National Aeronautics and Space Administration's (NASA) Aviation Safety Reporting System (ASRS). Descriptive statistics provided context for constructing a FRAM model that illustrates systemic interdependencies and potential collision pathways. The analysis provides an initial risk assessment, highlights gaps in existing mitigation strategies, and explores potential mitigation measures with a post-mitigation risk rating.

### Operational Risk Assessment Challenges

Evaluating the risks posed by sUAS in the National Airspace System (NAS) remains difficult due to the limited availability and reliability of data (Wallace et al., 2023). As aviation systems grow increasingly complex, identifying and assessing emerging hazards present significant challenges (Parnell et al., 2011). For commercial air carriers, this scarcity of robust data constrains the ability of SMSs to assess, share, and mitigate risks associated with unauthorized sUAS operations. While platforms such as the Aviation Safety Information Analysis and Sharing (ASIAS) system seek to centralize safety information, they may inadvertently create information silos by requiring airline personnel to filter through aggregated data to identify relevant sUAS reports.

Although SMS frameworks mandated under 14 C.F.R. Part 5 (2024) promote proactive hazard identification and data-driven risk management, they are not fully equipped to address the specific risks posed by sUAS. The lack of comprehensive data and limited mitigation options hinders the effective integration of drone-related hazards into operational risk assessments (Wang et al., 2024). Additionally, criteria traditionally used to evaluate near mid-air collisions (NMAC) in crewed aircraft are not readily applicable to sUAS, as drones exhibit different performance characteristics and behaviors (Weinert et al., 2022). This mismatch reduces the ability of commercial air carriers to respond to evolving threats and increases vulnerability to operational disruptions and safety incidents caused by unauthorized sUAS activity.

### Study Purpose and Anticipated Outcomes

The purpose of this study is to assess the potential risk of mid-air collisions between commercial aircraft and sUAS using FRAM as a systems-based tool. Previous research has mainly relied on probabilistic models, simulations, or analogies to bird strikes to estimate collision risks. While helpful, these methods often ignore the subjective and operational factors that influence the detection and management of hazards. This study is among the first to apply FRAM to the risk of sUAS mid-air collisions, offering a new systems-based perspective on this emerging threat. To fill this gap, the research conducts a systems-level risk assessment that integrates prior studies and reporting data, reflecting commercial operators' structured approaches to threat evaluation.

The study explores two main questions: What is the potential risk of mid-air collisions between commercial aircraft and sUAS when evaluated through a structured risk assessment process? And how can FRAM be applied to enhance the assessment of these risks? The results are expected to show the limitations of solely probabilistic or report-based methods and illustrate the added benefits of FRAM in identifying system interdependencies and hidden vulnerabilities. Theoretically, the study extends FRAM's use into sUAS collision risk by qualitatively modeling complex system interactions. At the same time, it provides airline operators and regulators with insights to guide mitigation efforts, enhance SMSs, and facilitate the safe integration of sUAS into the NAS.

## Literature Review: Mid-Air Collision Risk and Mitigation

### Background

In January 2024, British Airways Flight 641, an Airbus A321, came within five feet of a small recreational drone during approach to Heathrow Airport (UK Airprox Board, 2024). This event was critical for the aviation world, but not the first encounter. In 2017, a SkyJet Beechcraft King Air collided with a drone on final approach to Quebec City Jean Lesage International Airport. The aircraft sustained minor damage, and the flight crew was able to identify the drone before the collision (Transportation Safety Board of Canada, 2018). In January 2025, a drone struck the wing of a firefighting aircraft in California, causing a three-by-six-inch hole in the Super Scooper's left wing (United States Department of Justice, 2025).

Although events remain rare, the number of sUAS operating in the NAS has expanded considerably, heightening concerns about mid-air collisions (Federal Aviation Administration [FAA], 2024a; Kumar & Chaudhary, 2024; Lai & Lin, 2024). In 2023, over 800,000 drones were registered in the United States, including more than 500,000 for recreational use (Truong et al., 2024). By April 2025, registrations surpassed one million, with 383,000 classified as recreational (FAA, 2025a). The FAA suggests that lapses in re-registration might explain the apparent decline, but projections indicate ongoing long-term growth in sUAS operations (FAA, 2024a, 2025a).

### Collision Risks and Pilot Detection Limitations

Research consistently highlights the serious consequences of drone collisions with commercial aircraft (Franke et al., 2022; Marina et al., 2024; Zhang et al., 2020). Experimental evidence shows that small sUAS are extremely difficult for pilots to detect visually. Reported detection rates across studies vary widely, ranging from less than 10% (Woo et al., 2020) to approximately 30% (Wallace et al., 2019), with factors such as drone speed and distance affecting pilots' detection ability. In field trials, pilots identified quadcopter drones in fewer than 40% of encounters, often not until within 0.1 statute miles (Loffi et al., 2016).

