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Analyzing Trends in UAS Altitude Deviations in the United States: Exploring Human Factors Issues

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The usage of unmanned aircraft systems (UAS) for recreational and commercial purposes has been rapidly growing in the United States (U.S.). As of December 2023, over 1.54 million new recreational drones have been registered in the Federal Aviation Administration's (FAA) database. With the increase in the usage of UAS, violations related to flying UAS into unauthorized airspace are also accumulating. According to the Code of Federal Regulations, 14 CFR§107.51, "the altitude of a small, unmanned aircraft system cannot be higher than 400 feet above ground level." Human factors, such as difficulty in visual scanning, lack of multiple sensory cues, loss of communication, and spatial disorientation, play a significant role in altitude compliance problems with respect to UAS operations. Historically, various studies have examined the trends of UAS operations in unauthorized airspace. However, there is a dearth of research focused on examining the trends in altitude compliance issues related to UAS operations and their association with human factors constructs. Therefore, the purpose of the current study was to investigate the trends in UAS sightings over 400 feet in the U.S. and the associated human factors issues. All UAS sightings reported between January 2021 and December 2024 were obtained from the FAA's UAS sightings database. All the data were explored through Tableau and JMP. Results of the analysis, and the role of human factors issues, such as visual workload, multimodal cues, and situational awareness in UAS operations, are discussed.

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Introduction

Unmanned Aircraft Systems (UAS), including small UAS (sUAS), are defined by the Federal Aviation Administration (FAA) as aerial vehicles operated remotely without an onboard pilot (Huang et al., 2021, p. 1). Over the last decade, the use of UAS or drones in the United States (U.S.) has gained tremendous popularity across various commercial operations, such as package delivery, construction, firefighting, and inspection. Along with commercial operations, there has also been consistent growth in recreational UAS operations in the U.S. According to the FAA's Aerospace Forecast (n.d.), by 2028, the UAS fleet for recreational operations is projected to reach approximately 1.92 million units, and the commercial operations fleet is projected to reach approximately 1.12 million units. Their rapid integration into the national airspace reflects significant advances in affordability and accessibility. However, this growth has led to complex regulatory and safety challenges for the industry. Most operations involve a small sUAS and are restricted to 400-foot(ft) above ground level (AGL; FAA, 2024). The UAS operator is responsible for maintaining an altitude below 400 ft AGL throughout the mission. Despite these efforts, concerns remain regarding the ability of recreational and commercial users to consistently comply. As Okoli et al. (2024) noted, the influx of UAS operations introduces a novel set of risks to the National Airspace System, emphasizing the critical need for a literature-based understanding of altitude compliance.

FAA sighting reports from 2020 to 2021 revealed that a significant portion of UAS activity exceeded the legal altitude thresholds. Specifically, 93% of drones were observed flying above the 400 ft AGL limit, and 32% exceeded 4,000 ft, raising serious concerns regarding airspace violations (Howard, 2023). These unauthorized flights occurred most often during daylight hours and in proximity to airports (Howard, 2023), meaning that they also represent an increased safety risk to manned flights. Furthermore, demographic studies have shown a correlation between education level and compliance, with operators with higher education and income levels being more likely to follow altitude rules (Huang et al., 2021), underscoring the influence of sociocultural factors on regulatory behavior.

Previous studies have focused on trends in UAS sightings (Abraham, 2022; Howard, 2023; Huang et al., 2021), geographical factors causing UAS noncompliance, and the consequences of noncompliance within controlled airspace and in the vicinity of airports. These studies have highlighted the operational and safety issues posed by UAS activities in restricted areas, emphasizing the importance of regulatory enforcement and technological solutions for mitigating potential threats. Another prominent challenge in achieving full compliance with these regulations is the human element, where operator error and insufficient situational awareness significantly impact adherence to altitude constraints. Compounding these concerns is the need for ongoing investigations and enforcement measures to accommodate future technological developments and operational scenarios. As the FAA continues to refine its guidelines, a critical focus on addressing human factors is essential to enhance compliance and uphold airspace safety. Therefore, this study aims to extend beyond operational and future trends by establishing a foundation for understanding the human factors contributing to UAS noncompliance.

Purpose Statement

The purpose of the current study is multi-fold: (a) to investigate the trends and regional patterns in UAS altitude deviations in the U.S., (b) to predict future trends in UAS altitude deviations based on historical data in the U.S., and (c) to explore human factors issues related to UAS altitude deviations in the U.S.

Research Questions

Research Question 1: What are the trends in UAS altitude deviations in the U.S. between 2021 and 2024?

Research Question 2: What future trends in UAS altitude deviations can be predicted in the U.S. based on historical data between 2021 and 2024?

The third objective, related to human factors issues in UAS altitude deviations, was investigated from an exploratory perspective by grounding the findings into the Human Factors Analysis and Classification System (HFACS) framework (Wiegmann & Shappell, 2001). Therefore, the third research question is not presented here.

Literature Review

Various studies have been explored as a part of the current literature review and have been summarized into the following sections: safety risks and impact on controlled airspace, operator demographics and regulatory compliance, predictive models and future trends, and human factors in UAS operations.

