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Predicting Damaging Wildlife Strikes in Helicopter Operations: A Multi-Variable Analysis with Implications for AAM

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Abstract: Wildlife strikes, particularly bird strikes, pose significant safety and economic risks to aviation, with helicopters uniquely vulnerable due to low-altitude operations. The purpose of this study was to examine bird strike trends and risk factors on helicopters to inform safety strategies applicable to future Advanced Air Mobility (AAM) systems, which share similar operational profiles. Using ten years of data (2013-2022) from the Federal Aviation Administration National Wildlife Strike Database, key variables analyzed included altitude, airspeed, phase of flight, time of day, sky conditions, and bird size. Analyses employed trend assessment, chi-square tests, and logistic regression to identify predictors of strike severity. Results indicate that medium and large birds, daytime operations, and altitudes between 501-1000 feet are associated with a higher risk of damage. The predictive model performed well for non-damaging strikes but was less accurate for damaging ones. Findings provide critical insights for aviation operators and AAM system designers, highlighting the need for continuous data collection and consideration of operational variables to enhance wildlife strike mitigation and helicopter safety.

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Background

Bird strikes pose a significant threat to aviation, particularly to helicopters, due to their low-altitude flight profiles and operation near urban areas where bird populations are dense (Dolbeer et al., 2024). While helicopters account for less than 0.5% of all bird strike accidents, critical areas such as rotor blades, windshields, and engines are prone to severe damage (Hu et al., 2016). This section explores the key factors contributing to bird strikes, and discusses how operators, regulators, manufacturers, and other aviation stakeholders can apply this knowledge, particularly within the emerging field of Advanced Air Mobility (AAM), to mitigate risks and improve safety.

Wildlife strikes have long posed a safety concern to aviation operations. However, high-profile events, such as the 2009 emergency landing of US Airways Flight 1549 following multiple bird strikes, have significantly heightened global awareness of their potential severity (Metz et al., 2021). In the aftermath of this accident, industry and public attitudes have shifted notably, emphasizing the importance of reporting wildlife strikes as a proactive safety measure. The increase in reported bird strikes in subsequent years was also likely driven not only by ecological factors, such as changes in bird populations near airports and growth in air traffic, but also by heightened awareness of the critical role that accurate and consistent reporting plays in advancing aviation safety (Dolbeer et al., 2024). Although overall bird populations in North America have experienced long-term declines, populations of large and medium-sized species have increased, particularly within urban environments where these species exhibit strong adaptability to human-altered habitats (Dolbeer, 2020). This ecological shift has resulted in higher concentrations of these birds near airports and along flight paths, thereby elevating the risk of wildlife strikes, especially during the 2000–2023 period (Dolbeer et al., 2024).

A scientific analysis of the Federal Aviation Administration (FAA) National Wildlife Strike Database (NWSD) (2025) data enables not only the identification of high-risk locations and operational phases of flight, but also the examination of key trends, such as the ratio of total strikes to damaging strikes, seasonal and temporal patterns, and the relationship between altitude and strike probability (Altringer et al., 2023; Dolbeer et al., 2024; Misra et al., 2022). These data-driven insights support the development of proactive safety strategies by airport operators, strengthen wildlife hazard mitigation programs, and inform regulatory policies, including aircraft certification standards and operational guidelines established by the FAA and industry stakeholders. Beyond informing strategic planning and policy development, the analysis of NWSD data also yields critical operational insights. Understanding when and where strikes are most likely to occur allows for more targeted and effective risk mitigation measures. This vulnerability has clear implications for AAM, which will operate extensively in low-altitude urban environments with dense bird populations (Metz & Schler-Morgenthal, 2024).