Commercial air carrier aircraft are especially vulnerable to sUAS encounters during low-altitude phases of flight, particularly below 500 feet above ground level (AGL) (Wallace et al., 2023). Long-term monitoring at a major U.S. airport revealed nearly 460,000 drone flights in the vicinity over 36 months; yet only a small fraction were identified as NMACs, and even fewer were captured in pilot reporting databases (National Aeronautics and Space Administration [NASA], 2025; Wallace et al., 2023). This discrepancy illustrates both the limitations of pilot visual detection and the underreporting constraining the reliability of existing NMAC datasets for safety analysis.

Pilots face complex decisions even when drones are visually detected; executing evasive maneuvers at low altitudes can introduce additional risks, such as loss of control or unstable approaches. Evidence shows that pilots rarely take evasive action, with less than 10% of reported encounters involving such maneuvers. Additionally, sightings of sUAS are predominantly near airports, mostly between 400 and 4,000 feet and within 10 miles of an airport (Gettinger & Michel, 2015; Wang & Hubbard, 2021). This suggests that pilots often judge the potential disruption caused by avoidance maneuvers to outweigh the threat posed by the drone itself, highlighting the trade-offs involved in real-time decision-making. Consequently, assessing the risk of mid-air collisions in the terminal area remains crucial for ensuring safety.

## Recreational sUAS

Small uncrewed systems weigh between 0.55 and 55 pounds (14 C.F.R. Part 107, 2021). This study focuses solely on sUAS, excluding larger systems that exceed this weight, which present hazards similar to those of crewed aircraft and are regulated separately. Additionally, sUAS are much more common in the NAS and are the main concern for mid-air collision risk (Mulero-Pázmány et al., 2017).

Operationally, sUAS are divided into two main categories: recreational users and Part 107-certified operators. While 14 C.F.R. Part 107 (2021) establishes the general regulatory framework for commercial sUAS activities, 49 U.S.C. § 44809 (2025) provides exceptions for recreational use. Recreational operators are not required to hold a remote pilot certificate. Yet, operators remain subject to restrictions, including prohibitions of flights near airports that could interfere with air traffic and altitude limits of 400 feet in uncontrolled airspace. In controlled airspace surrounding most commercial airports, prior authorization from air traffic control is required for operations, and approval can be granted on a case-by-case basis.

The severity of drone collisions with crewed aircraft depends on multiple factors, including the types of drones and crewed aircraft, impact velocity, and the point of collision. Research by the Alliance for System Safety of UAS through Research Excellence (2023) indicates that fuselage strikes are the most likely collision points for commercial aircraft, whereas impacts on the horizontal stabilizer pose the highest severity due to potential loss of controllability. These findings highlight the importance of considering the collision probability and the consequences of different impact scenarios.

## Bird and Drone Composition Disparity

Drone collisions are often compared to bird strikes; however, drones of similar mass pose a greater risk of catastrophic damage due to differences in composition and structural rigidity (Che Man et al., 2022; May et al., 2024). For comparison, the Trumpeter Swan, the heaviest flying bird in North America, can exceed 26 pounds (Cornell Lab of Ornithology, 2025). While impacts with large birds can cause significant damage depending on the point of contact, an equally weighted drone presents a more serious threat because of the structure's durability. Nevertheless, most recreational drones are considerably lighter. A study commissioned by Transport Canada found that the average recreational drone weighs approximately 3.7 pounds, with many models closer to one pound (Léger Marketing Inc., 2019). As with birds, larger drones are relatively rare, but structural differences make direct comparisons impossible.

The increased threat posed by drones stems from their materials and design. Unlike birds, drones are typically constructed from carbon fiber, aluminum alloys, titanium, and fiberglass. They also include rigid components, such as circuit boards, lithium batteries, and propulsion systems, which increase the risk of damage (Magdolna, 2025). These features pose risks beyond damage to the airframe, as ingesting drone parts into aircraft engines can lead to engine failures, posing serious risks during takeoff and landing (Che Man et al., 2020). High-speed collisions can further escalate the threat, with studies showing that impacts at terminal approach speeds can compromise aircraft integrity. Experimental tests indicate that drone strikes at 200 knots can damage aerodynamic components, and simulations suggest that structural integrity may be compromised at speeds as low as 155 knots (Franke et al., 2022; McNeil & Abdulrahim, 2022).

Despite risks, current certification standards depend on bird strike testing thresholds of four to eight pounds to evaluate airframe resistance to impacts without catastrophic failure (14 C.F.R. § 25.307, 2014). Importantly, certification does not include testing against drones or other foreign objects, thereby creating a critical gap in safety evaluation.

## Existing Mitigation Strategies

From the perspective of airline operators, current mitigation strategies against drone encounters are limited and mostly ineffective. Visual scanning is unreliable because pilots often lack sufficient time to detect and avoid sUAS, especially at low altitudes, where aggressive avoidance can create additional hazards. Although collision detection and avoidance technologies exist in theory, they remain complex, are not required, and lack interoperability with sUAS platforms (Cereceda, 2018; Feng et al., 2020). As a result, neither commercial aircraft nor sUAS are equipped with standardized onboard detection systems to reduce collision risk. Other mitigation strategies face similar obstacles. Redesigning airspace is a time-consuming and intricate process, and relying on drone operators to comply with published regulations has proven insufficient. Incidents indicate that compliance varies, and some drones, such as racing models, do not rely on GPS, thereby rendering certain geofencing technologies ineffective (McNeil & Abdulrahim, 2022). Given these limitations, airline operators encounter a shortage of effective risk controls. This reinforces the importance of conducting thorough and proactive risk assessments to identify vulnerabilities and guide the development of stronger mitigation strategies.