Safety Risks and Impact on Controlled Airspace

Altitude violations by UAS pose tangible risks to controlled airspace, particularly near busy airport corridors. Howard (2023) identified 241 close encounters between UAS and manned aircraft, with six classified as near mid-air collisions. These incidents often necessitate evasive maneuvers, jeopardizing the safety of both the aircraft and passengers. Okoli et al. (2024) highlighted the systemic nature of this risk, pointing to the lack of detection and response capabilities that could otherwise mitigate these threats. As drone operations continue to expand, their unchecked presence in regulated airspace could result in significant disruptions or disasters without improved risk management strategies being implemented.

Operator Demographics and Regulatory Compliance

The vast majority of UAS operations are conducted by recreational users, who comprise approximately 80% of the user base (Huang et al., 2021). This group is significantly less likely to adhere to altitude restrictions, in part due to limited formal training or a lack of regulatory awareness. In contrast, commercial operators are required to obtain FAA certification and demonstrate their aeronautical knowledge. These credentialed users are statistically more compliant (Huang et al., 2021). Although the FAA has issued more than one million airspace authorizations, Howard (2023) noted that these are often highly location-specific and temporary, raising concerns about the apparent mismatch between issued waivers and the number of high-altitude UAS operations reported.

Predictive Models and Future Trends

Recent advances in predictive analytics have offered promising tools for managing UAS safety. Abraham (2022) trained a machine learning model using Bidirectional Encoder Representation from Transformers (BERT) to classify drone incident data with 96% accuracy, demonstrating that textual FAA reports can be processed to identify hazardous behavior patterns. Howard (2023) cautioned that unverified sightings, inconsistent levels of detail, and a lack of standardized reporting limit the reliability of FAA UAS data for researchers and predictive modeling. While emerging technologies such as Remote ID and low-level airspace traffic management show promise, their effectiveness will hinge on operator participation and robust enforcement mechanisms.

Human Factors Issues in UAS Operations

Understanding human factor issues associated with UAS operations is critical for the safe integration of UAS into the National Airspace System (NAS). According to Reason's Swiss Cheese Model (Reason, 1990), an accident is a breakdown or is caused by the absence of a safety barrier across four levels within a sociotechnical system, including Unsafe Acts, Preconditions for Unsafe Acts, Supervisory Factors, and Organizational Failures. Based on the Swiss Cheese Model, the HFACS framework was developed to identify human error at each of the four levels (Wiegmann & Shappell, 2001). The current study employs the HFACS framework, which classifies unsafe acts as operator errors or violations. Operator errors are further classified into skill-based, rule-based, and decision-making errors. Skill-based errors are associated with slips and lapses due to attention failure during routine tasks. For instance, a recreational UAS operator may lose control due to high-speed winds or get distracted. Perceptual errors occur when an operator's sensory inputs are distorted owing to environmental conditions (Endsley, 1995). For example, a UAS operator misjudged the altitude owing to low visibility. However, in contrast, decision errors are associated with an operator's flawed judgment after the operator knowingly accepts the risk (Reason, 1990). For instance, a commercial or recreational operator exceeding the 400 ft altitude to capture an image or complete an operational task.

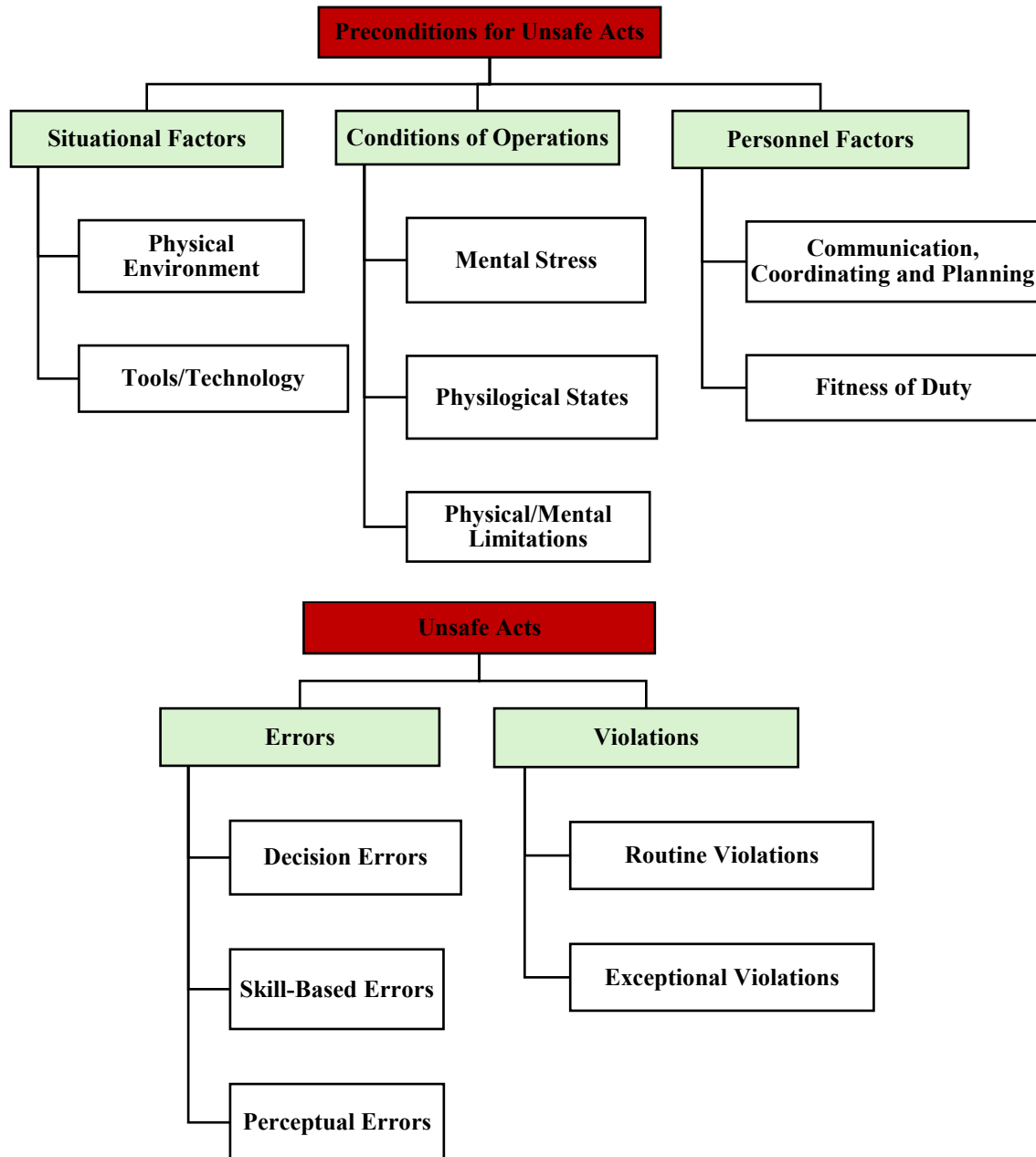
According to Wiegmann and Shappell (2001), preconditions such as environmental factors, conditions of operations, and personnel factors make the outcome of an unsafe act more likely. Factors such as limited situational awareness due to poor display design, insufficient training, fatigue, high workload situations, and environmental stressors create conditions where errors are more likely to occur (Carmody et al., 2023; Hobbs & Lyall, 2016). For example, an inexperienced recreational operator may lack perceptual accuracy while scanning the sky for altitude in an urban environment. A commercial UAS operator may struggle with limited situational awareness by focusing their entire attention on the live video feed and failing to recognize controlled airspace boundaries.