Most bird strikes occur during the arrival phases of flight, particularly below 500 feet above ground level (AGL), where birds of all sizes are more commonly encountered (Dolbeer et al., 2024). In the FAA NWSD, the arrival phases of flight include descent, approach, and landing roll, indicating that these encounters occur throughout the broader arrival profile rather than only during runway operations. Although helicopters represent only 0.5% of all reported bird strike incidents, they account for approximately 4% of aircraft destruction cases, reflecting their heightened vulnerability during low-altitude operations (Hedayati et al., 2013). Temporal patterns further indicate that more than 50% of bird strikes occur between July and October, with the majority taking place during daylight hours (Dolbeer et al., 2024). Collectively, these findings highlight that while helicopter encounters with wildlife are less frequent, their consequences can be disproportionately severe, underscoring the need for mitigation strategies that are species-specific, altitude-sensitive, and seasonally adaptive. These considerations may also have broader relevance for other low-altitude aviation systems, including emerging Advanced Air Mobility (AAM) concepts.

Economic Impact

The economic impact of bird and other wildlife strikes on civil aviation is considerable. Between 1990 and 2023, such events cost the U.S. civil aviation sector an average of approximately 100,105 hours of aircraft downtime and $248 million annually, comprising an estimated $205 million in direct expenses (e.g., aircraft repairs) and an additional $43 million in indirect losses such as delays and cancellations (DeVault et al., 2018; Dolbeer et al., 2024). In 2023 alone, wildlife strikes were responsible for over 62,000 hours of downtime and an estimated $461 million in total economic losses. These findings are consistent with Ferra et al. (2021) who documented over 67,000 hours of downtime and $386 million in economic losses in a single year. Collectively, these figures underscore the substantial and persistent financial burden these events impose on aviation operations in the United States (Altringer et al., 2021; DeVault et al., 2018).

For example, in March 2024, a medical transport helicopter struck two or more birds during en route operations, resulting in $125,000 in repair costs and 200 hours of aircraft downtime (Dolbeer et al., 2024). DeVault et al. (2018) estimated that wildlife strikes cost the civil aviation industry more than $1.2 billion annually when accounting for both direct damages, such as aircraft repairs, and indirect costs, including delays, flight cancellations, and lost operational revenue. Large-bodied bird species such as Canada geese, Red-tailed hawks, and Turkey vultures have been identified as among the most economically hazardous, primarily due to their body mass and strike frequency.

In recognition of the escalating financial impact of wildlife strikes, the FAA invested over $400 million through the Airport Improvement Program (AIP) between 2009 and 2023 to support wildlife hazard mitigation measures. These include wildlife hazard assessments, habitat modification programs, and the installation of perimeter fencing aimed at deterring bird activity in and around airports (Dolbeer et al., 2024). Wildlife-strike risk is shaped by a variety of operational and ecological factors, including aircraft altitude, flight phase, seasonality, time of day, bird behavior, and aircraft airspeed.

Research consistently shows that the likelihood of a bird strike decreases with altitude. For instance, Dolbeer (2006) reported a 32% reduction in strike risk for every 1,000 feet gained above 500 feet AGL. Seasonal bird migration significantly influences strike probability, as large numbers of birds traverse specific flyways near airports during specific times of the year. The risk is particularly elevated during the critical takeoff-and-landing phases of flight, when aircraft operate at lower altitudes where bird activity is more concentrated (Dolbeer et al., 2024). Diurnal activity patterns further compound this risk, with bird activity peaking during daylight hours and thereby increasing the likelihood of strikes during daytime operations across the aviation system (Dolbeer et al., 2024; Pokrovsky et al., 2021).Aircraft speed is another important factor, as slower-moving aircraft generally experience lower impact forces and potentially less damage during strikes (Lopez-Lago, 2017; Mendonca & Keller, 2022). Increasingly, such operational and biological variables are being incorporated into predictive modeling efforts. Using data from the FAA's NWSD, Misra et al. (2022) applied machine learning techniques to identify key predictors of damaging bird strikes. Their results indicated that bird size was the most influential variable associated with aircraft damage, followed by height of impact (altitude) and aircraft airspeed, with aircraft mass also contributing to the prediction of damage outcomes. Feature importance, permutation importance, and SHAP analyses consistently identified these variables as the strongest contributors to the predictive model. The authors reported that the random forest classifier achieved a balanced accuracy of 78.81% in predicting whether a strike would result in aircraft damage. These findings suggest that both biological factors (e.g., bird size) and operational parameters (e.g., aircraft speed and altitude) play an important role in determining strike severity and support the integration of predictive analytics into wildlife hazard management programs.By understanding how operational variables affect strike risk and severity, aviation stakeholders, especially rotorcraft and low-altitude operators, can implement evidence-based mitigation strategies, such as adjusting flight profiles during high-risk periods, to enhance safety and reduce economic losses.