## Safety Risk Management Framework

Collisions involving sUAS pose safety challenges that differ significantly from those of traditional aviation, underscoring the need for proactive management. Safety Risk Management (SRM) provides a structured approach to anticipate and mitigate such risks before they lead to incidents or accidents (Truong et al., 2024). SRM is vital to aviation safety oversight (FAA, 2024b). The SRM process includes five main steps: system analysis, hazard identification, safety risk analysis, safety risk assessment, and the implementation of risk controls (FAA, 2024b; Stolzer et al., 2023). These activities can be triggered by planned operational changes that introduce new hazards or by the detection of inadequate controls (FAA, 2023). SMS processes rely on ongoing hazard analysis, data review, and control evaluation to effectively manage evolving threats, such as the risk of mid-air collisions involving sUAS.

### *Risk Assessment*

Risk assessment is a crucial yet inherently subjective part of the SRM framework. Guidance for air carriers is provided through FAA resources, including Advisory Circular 120-92D on Safety Management Systems (FAA, 2024c) and Safety Risk Management Policy Order 8040.4C (FAA, 2023). Collectively, these documents establish standardized definitions and procedures for evaluating operational risk and decision-making. The FAA (2023) uses a basic risk formula of Risk = Likelihood × Severity. Severity denotes the potential consequences of a hazard in terms of loss or harm, whereas likelihood denotes the probability of an occurrence. These levels should be independently calculated by using analytical, empirical, and judgmental data. When put together in a matrix, a risk level can be determined. When data are limited, risk assessments rely on judgment, interpolation, and predicted outcomes, rather than purely statistical measures. After completing a risk assessment, safety assurance ensures that the assessment remains valid and adapts to emerging hazards (Stolzer et al., 2023).

### *Modeling Approaches to Collision Risk*

Probabilistic modeling provides a structured approach for assessing collision risk between drones and crewed aircraft and helps establish separation thresholds in shared airspace (Bijjahalli et al., 2021; Vila Carbó et al., 2023). Most prior research has relied on probabilistic modeling, with some evaluations suggesting that collisions may be unavoidable in certain high-traffic airport scenarios (Snyder & Vidhyadharan, 2023). However, models are constrained by uncertainties arising from non-compliant drone operations and failure scenarios, which reduce predictive accuracy, particularly in terminal areas (Zhu et al., 2022). While these models improve theoretical understanding and help establish safety design parameters, commercial operators often revert to simpler means.

## Methodology

This study employed an exploratory sequential mixed-methods design, which begins with quantitative analysis followed by qualitative exploration to provide a deeper understanding (Creswell & Creswell, 2022). Quantitative data were obtained from the FAA's Near Mid-Air Collision System (2021) and NASA's ASRS (2025). Descriptive statistics were used to identify encounter frequencies and altitude distributions. Because voluntary safety reports are intended to provide operational insights rather than establish causal relationships, descriptive statistics in this study are presented as contextual detail rather than as measures of statistical inference (Leedy & Ormrod, 2019). NMAC reports are considered meaningful indicators of underlying collision risk in sUAS research (Weinert et al., 2022), supporting their use in this study as early-warning evidence of mid-air collisions. Moreover, prior research has further shown the value of voluntary pilot safety reports for providing narrative context and identifying event precursors (Ruskin et al., 2021; Ross & Tomko, 2016; Vempati et al., 2023).

### Pilot Safety Reports

The ASRS dataset included reports submitted between January 2016 and December 2024, a period selected to capture both long-term operational trends and fluctuations in commercial traffic volume. Reports were identified using the keywords *UAS, unmanned, drone,* and *UAV,* and included NMAC events involving Part 121 aircraft and sUAS. To address inconsistencies in altitude reporting between AGL and mean sea level (MSL), events were grouped into three categories: at or below 500 feet AGL, between 501 and 1,000 feet AGL, and above 1,000 feet AGL. Specific altitude values were not analyzed.

FAA Near Mid-Air Collision System data were reviewed for the period from June 2016 through June 2020, which represents the most consistent reporting period. Only events involving Part 121 aircraft and sUAS were included. Unlike ASRS, this system requires confirmation of a proximity of less than 500 feet or identifying a collision hazard (FAA, 2021). Because the database stopped recording after 2021, the dataset ends in 2020.

To ensure consistency across both datasets, international reports, air traffic controller submissions, and incidents involving balloons or other unrelated objects were excluded, thereby focusing the analysis solely on encounters between Part 121 aircraft and sUAS relevant to mid-air collision risk.