UAS operations have several challenges related to human factors, such as Excessive Alertness, Excessive Mental Fatigue, Monitoring, Excessive Concentration, Discernibility, Distraction, and Workload (Namukasa et al., 2023), which play a significant role in non-compliance in UAS operations, especially regarding inadequate sensory clues that may impact situational awareness. The UAS display design and command interface play a significant role in

the presentation and availability of data to operators (Howe, 2017). A new UAS operator would have limited aeronautical knowledge, training, and/or ability to effectively control and understand operational complexities.

Figure 1

HFACS Framework Emphasizing Pre-conditions from Unsafe Acts and Unsafe Acts



Note. HFACS Framework Adopted from Wiegmann and Shappell (2001).

The lack of command, control, and communication (C3) are critical human factor issues in UAS operations that can significantly affect operators' performance and decision-making (Balog et al.,

2017). Neff and Garman (2016) identified skill-based errors and decision errors as the top two human factors contributing to UAS mishaps, emphasizing the need for prioritized training strategies to mitigate these recurring issues. Williams (2005) found that many UAS accidents could have been prevented with better interface design and procedural safeguards, noting that human error contributed to 21% to 68% of mishaps across different systems. Interface design has also proven problematic: 24% of UAS mishaps have been linked to poorly designed ground control stations (Waraich et al., 2013, p. 26). These human-machine interface failures point to the need for better ergonomic standards and training protocols tailored to UAS operation.

Environmental and operational demands further complicate the altitude deviation. Howard (2023) reported that drone operations at high altitudes face significant environmental challenges, including increased wind speeds and freezing temperatures, which impair control and elevate the risk of flight instability (p. 10). (Carmody et al., 2023; Hobbs & Lyall 2016). interfering with emergency response activities is explicitly prohibited without special FAA permission and emphasized that compliance is influenced by the type of use, user knowledge, and operational location (p. 4). Limitations, such as battery duration and range of communication systems, also push operators to take risks, underscoring the importance of designing technology and rules that reflect real-world challenges.

Research Gap

Historically, very few studies have explored trends in UAS operations (Abraham, 2022; Howard, 2023; Huang et al., 2021). However, there are limited studies that have analyzed the altitude deviations of UAS operations in the U.S. Several studies have investigated human factor issues associated with UAS operations from both commercial and recreational perspectives (Carmody et al., n.d.; Hobbs & Lyall, 2016; Hobbs & Shively, 2012; Namukasa et al., 2023). According to Hobbs and Shively (2022), operators' workload management, interface design, and reduced sensory control are major concerns associated with UAS operations. Carmody et al. (2023) stated that training considerations for UAS operators will play a huge role in safe integration of UAS into the NAS. However, there is a dearth of research on the human factor issues associated with altitude deviations during UAS operations. Moreover, despite the growth in regulatory and technical literature, research on operator behavior and long-term trends remains limited. Therefore, the current study will fill the gap by examining the trends in altitude deviation from 2021 to 2024 and grounding them in the HFACS framework (Wiegmann & Shappell, 2001).

Methods

Population and Sample

The current research focuses on all UAS operations in the U.S. Therefore, the target population constituted all FAA Part 107 and recreational operations in the U.S. The accessible population consisted of all the operations that were reported in the FAA's UAS sightings database between 2021 January and 2024 December that are over 400 feet (Federal Aviation Administration, 2025). The sample for the current study was similar to the accessible population.