Helicopter Vulnerability

Helicopters are particularly vulnerable to bird strikes because they typically operate at low altitudes where most wildlife activity occurs. Analyses of the FAA National Wildlife Strike Database indicate that approximately 71% of all wildlife strikes occur at or below 500 ft AGL, and about 82% occur at or below 1,500 ft AGL, which corresponds to the altitude band associated with takeoff, landing, and other low-altitude operations (Dolbeer et al., 2024) In contrast to fixed-wing aircraft, helicopters feature exposed rotor systems and relatively unprotected windshields, factors that increase their susceptibility to substantial damage. Although helicopters represent only a small fraction of total wildlife strike incidents, they account for a disproportionate share of associated fatalities, approximately 17% of all bird strike-related deaths (Hu et al., 2016). This disproportionate impact underscores the need for risk assessment and mitigation strategies specifically tailored to rotorcraft operations. Mitigating bird strike risks for helicopters requires the use of predictive models that incorporate variables such as altitude, time of day, and seasonal bird activity. Analysis of historical strike data enables operators to identify high-risk conditions and adjust flight paths or procedures accordingly. These data-driven strategies are equally relevant to AAM platforms, which share similar low-altitude, urban flight profiles and VTOL operations (Metz et al., 2024). Consequently, insights derived from helicopter strike data could provide a critical foundation for anticipating and managing wildlife hazards in future AAM environments.

Advanced Air Mobility: A Transformative Solution for Urban Transportation

AAM represents a transformative development in the aviation sector, driven by innovations in electric vertical takeoff and landing (eVTOL) aircraft and other enabling technologies. AAM has the potential to revolutionize urban transportation by enhancing travel efficiency, reducing environmental impact using renewable energy, and improving the effectiveness of daily mobility systems (Bridgelall, 2024). Rapid urban population growth and increasing traffic congestion in large and mid-sized cities have intensified pressure on existing ground transportation infrastructure, making the need for alternative solutions more urgent (Arafat & Pan, 2024). In this context, AAM could offer a viable solution by alleviating congestion and expanding transportation capacity through aerial corridors.

Beyond passenger mobility, AAM platforms could also support a range of additional services, including cargo transport, emergency deliveries, and integration with the broader air transportation network. Goyal and Cohen (2022) highlight the potential for AAM to facilitate air ambulance operations, although such applications would pose unique operational and regulatory challenges. While the promise of AAM lies in its ability to address longstanding transportation inefficiencies, its implementation will likely encounter unforeseen technical, regulatory, and safety-related obstacles. Continued research, testing, and infrastructure planning will be essential to realize the full benefits of this emerging mode of aerial transportation.

While AAM offers promising solutions to modern transportation challenges, its successful implementation will require overcoming a range of operational and safety-related obstacles. With the introduction of any new transportation technology, especially one involving low-altitude, high-frequency urban operations, numerous challenges must be addressed before widespread deployment can occur. As noted by Gordo et al. (2023), the full integration of AAM into the national airspace system (NAS) will necessitate adjustments to existing airspace structures. One proposed solution involves establishing dedicated AAM corridors to minimize delays and deconflict operations with both smaller unmanned aerial systems (UAS) and larger, conventional aircraft. In this conceptual framework, smaller UAS would operate below AAM corridors, while traditional fixed-wing aircraft would fly above them. However, such low-altitude airspace allocation introduces a critical safety concern: increased exposure to wildlife strikes.