### Developing a FRAM Model

A qualitative FRAM model was developed to complement the quantitative findings and illustrate system interdependencies and resonance in drone operations near airports and within controlled airspace. FRAM is designed to model complex sociotechnical systems by capturing variability in system functions (De Souza et al., 2022; Kumar et al., 2024). Each function is characterized by six aspects: input, output, precondition, resource, control, and time (Hollnagel, 2017). Inputs trigger functions, outputs indicate results, preconditions establish prerequisites, resources enable performance, controls direct execution, and time constraints influence sequencing and duration. These functional aspects help reveal how system architecture and interactions contribute to events and potential hazards (Bellini et al., 2016). The FRAM model developed for this study provides an intuitive way to visualize functional variability and identify system component interactions that could lead to collision risks.

## Results

The ASRS search from January 2016 through December 2024 identified 358 reports of NMACs involving sUAS. Following review, 337 reports were retained for analysis, while 21 were excluded because they involved balloons, other aircraft, or international events outside the study's scope. Table 1 summarizes the number of reports by year and altitude category. Reports consistently indicated encounters above 1,000 feet AGL, suggesting that sUAS are frequently observed at altitudes exceeding regulatory limits.

**Table 1**

*NMAC ASRS Report Counts Between Part 121 and sUAS*

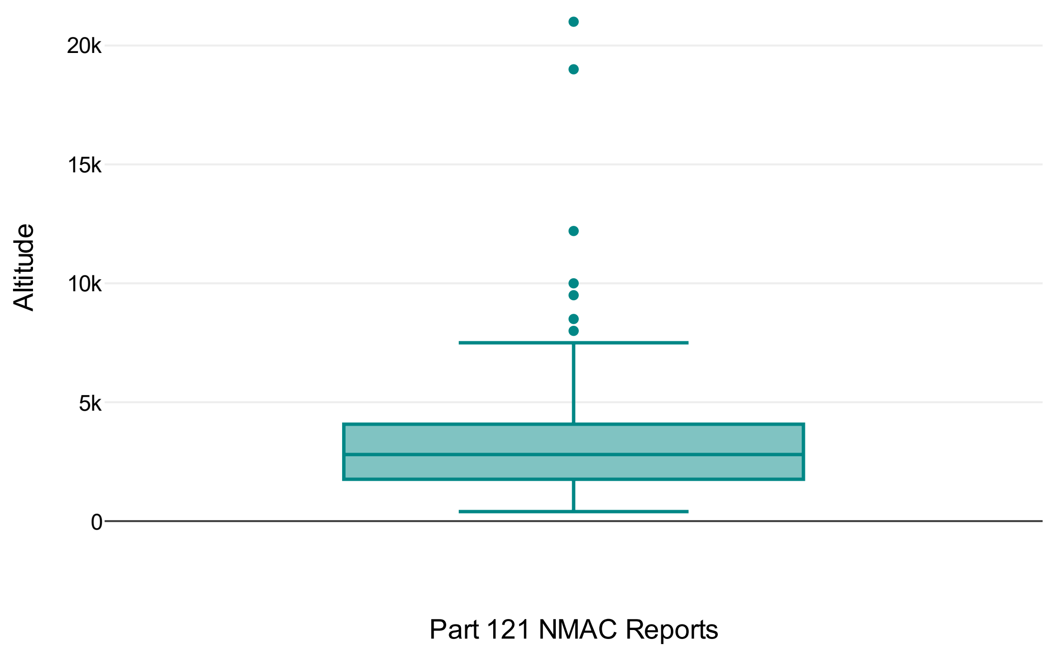
| | Altitude | | | | |
|---|---|---|---|---|---|
| Year | 500 AGL and below | Between 501 – 1,000 AGL | Above 1,000 AGL | Unknown | Annual total |
| 2016 | 4 | 1 | 21 | 0 | 26 |
| 2017 | 2 | 5 | 28 | 0 | 35 |
| 2018 | 5 | 1 | 29 | 0 | 35 |
| 2019 | 3 | 5 | 48 | 0 | 56 |
| 2020 | 1 | 4 | 25 | 4 | 34 |
| 2021 | 2 | 3 | 39 | 3 | 47 |
| 2022 | 1 | 2 | 21 | 2 | 26 |
| 2023 | 0 | 5 | 29 | 0 | 34 |
| 2024 | 0 | 6 | 35 | 3 | 44 |
| Total | 18 | 32 | 275 | 12 | 337 |

*Note.* The table was created from NASA ASRS (2025) reports. Reports are NMACs between Part 121 aircraft and sUAS.

FAA Near Mid-Air Collision System data from June 2016 to June 2020 provided a second dataset for comparison. The system generated 177 NMAC reports; however, after applying exclusion criteria, 44 reports remained. Reported altitudes ranged from 400 ft to 21,000 feet ($M$ = 4,099.55, $SD$ = 4,444.73, 95% CI [2,748.22, 5,450.87]). Figure 1 shows the altitude distribution of these reports.