Research Methodology

A predictive correlational research methodology was used for the current study, as one of the objectives was to examine the historical trends in UAS sightings and predict future UAS altitude compliance sightings. In addition, an exploratory research design was used to summarize UAS sightings based on different operational characteristics.

Data Collection

All data for the current study were collected from the FAA's drone sightings near airports database (Federal Aviation Administration, n.d.). All data in the current study were archival and collected from a federal database accessible to the public. Although we did not have any direct control over data collection, we assume the data to be valid and reliable as it is coming from a federal database accessible to the public.

Table 1
UAS Report Counts by Year and Month

Month	Year			
	2021	2022	2023	2024
January	120	90	75	70
February	132	159	114	128
March	199	162	108	116
April	214	166	162	138
May	321	221	225	194
June	385	200	189	222
July	203	157	161	147
August	219	168	118	126
September	224	131	142	118
October	190	126	126	130
November	138	85	113	97
December	113	48	81	128

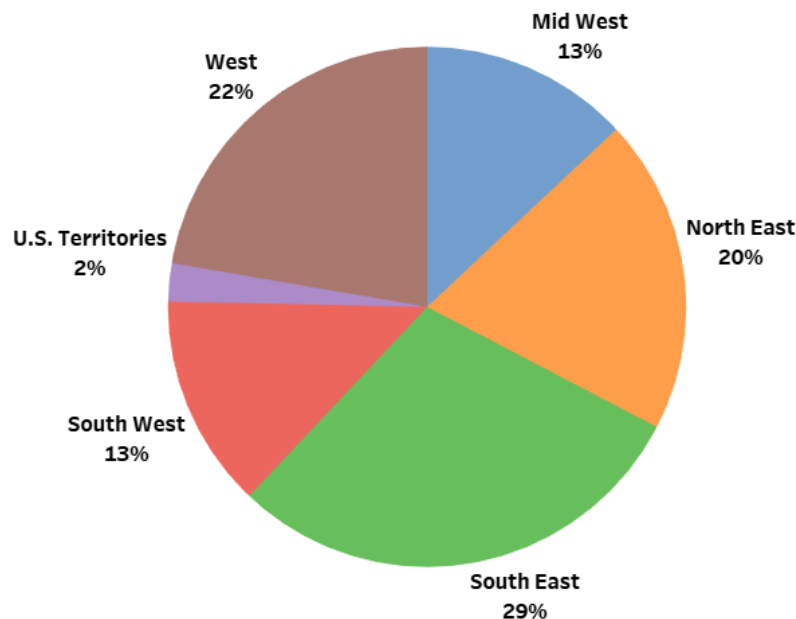
Note. $N = 7,392$. Data from FAA (n.d.).

Table 2
UAS Altitude Compliance Issues by Region

Region	N	%
West Region	1,674	22.64
Southwest Region	981	13.27
Mid-West Region	963	13.03
South-East Region	2,196	29.71
North-East Region	1,406	19.03
U.S. Territories	175	2.37

Note. $N = 7,392$. Data from FAA (n.d.).

Figure 2
Proportion of UAS Reports by Region



Note. The percentages are based on $N = 7,392$. Data from FAA (n.d.).

Results

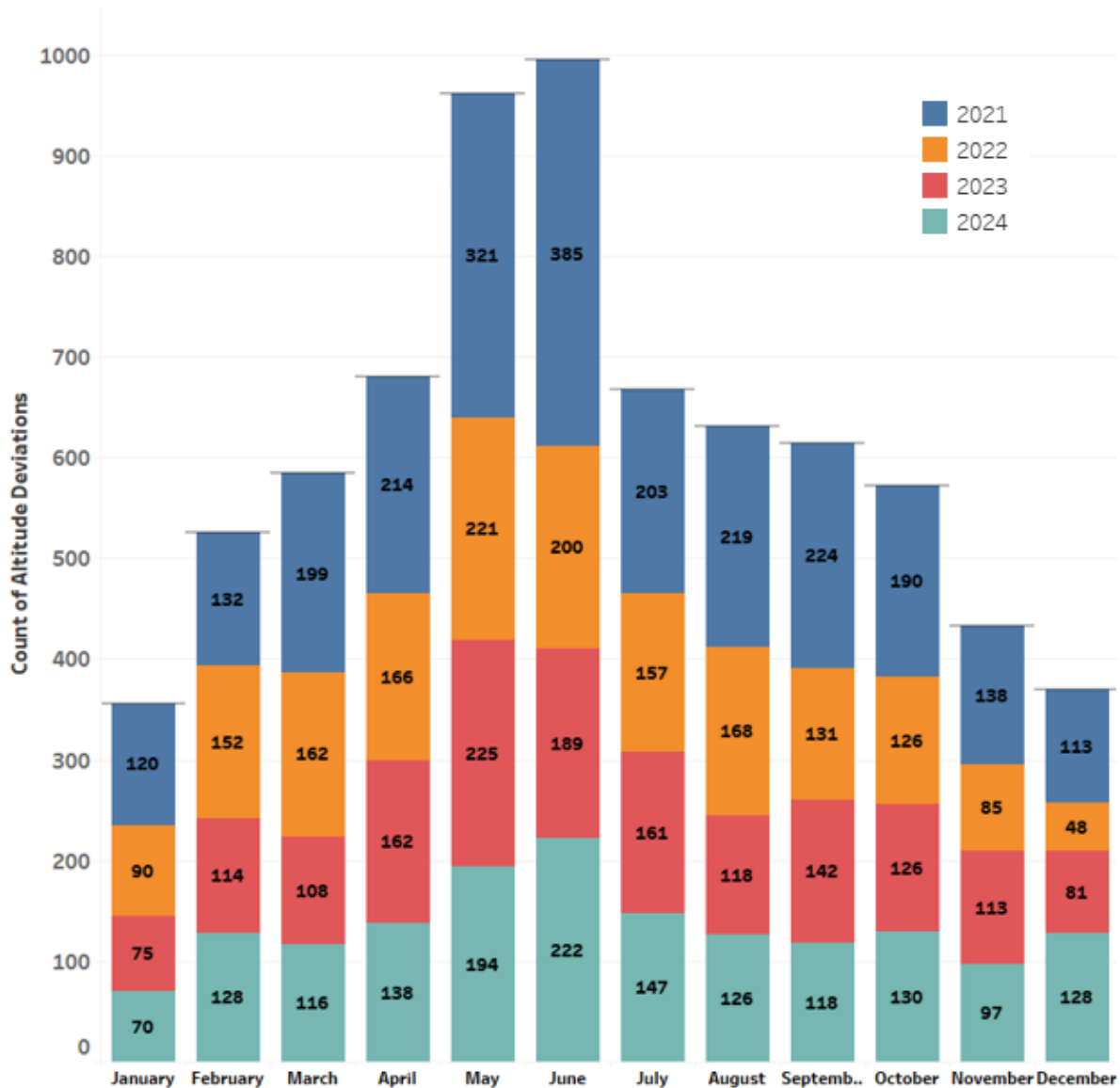
The current study involved two primary research aims: (a) What are the trends in UAS altitude deviations in the U.S. between 2021 and 2024? and (b) What future trends in UAS altitude deviations can be predicted in the U.S. based on the historical data between 2021 and 2024?