Approximately 92% of all wildlife strikes to commercial aircraft occur below 3,500 feet AGL (Dolbeer et al., 2024), which is precisely the altitude range where AAM vehicles are expected to operate. Metz et al. (2024) emphasize that sustained operations at these lower altitudes will heighten the likelihood of wildlife encounters. This risk is further exacerbated by using quieter electric propulsion systems, which reduce the auditory cues birds rely on to detect and avoid approaching aircraft. As a result, it is imperative to develop and implement comprehensive wildlife strike mitigation strategies tailored to AAM operations to ensure the safety, reliability, and public acceptance of this emerging mode of air transportation. Despite the growing interest in low-altitude aviation and the emergence of AAM, there is a lack of research specifically focused on wildlife strike risks associated with rotorcraft operations and their applicability to future AAM platforms. This gap is particularly concerning given the operational similarities between helicopters and AAM vehicles, including flight at low altitudes, slower speeds, and urban-centric routes (Kim et al., 2024; Metz et al., 2024).

The purpose of this study was to examine trends in wildlife strikes involving helicopters, and to assess their implications for AAM operations. Specifically, the study sought to evaluate the frequency and severity of these events while identifying key contributing factors including time of day, phase of flight, sky condition, bird size, airspeed, and altitude. By analyzing these variables, the study sought to identify the factors that most reliably predict the likelihood of damaging strikes. The findings are intended to inform the advancement of targeted mitigation strategies for rotorcraft operations and to guide the development of safety policies applicable to AAM platforms, which share similar low-altitude flight profiles and operational characteristics with helicopters. Both rotorcraft and proposed AAM aircraft are expected to conduct frequent takeoff and landing operations from distributed infrastructure and operate primarily within the low-altitude airspace (Metz et al., 2024) where the majority of wildlife strikes occur (Dolbeer et al., 2024).

Importantly, empirical wildlife strike data specific to AAM aircraft are currently unavailable because AAM operations remain limited, and comprehensive operational datasets have not yet been established. Consequently, rotorcraft wildlife strike datasets represent one of the most relevant operational analogs currently available for examining potential wildlife hazards associated with emerging low-altitude aviation systems. In this study, helicopter wildlife strike data are therefore used as a proxy dataset to explore potential wildlife strike risk patterns relevant to future low-altitude aviation environments. This approach does not imply a direct causal relationship between the findings of this analysis and future AAM operations; rather, references to AAM are intended to highlight potential forward-looking implications of the results while the primary analytical focus of the study remains on rotorcraft wildlife strike risk patterns. It is also acknowledged that important technological and operational differences exist between conventional rotorcraft and emerging AAM vehicles (e.g., propulsion architecture, detect-and-avoid capabilities, acoustic signatures, and operating infrastructure), and these differences may influence future wildlife strike risk profiles.

Methodology

Research Design

The authors of this study conducted an exploratory data analysis (EDA) to identify trends, patterns, and operationally relevant factors associated with wildlife strikes involving helicopters. EDA is particularly suited for examining observational datasets as it facilitates the discovery of meaningful relationships without the need for strict prior assumptions about the data structure (Chatfield, 1986; Lau et al., 2023). In this study, the EDA focused on descriptive statistics, frequency distributions, and categorical comparisons of key variables in the dataset, including phase of flight, altitude, airspeed, time of day, bird size, and sky condition. Univariate analyses were used to examine the distribution of individual variables, while bivariate comparisons were conducted to explore relationships between these variables and strike severity (damaging vs. non-damaging). The insights obtained from this exploratory stage informed the subsequent chi-square tests and logistic regression analysis.