**Figure 1**

*Reported Altitudes of Near Mid-Air Collisions Between Part 121 Aircraft and sUAS*



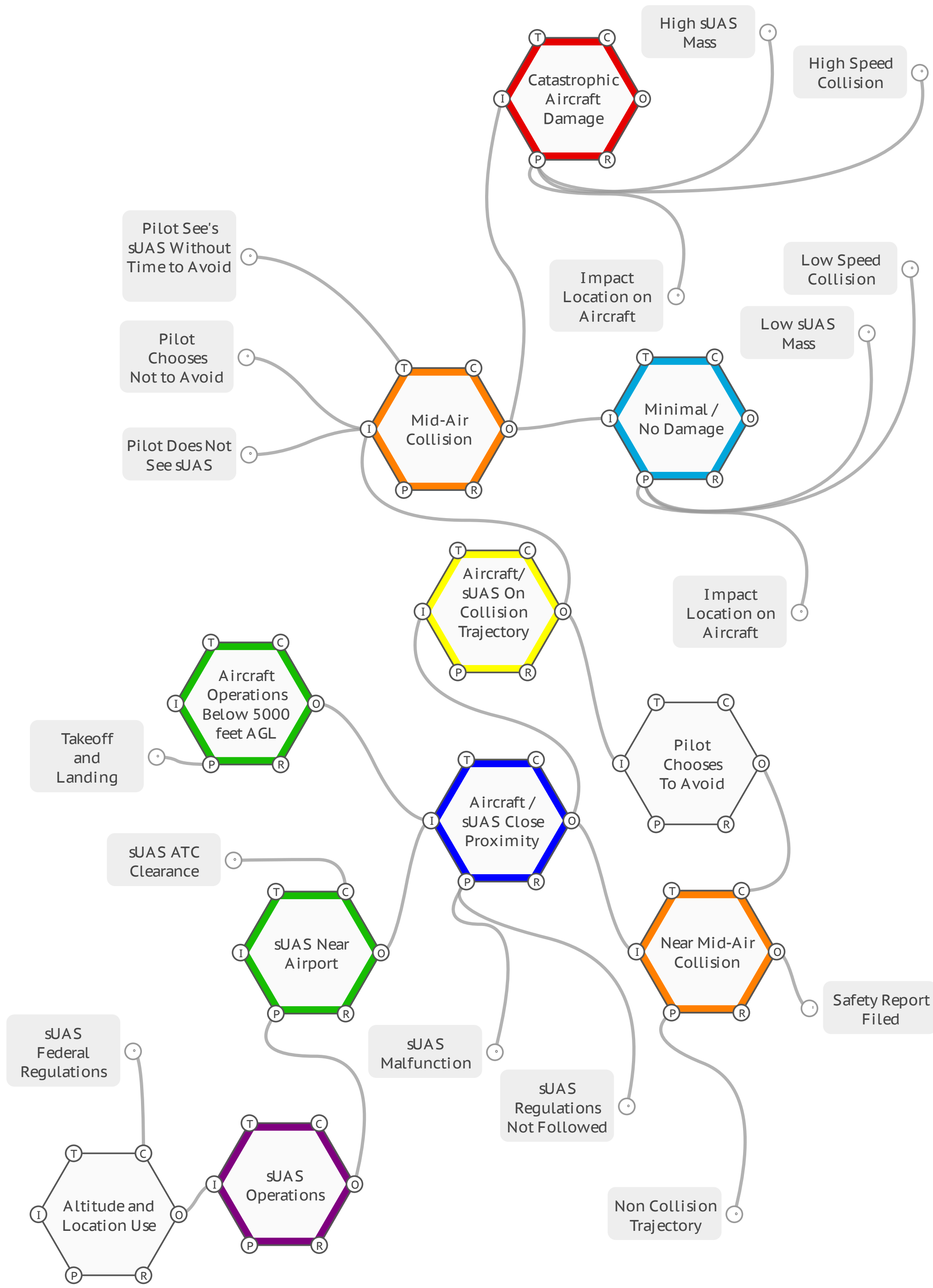

*Note.* This figure was created from the FAA Near Mid-Air Collision System (2021) data to determine reported NMAC altitudes between Part 121 aircraft and sUAS.

**FRAM Results: System Component Interactions**

A FRAM model was created using quantitative analysis and background research to demonstrate system interdependencies (Figure 2). The primary function, “Aircraft / sUAS Close Proximity”, outlines scenarios where aircraft and drones operate in the same airspace. Inputs include aircraft operations below 5,000 feet and sUAS activities near airports. Interactions can lead to a near mid-air collision (orange function) or, if trajectories intersect, an actual collision (yellow function). The model also highlights potential severity outcomes, ranging from minimal or no damage (light blue) to catastrophic effects (red), depending on drone weight, speed, and impact location. The model identifies both the worst-case outcome (catastrophic) and the least-case outcome (minimal damage) of a collision. These results do not reflect the determined risk rating; rather, they represent the range of collision outcomes based on varying factors.