Figure 3 shows the monthly breakdown of reported UAS sightings over 400 feet altitude between 2021 and 2024. May, with average sightings of $M = 240$, and June, with average sightings of $M = 246$, were the months with the most UAS sightings over 400 feet in a calendar year. In most regions of the U.S., these months mark the beginning of summer. During these months, the weather is more favorable, with longer daylight hours, providing ideal recreational and commercial UAS operations. A geographical breakdown of UAS sightings by state is provided in Figure between 2021 and 2024, with California ($N = 966$), Florida ($N = 941$), Texas

($N = 580$), New York ($N = 521$), and Illinois ($N = 335$) reporting more than 300 sightings. The higher number of altitude deviations in the above-mentioned states could be the result of some cities within states that are densely populated and have complex airspace structures.

Figure 3

Monthly Breakdown of UAS Altitude Deviations Between 2021 and 2024



As reported in Figure 5, cities with airports serving as major hubs for airlines reported more sightings than cities with non-hub airports. Cities such as New York, Chicago, Seattle, Los Angeles, and Miami, which serve as hubs for some major airlines, such as American, Delta, JetBlue, and United Airlines, reported more than 100 sightings between 2021 and 2024.

Figure 4

Geographical Breakdown of UAS Altitude Deviations Between 2021 and 2024

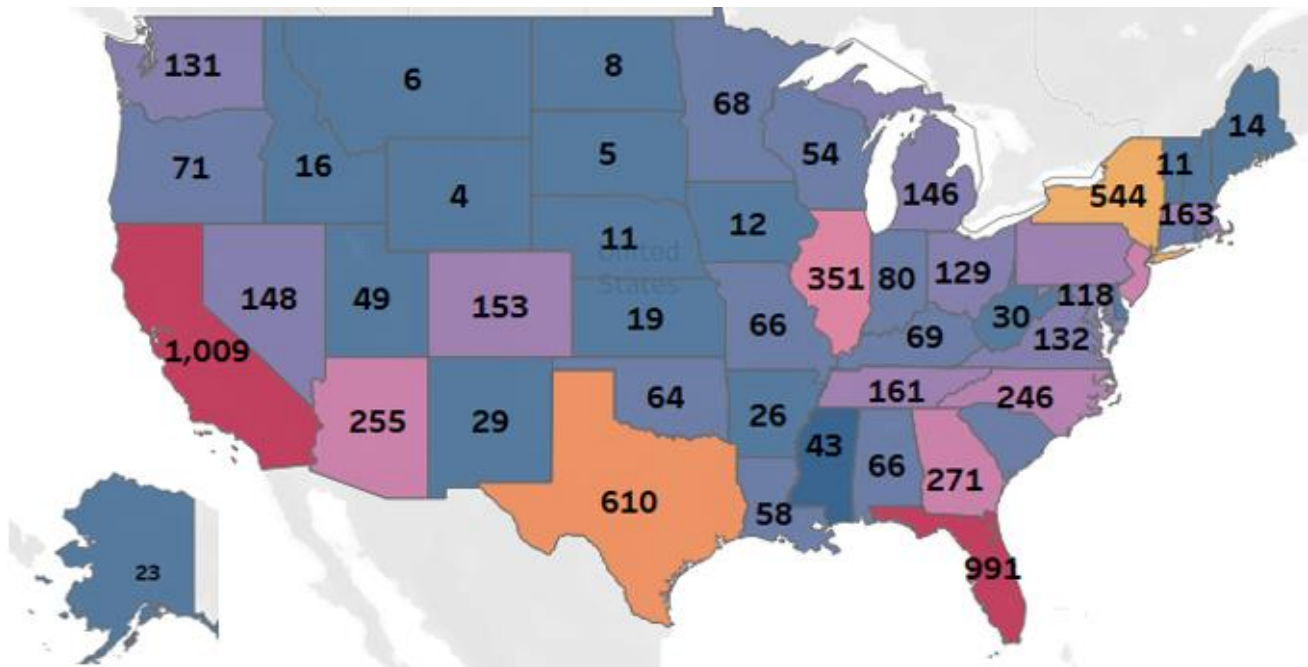
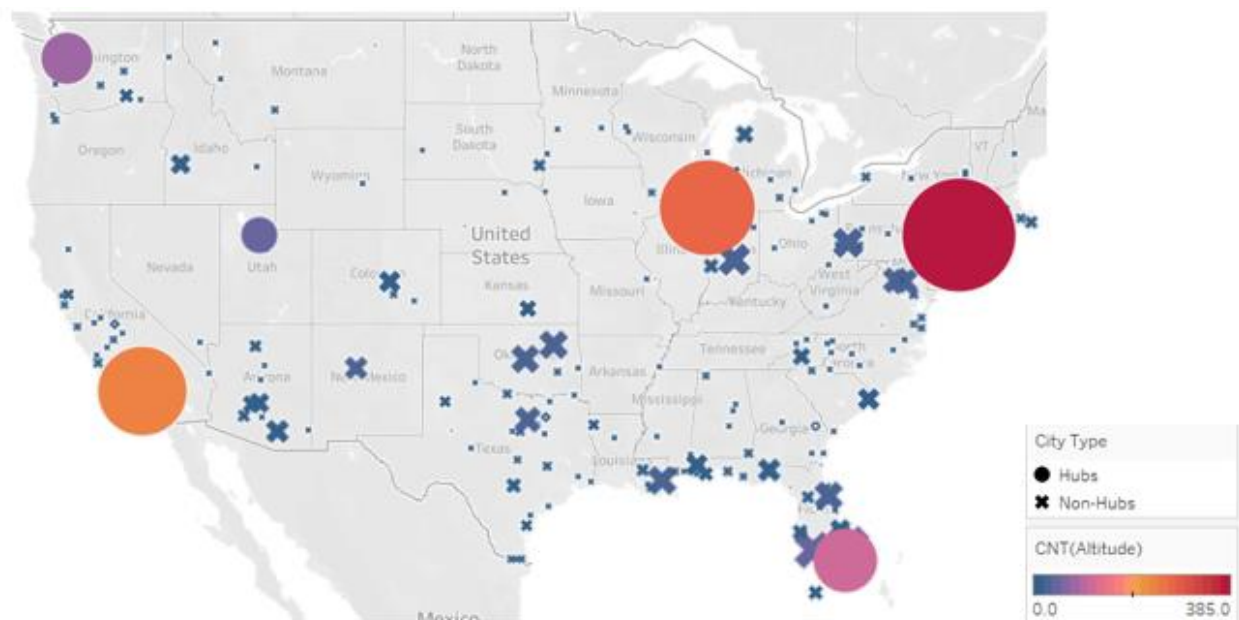