The data for this research were obtained from the FAA NWSD, a comprehensive repository of voluntarily reported wildlife strike incidents across the United States, including those involving helicopters. This study focused specifically on helicopter-related strike records reported between 2013 and 2022. This period represents the most recent complete decade of data available in the FAA NWSD when the study was initiated in 2023, as reporting for 2023 was still incomplete at the time of data extraction. The dataset included detailed information on each incident such as phase of flight, aircraft altitude and airspeed, time of day, bird size, sky condition, and strike severity categorized as damaging or non-damaging.

Data Analysis

The analysis was conducted in three stages: (1) descriptive trend analysis to examine temporal and categorical distributions of strikes; (2) statistical testing to assess relationships between the selected variables and strike severity; and (3) a logistic regression model to evaluate the predictive strength of these variables in determining the likelihood of a damaging event.
The dataset initially contained 2,816 wildlife strike incidents involving helicopters, which were used in the first stage of the analysis. To ensure data integrity and analytical consistency, records with incomplete or missing information for any of the six selected variables, including phase of flight, altitude, speed, time of day, bird size, and sky condition, were excluded. This resulted in 1,676 valid incidents for stages two and three of the analysis. While this exclusion was necessary to meet the assumptions of the statistical tests, it may introduce some bias by skewing the representation of damaging and non-damaging strikes or the effect of the variables.
This structured approach allowed for a comprehensive assessment of the conditions contributing to helicopter wildlife strike severity and offered valuable insights applicable to emerging low-altitude urban airspace operations.

The first stage of the analysis involved examining trends across six variables - phase of flight, altitude, speed, time of day, bird size, and sky condition. This exploratory step sought to identify general patterns or trends that may exist between these variables and the occurrence of wildlife strikes. Trends in these variables were examined between strike outcomes (damaging vs. non-damaging) to evaluate whether certain conditions may influence a flight to a higher likelihood of a damaging strike. Insights from this analysis informed the design of subsequent statistical tests and modeling.

The second stage of the analysis employed a chi-square independence test to evaluate potential associations between the six variables (phase of flight, altitude, speed, time of day, bird size, and sky condition) and strike damage outcome, defined as whether the wildlife strike resulted in reported aircraft damage (damaging vs. non-damaging). Each variable was treated as categorical, and chi-square tests were conducted to determine whether statistically significant associations existed between the categories of the independent variables and the strike damage outcome. Significant associations were identified between the independent variables and the dependent variable. This approach provided valuable insight into whether specific operational flight conditions or bird characteristics were significantly related to the severity of wildlife strikes.

In the final phase, a logistic regression model was employed to estimate the likelihood of a damaging wildlife strike based on the six independent variables: phase of flight, altitude, speed, time of day, bird size, and sky condition. These independent variables were included as predictors in the model, allowing for the estimation of their contributions to the likelihood of a damaging strike. Potential interaction effects were examined to account for the possibility that specific combinations of operational conditions and bird characteristics may amplify risk. The model's predictive accuracy was evaluated using a hold-out validation set or cross-validation techniques to ensure its generalizability and robustness. Because the analysis is based on reported wildlife strike events in the FAA NWSD, the model evaluates factors associated with damage outcomes conditional on a strike occurring rather than estimating the overall probability of wildlife strike encounters.

Results

A total of 2,816 helicopter wildlife strike incidents reported between 2013 and 2022 were analyzed in this study, of which 405 (14.38%) resulted in reportable damage. The exploratory analysis revealed several notable patterns across key operational and environmental variables. With respect to the phase of flight, the majority of damaging strikes occurred during the en route phase, with 325 damaging strikes (15.74%) of all en route strikes. Approach and climb phases contributed to smaller, yet noteworthy proportions, while departure, local operations, and events with unknown phase of flight accounted for relatively few damaging incidents. Overall, the distribution highlights the heightened risk during en route operations, where exposure time, airspeed, and low-altitude profiles converge to increase vulnerability (see Table 1).