**Figure 2**

*Developed Baseline FRAM Model Without Recommended Mitigations*



## Risk Analysis and Assessment Findings

Industry research and the quantitative and qualitative data presented in this study both identify a potential systemic hazard. This section will provide an initial risk assessment for the likelihood of mid-air collisions between commercial aircraft and sUAS, suggest mitigation strategies, and evaluate the post-mitigation risk level. Although collisions are rare, NMAC data serve as critical early-warning signs of underlying risks that, if ignored, could lead to catastrophic accidents under certain circumstances.

Findings from this study indicate that pilots report observing sUAS across a wide range of altitudes. While some studies suggest most encounters occur below 500 feet AGL (Wallace et al., 2023), pilot reports reveal numerous events between 1,000 and 5,000 feet AGL, consistent with Gettinger and Michel (2015). Encounters at these altitudes are especially concerning because commercial aircraft operate at higher speeds, reducing pilot reaction time and increasing impact severity.

Although recreational operations are legally restricted to 400 feet AGL in uncontrolled airspace, many reported encounters likely reflect unauthorized or illegal activity. Operations exceeding regulatory limits or near airports imply intentional non-compliance or limited operator awareness. Observational factors also influence reporting patterns: pilots are more alert during approach and departure, when collision risk is higher, yet even in these conditions, detection remains unreliable. Prior studies confirm that pilots have difficulty visually identifying sUAS (Wallace et al., 2019; Woo et al., 2020), suggesting many encounters go unnoticed and are underreported.

### Initial Risk Rating

Using a risk severity matrix (shown in Figure A1) and definitions provided by the FAA (2023), the severity and likelihood of a collision can be determined. The severity is classified as *hazardous.* Although a catastrophic outcome is theoretically possible, previous research, NMAC data, and the use of FRAM indicate that the most credible outcome involves significant structural damage and the potential for serious but likely non-fatal injuries, placing it in the hazardous severity level.

The likelihood of a mid-air collision is considered *remote*. Operationally, a remote likelihood corresponds to an event occurring with an estimated probability of once per year, to more than once every 10 years. Given the number of NMACs reported, recent confirmed mid-air collisions, the increasing growth of sUAS operations, and known underreporting, the likelihood of a collision is plausibly remote.

Combining hazardous severity and remote likelihood classifies the initial risk rating for mid-air collisions between sUAS and commercial aircraft as *high.* A high rating is considered unacceptable. According to the FAA (2023), a hazard at this level requires mitigation, ongoing monitoring, and approval at the highest organizational level.

## Recommended Mitigation Measures

The initial risk rating emphasizes the urgent need for effective system controls to mitigate the hazard. Current measures offer partial mitigation. These include FAA restrictions on sUAS operations in controlled airspace and the Remote Identification (Remote ID) requirement, which took effect in 2024. Remote ID is a digital license plate that enables authorities to monitor and track drones in real time (Phadke et al., 2023; Svaigen et al., 2022). Although this requirement represents significant regulatory progress, it is relatively new and not yet fully reflected in existing datasets. Other measures, such as the Low Altitude Authorization and Notification Capability (LAANC), enable real-time air traffic control approval for sUAS operations in controlled airspace (FAA, 2025b). Expanding regulatory frameworks could further improve safety. While 14 C.F.R. Part 107 (2021) requires operators to conduct pre-flight risk assessments, recreational users are currently exempt from this requirement (49 U.S.C. § 44809, 2025). Extending such assessments to all operators would better align recreational standards with those for commercial operations and enhance overall system safety.

### *Education and Training*

Education, training, and awareness programs can enhance compliance among recreational drone operators, who account for a large share of sUAS flights (Mandourah & Hochmair, 2022; Rahmani & Weckman, 2023). Similarly, airline pilots should receive targeted training to improve drone recognition and be reminded that aggressive low-altitude maneuvers may increase, rather than decrease, risk. Encouraging pilots to report sUAS sightings through formal safety channels would also improve data sharing across airlines and enable more accurate risk assessments.

### *Technological Mitigations*

Advances in technology can add extra layers of protection. Detect-and-avoid systems made for sUAS could allow autonomous separation from crewed aircraft, reducing the need for pilot intervention (Consiglio et al., 2019; Riedel, 2025; Snarski et al., 2022). Additionally, counter-UAS technologies, including geofencing, may stop drones from entering restricted zones around commercial airports (Kim & Atkins, 2022). Although these methods present technical and regulatory challenges, they offer proactive ways to lower mid-air collision risks.

### *Regulatory Enforcement and Legal Frameworks*

The effectiveness of mitigations ultimately depends on consistent enforcement and legal clarity. Federal authorities retain primary jurisdiction over airspace safety; however, the enforcement role of local and state agencies remains limited. State regulations often prioritize privacy issues, and their wide variation reduces uniformity in enforcement (Cody, 2018; Friedenzohn & Simoneau, 2024; Gonzalez, 2017; Smith, 2014). Enhancing coordination among federal, state, and local authorities, as well as the consistency of legal frameworks, could deter unauthorized sUAS operations near airports (Galante & Halawi, 2024).