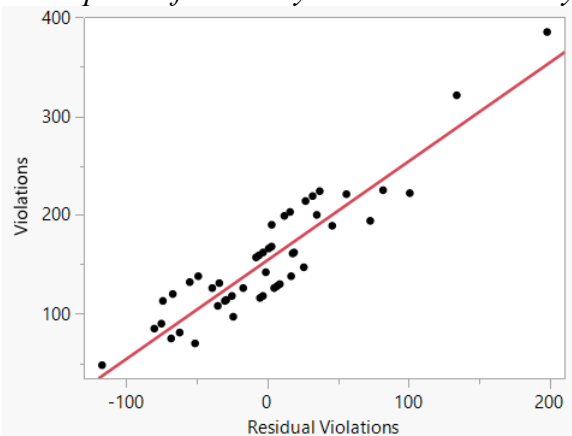
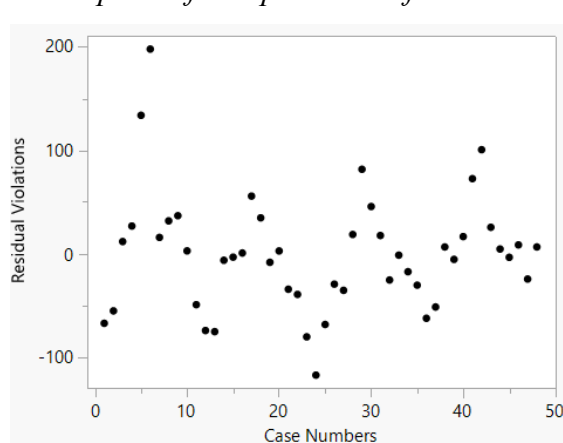


Figure 5

UAS Altitude Violations Between 2021 and 2024 Based on Hub and Non-Hub Airports



A bivariate linear regression analysis was conducted to predict future UAS sightings at over 400 ft in the U.S. Before conducting the primary analysis, all four assumptions for bivariate regression—linearity, homoscedasticity of residuals, independence of residuals, and normality of residuals—were tested. To confirm linearity, a bivariate scatterplot was created with residuals of Y = altitude violations on the x -axis and Y = altitude violations on the y -axis, as shown in Figure 6 (Gallo et al., 2023). A similar plot was also used to determine homoscedasticity, as shown in Figure 6. In addition to linearity, no other discernible pattern was observed. To test for independence a scatterplot was conducted with case numbers on x -axis and residuals of violations on y -axis (Gallo et al., 2023). As shown in Figure 7, there appears to be no detectable pattern, indicating that the residuals are independent of each other. Shapiro-Wilk Goodness of Fit test was conducted to test normality which yielded a p value of .018, indicating a non-normal distribution. However, as the sample size was $N = 48 > 30$, the central limit theorem (CLT) was applied, which indicates that “even if the parent population is not normal in form, the sampling distribution of sample means will approximate a normal distribution if the samples are sufficiently large ($n > 30$)” (Gallo et al., 2023, p. 78).