Table 1

Number of Bird Strikes and Damaging Strikes per Phase of Flight

Phase of Flight	Total Strikes	Damaging Strikes	Percentage of Total
En Route	2,064	325	15.75%
Approach	309	41	13.27%
Climb	196	19	9.69%
Departure	18	2	11.11%
Local	34	4	11.76%
Unknown	195	14	10.77%
Total	2,816	405	14.72%

Bird size exhibited a clear relationship with strike severity. Medium-sized birds accounted for the largest number of damaging strikes (n = 155; 38.27%). Although large birds were involved in fewer total strikes (n = 171; 6.07%), they produced a substantially higher proportion of damage (approximately 48%), reinforcing that larger species pose greater risks due to higher mass and impact energy (Dolbeer et al., 2024). In contrast, small birds comprised the majority of total strikes (n = 1,580) but were associated with a comparatively low damaging-strike rate (about 6%), indicating that frequency alone does not predict severity (see Table 2).

Table 2

Number of Bird Strikes and Damaging Strikes per Bird Size

Bird Size	Total Strikes	Damaging Strikes	Percentage of Total
Large-sized birds	171	82	47.95%
Medium-sized birds	472	155	32.84%
Small-sized birds	1,580	97	6.14%
Unknown	593	71	11.97%
Total	2,816	405	14.38%

Aircraft airspeed was grouped into four 50-knot intervals to examine its relationship with strike severity. This categorization was selected to represent meaningful operational speed ranges while maintaining sufficient observations within each category for statistical analysis and to reflect the established relationship between aircraft speed and the kinetic energy involved in wildlife strike impacts (Dolbeer et al., 2024; Eschenfelder & Hull, 2006). Although the 101-150-knot range accounted for the majority of total strikes in the dataset (n = 1,375), the 51-100-knot range exhibited the highest proportion of damaging strikes within its category (19.04%). In contrast, the larger strike volume at 101-150 knots produced a comparatively lower within-group damage rate (approximately 15%). This pattern indicates that strike severity is not solely a function of strike frequency or higher airspeed, highlighting the nuanced relationship between helicopter operating speed and wildlife strike outcomes. These findings indicate that moderate airspeeds, particularly those aligned with typical helicopter cruise profiles, pose the highest risk, likely due to the combined effects of aircraft vulnerability and increased bird activity at these operational speeds (see Table 3).

Table 3

Number of Bird Strikes and Damaging Strikes per Speed Groups

Aircraft Airspeed	Total Strikes	Damaging Strikes	Percentage of Total
Group 1 (0-50kts)	90	4	4.44%
Group 2 (51-100kts)	562	107	19.04%
Group 3 (101-150kts)	1,375	205	14.91%
Group 4 (151-200kts)	5	1	20.00%
Unknown	784	88	11.18%
Total	2,816	405	14.38%

Sky condition revealed two meaningful patterns in the occurrence of damaging strikes. Clear-sky operations accounted for the largest number of damaging events (n = 188), which likely reflects higher overall helicopter activity under favorable conditions. At the same time, overcast conditions showed a higher within-category damage rate (15.53%), indicating that lower visibility or environmental complexity may contribute to strike severity. Together, these findings demonstrate that damaging strikes occur across all sky conditions, but operational exposure and environmental factors influence both their frequency and severity (see Table 4).

Table 4

Number of Bird Strikes and Damaging Strikes per Sky Condition

Sky Condition	Total Strikes	Damaging Strikes	Percentage
Clear Skies	1,349	188	13.94%
Overcast	206	32	15.53%
Some Cloud	604	99	16.39%
Unknown	657	86	13.09%
Total	2,816	405	14.38%