### *Collision Testing and Risk Validation Needs*

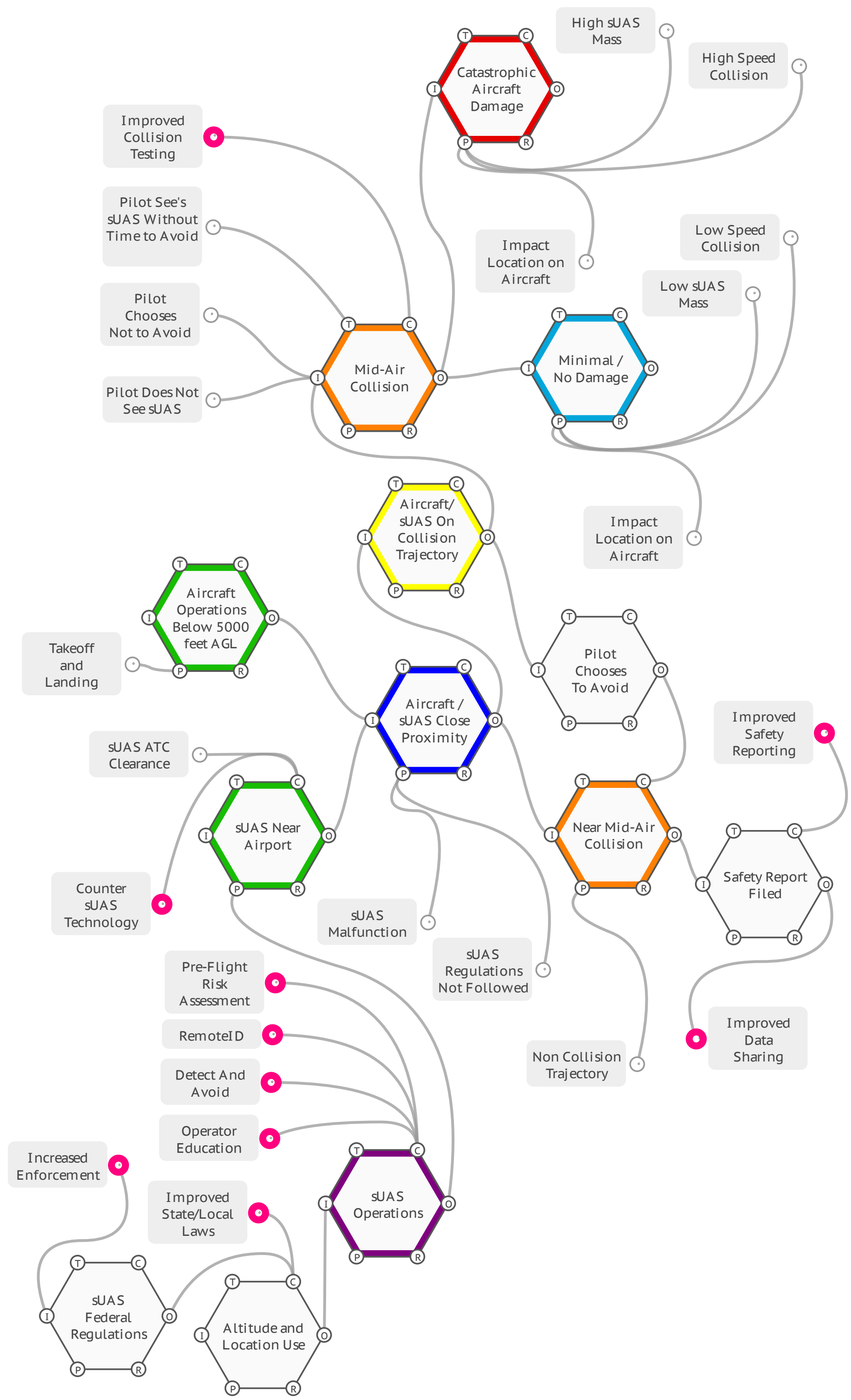
Enhanced collision testing can also lower uncertainty and improve severity estimates. Broader studies across aircraft types, drone models, impact speeds, and collision locations would yield more accurate insights into structural weaknesses and guide regulatory standards. These efforts should follow established bird-strike certification protocols, creating a more systematic basis for understanding and reducing collision impacts.

### *Integrated Safety Approach*

Although no single control can eliminate the hazard, a layered strategy that includes regulatory oversight, operator education, technological innovation, enforcement mechanisms, and thorough testing can significantly lower overall risk. In an updated FRAM model, these recommended mitigations are shown as additional functions (highlighted in pink), demonstrating how targeted interventions can strengthen system resilience (Figure 3).

**Figure 3**

*Updated FRAM Model with Recommended Mitigations*



## Post-Mitigation Risk Rating

After proposed mitigations are implemented, the most likely outcomes involve substantial aircraft damage or one to two serious but non-fatal injuries. Advances in collision testing and structural modeling can help reduce uncertainty in severity assessments, thereby improving accuracy and potentially enhancing the structural integrity of crewed aircraft. As a result, the severity level drops from *hazardous* to *major*.