Figure 6*Assumption of Linearity & Homoscedasticity***Figure 7***Assumption of Independence of Residuals*

As reported in Figure 8, the annual altitude deviations declined between 2021 and 2024. As reported in Table 3, the prediction model was found to be $\hat{Y} = -21.93 (\text{Year}) + 44,497.45$. The R^2 was .16, and the model was significant at $F(1, 46) = 8.80, p = .005$, indicating that approximately 16% of the variance in altitude violations was explained by year. A Post-hoc effect size was conducted to determine the true magnitude of the effect, based on Cohen's (1998) formula $f^2 = \frac{R^2}{1-R^2} = \frac{.16}{(1-.16)} = .19$, which is considered as medium effect. A post-hoc power analysis was also conducted to help interpret the reliability and robustness of the results of the current study and was found to be .86, indicating that 86% of the effect found in the sample existed in the population (Gallo et al., 2023; Kelly et al., 2024; Osman et al., 2022). A forecast model was also built using the 95% confident interval derived from the regression model (see Figure 9) based on the data available between 2021 and 2024, which predicted 1,303 UAS sightings in 2027, which is approximately 300 fewer sightings than in 2024.

Table 3
Regression Summary of UAS Altitude Deviations

Statistics	Estimates	R^2	F	p
		.161	8.801	.0048
B_0	44497.45**			
B	-21.93**			

Note. $N = 45$, * $p < .05$, ** $p < .01$, *** $p < .001$

Figure 8
Prediction Model of UAS Sightings by Year

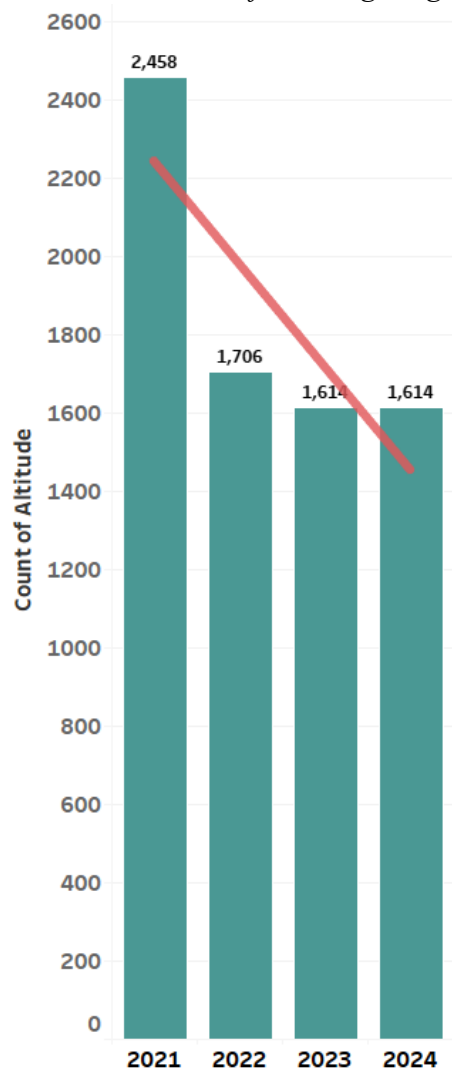
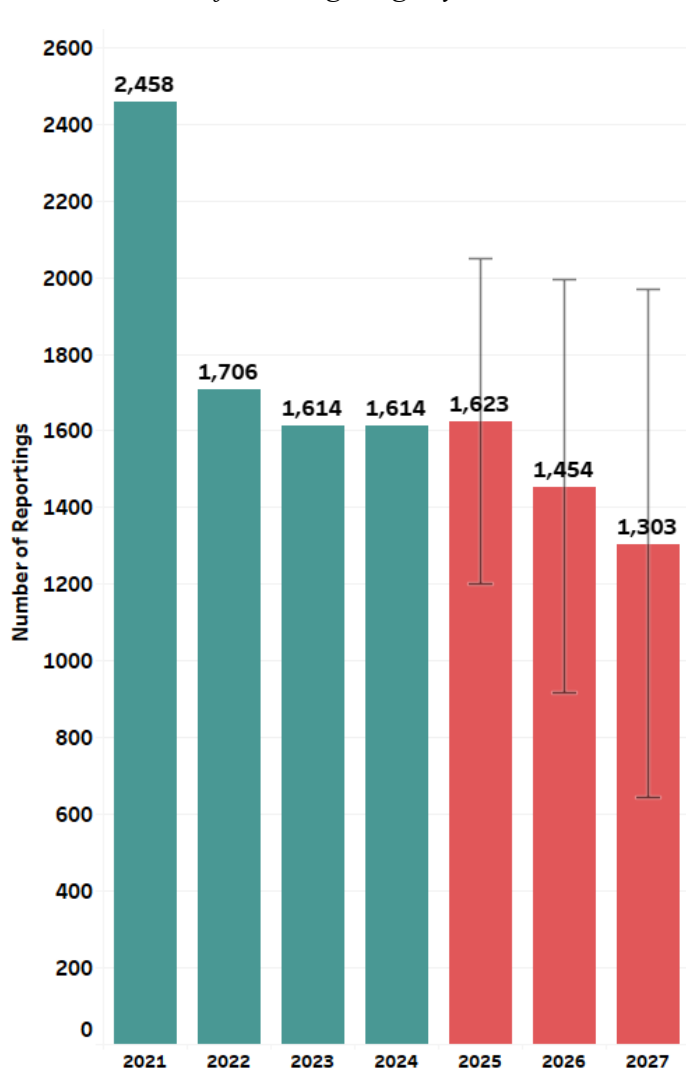