Implementing new technical, regulatory, and operational controls can significantly reduce the likelihood of collisions from *remote* to *extremely remote*. The adoption of Remote ID, geofencing, and improved detect-and-avoid systems will directly lower unauthorized sUAS activity near airports. Additionally, requiring pre-flight risk assessments for recreational operators and launching targeted educational campaigns will boost compliance and awareness. An extremely remote likelihood indicates that a collision is expected to occur approximately once every 10 years to more than one time every 100 years. With the implemented measures reducing drone activity around airports, this rating is plausible. As a result, the post-mitigation overall risk decreases from *high* to *medium*.

These findings directly address the study's research questions, confirming that mid-air collisions between commercial aircraft and sUAS pose a high risk. However, effective mitigation can lower the overall risk to a medium level, which is considered tolerable with ongoing monitoring and periodic reevaluation. Improved reporting practices could provide more comprehensive and actionable data, leading to more accurate future risk assessments. Although regulatory enforcement remains a challenge, stronger cooperation between federal and local agencies can help close compliance gaps. The study's findings also highlight the value of FRAM, demonstrating that layered safety measures improve system resilience. Overall, this analysis highlights the practicality of FRAM for identifying system interdependencies and the importance of mitigation measures in safety management.

## Limitations and Future Research

The use of ASRS data is subject to limitations, as the FAA (2023) warns against relying on these reports for detailed system-level analysis. This study was intended to demonstrate how risk assessments can address emerging threats with limited data and mitigation options. Because a complete system-level analysis requires operator-specific data, this assessment remains broad and focuses on general systemic processes, relying on assumptions and conservative estimates.

Several scope limitations impact accuracy. The brief data-collection period and a generalized approach limit applicability at the organizational level. Additionally, the study assumed that most unauthorized operations, and therefore most NMAC events, involved recreational users. The study assumed that commercial sUAS operations under Part 107 or those with air traffic control clearance are less likely to cause NMACs due to structured procedures and separation standards. This assumption might overlook important operational scenarios. Moreover, the use of a FRAM model and risk ratings introduces subjectivity, as both reflect the researcher's interpretation of system hazards. While useful for revealing functional resonance, FRAM relies on the researcher's judgment and will yield different models among subject-matter experts. Although risk ratings can be based on data, scores may also be subjective and differ among operators.

This study contributed to the growing body of literature on sUAS by highlighting the emerging hazard posed by sUAS to commercial aircraft. The research provides regulators, operators, and the research community with clearer visibility into where system enhancements can be implemented to reduce risk. Future research should expand datasets to include recreational and commercial sUAS operations, enabling more robust and representative risk assessments. Empirical collision testing across aircraft types, drone sizes, approach speeds, and impact locations is also needed to understand collision dynamics better and inform regulatory standards.

## Conclusion

This study employed a systems-based risk assessment to evaluate the potential for mid-air collisions between commercial aircraft and sUAS. Although reported encounters remain relatively rare, the consequences of a collision could be hazardous without proper mitigation. By integrating reporting data, pilot detection limitations, and regulatory factors into a FRAM model, the research provided a practical, real-world perspective that is often absent in purely probabilistic or simulation-based approaches. This is among the first studies to apply FRAM to assess collision risk between sUAS and commercial aircraft, offering a novel, systems-oriented perspective on this emerging hazard. Initially, the risk was assessed as high; however, implementing layered mitigation strategies reduced the residual risk to medium, demonstrating that systemic controls can effectively mitigate collision hazards. The findings underscore the importance of regulatory enforcement, pilot awareness, detect-and-avoid technologies, and enhanced legal frameworks, which, when combined, can reduce risks.

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## Appendix

**Figure A1**

*Risk Severity Matrix*

| **Likelihood** | | **Severity** Minimal 5 | Minor 4 | Major 3 | Hazardous 2 | Catastrophic 1 | |
|---|---|---|---|---|---|---|---|
| Frequent | A | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-1 |
| | | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-2 |
| | | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-3 |
| | | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-4 |
| | | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-5 |
| Infrequent | B | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-6 |
| Extremely Infrequent | C | [Green] | [Yellow] | [Red] | [Red] | [Red] | 1x10-7 |
| Remote | D | [Green] | [Yellow] | [Yellow] | [Red] | [Red] | 1x10-8 |
| Extremely Remote | E | [Green] | [Green] | [Yellow] | [Yellow] | [Red] | 1x10-9 |
| Improbable | F | [Green] | [Green] | [Green] | [Yellow] | [Yellow] | 1x10-10 |
| Extremely Improbable | G | [Green] | [Green] | [Green] | [Green] | [Green] | 1x10-11 |

| |
|---|
| **High Risk [Red]** |
| **Medium Risk [Yellow]** |
| **Low Risk [Green]** |

*Note.* Risk Matrix adapted from FAA (2023) and designed for commercial aviation.