Figure 9
Forecast of UAS Sightings by Year



Discussion

The current study's findings highlight the positive trends in UAS altitude deviations in the proximity of airports serving as hubs, which are part of urban cities such as New York,

Miami, Chicago, and San Francisco. The findings can be attributed to multiple factors, such as the lack of awareness of recreational fliers in highly restricted airspace near the hubs; urban cities tend to have a higher demand for commercial operations, including last mile delivery, photography, and inspection; and the lack of awareness or limited pilot training of recreational fliers with respect to the FAA's regulation on UAS altitude requirements. The current study's findings suggest that there is a downward trend in altitude deviations between 2021 and 2024; projected trends over the next three years also indicate a similar downward trend. A plausible explanation for the declining reports could be the FAA's efforts to improve the awareness of UAS regulations with respect to recreational fliers through programs such as the recreational UAS Safety Test (TRUST), Low Altitude Authorization Clearance (LAANC), and the increased emphasis on UAS registration. However, the findings also revealed that the problem of UAS altitude deviations is not fully resolved, especially near airports.

The findings of the current study can also be interpreted from the perspective of the HFACS framework. For instance, as shown in Figure 5, a larger number of altitude deviations in cities with large hub airports, such as Miami, New York, and Chicago, demonstrate the decision errors of UAS operators' when operating in a complex airspace with high workloads. Altitude deviations in non-hub cities can be attributed to skill-based errors such as attention lapse due to reduced situational awareness. The seasonal trends shown in Figure 3, with more deviations during the summer months, can be attributed to unsafe acts by either recreational or commercial operations that plan to finish the mission during favorable weather conditions. The low count of altitude deviations during the winter months can be attributed to perceptual errors due to reduced daylight or visibility.

Based on the study's findings, we have recommendations from three perspectives: regulatory, original equipment manufacturers (OEMs), and designers. From a regulatory perspective, increasing awareness of UAS altitude regulations by the FAA will likely enhance recreational fliers' airspace and operational knowledge. From the designer's perspective, promoting geofencing and real time altitude warning features in drones that give real time safety alerts to the drone operators will likely reduce the altitude deviation issues. From the OEMs' perspective, training programs, such as TRUST and LAANC, should be integrated as part of training modules to enhance awareness relayed to UAS regulations among recreational flyers. The literature reviewed here confirms that UAS altitude compliance is a multifaceted challenge involving technical systems, human behavior, environmental dynamics, and policy gaps. Unsafe operations are driven by a mix of limited training, flawed interface design, and mission-driven risk tolerance. Future strategies must integrate human factors into policy design, training, and system architecture to ensure that drones can safely coexist with manned aircraft in shared airspaces.

Limitations, Delimitations, and Future Research

The findings of the current study have to be interpreted with the following limitations: (a) all the data for the current study were obtained from FAA's UAS sightings database, including all reported UAS sightings, which may have incomplete information, (b) the correlational research design, prevents causal inferences between year and altitude deviation frequency, and (c) some of the states had sparse data, limiting the generalizability across all U.S. regions. Some of the

delimitations of the current study were (a) time period, data between only 2021 and 2024 were collected, (b) all the data with missing altitude were removed from the database before analyzing the trends, (c) A simple bi-variate regression model was selected over some advance time-series models such as Autoregressive Integrated Moving Average (ARIMA), due to low sample size, and (d) The reader is also cautioned that the forecast model presented in Figure 9 was based on limited data between 2021 and 2024, and therefore the readers need to treat them as an illustrative trend rather than precise limitations. Future research should combine sighting data with other sources of UAS incident reports, such as the Aviation Safety Reporting System (ASRS) database and LAANC authorizations. Moreover, critical datasets, such as National Aeronautics and Space Administration's (NASA's) ASRS (ASRS, n.d.), have not yet been fully leveraged to understand non-compliance. Filling these gaps is vital for developing evidence-based strategies that blend human factor insights with technological solutions. Another recommendation for future research is to examine the qualitative data in the reports, using machine learning – natural language processing (NLP) techniques to analyze the human factor issues related to altitude deviations.

Conclusion

The findings of the current study were able to demonstrate meaningful patterns in altitude deviations with respect to UAS operations in the U.S. between 2021 and 2024. The sightings demonstrated a steady decline in altitude deviations between 2021 and 2024. The results from the prediction model also project a declining trend in altitude deviations. The study also highlights human factor issues, such as workload, situational awareness, communication, design, and training, as critical factors associated with altitude deviations.

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