Time of day revealed differences between exposure and strike severity patterns. Daytime operations accounted for 872 total strikes and 180 damaging events, producing the highest proportion of damaging strikes within any time-of-day category (20.64%). Nighttime operations, however, recorded the largest number of total strikes (n = 1,623) and a similar number of damaging events (n = 188), but with a lower within-category damage rate (11.58%). These results indicate that while damaging strikes represent a greater proportion of encounters during daytime operations, the overall number of strikes, including damaging events is highest at night. Collectively, these findings suggest that wildlife strike risk persists across all lighting conditions and reflects differences in both operational exposure and wildlife activity patterns. Time of day revealed clear differences between exposure and severity. Nighttime operations recorded even more total strikes (n = 1,623) but produced a similar number of damaging events (n = 188), yielding a proportionally lower damage rate and suggesting that nocturnal species may be smaller or less hazardous upon impact. These findings indicate that damaging strikes are most common during daylight hours primarily due to greater operational exposure, while meaningful risk persists across all lighting conditions (see Table 5).

Table 5

Number of Bird Strikes and Damaging Strikes per Time of Day

Time of the Day	Total Strikes	Damaging Strikes	Percentage
Dawn	32	1	3.13%
Dusk	54	9	16.67%
Day	872	180	20.64%
Night	1,623	188	11.58%
Unknown	235	27	11.49%
Total	2,816	405	14.38%

Altitude strongly influenced the distribution of helicopter wildlife strikes. In the 0-500 ft block, there were 469 total strikes and 63 damaging strikes, reflecting the elevated bird activity and operational exposure close to the ground. When expanded to the 0-1,500 ft block, the concentration of risk becomes even clearer, with 1,691 total strikes and 269 damaging strikes, representing roughly two-thirds of all damaging events in the dataset. Beyond 1,500 ft, both strike frequency and the likelihood of damage decreased sharply, indicating that the vast majority of helicopter wildlife strike risk is concentrated at lower altitudes where aircraft operations and bird activity most commonly overlap (see Table 6).

Table 6

Number of Bird Strikes and Damaging Strikes by Height AGL

Height of Strike – Feet AGL	Total Strikes			Strikes with Damage		
	2013-2022	% of Total Known	% Cumulative Total	2013-2022	% of Total Known	% Cumulative Total
0-500	469	20.83	20.83	63	19.09	19.09
501-1000	639	28.39	49.22	115	34.84	53.93
1001-1500	583	25.89	75.12	91	27.57	81.51
1501-2000	304	13.48	88.62	39	11.81	93.33
2001-2500	135	5.99	94.62	14	4.24	97.58
2501-3000	67	2.97	97.61	8	2.42	100
3001-3500	36	1.59	99.21	0		100
3501-4000	18	0.79	100	0		100
Total Known	2,251			330		
Unknown	367			75		
Total	2,618			405		

Our findings, drawn from a decade of data (2013–2022), suggest that damaging strikes are more likely under specific operational profiles, particularly during en route segments characterized by moderate speeds and low to mid altitudes, and during daytime operations. Together, these conditions highlight areas of elevated risk for rotorcraft operators.

Strike Severity and Flight Variables: A Chi-Square Approach

Chi-square tests of independence were performed to examine the relationships between strike severity (damaging vs. non-damaging) and six categorical variables: sky condition, phase of flight, airspeed, bird size, altitude, and time of day. No significant association was found between strike severity and sky condition (χ^2 (2) = 1.852, p = 0.396), phase of flight (χ^2 (2) = 3.856, p = 0.145), and airspeed (χ^2 (1) = 1.953, p = 0.162) (see Table 7). However, a statistically significant association was found between strike severity and bird size (χ^2 (2) = 258.872, p < 0.001, with a moderate effect size (Cramer's V = 0.395). The Sidak post-hoc test was conducted. It showed significant results in three group comparisons. Medium- and large-sized birds were more frequently associated with damaging strikes, whereas small birds were predominantly involved in non-damaging strikes. For altitude groups, the test indicated a significant but small effect (χ^2 (5) = 11.789, $p = 0.038$, Cramer's V = 0.084). The Sidak post-hoc test was conducted. It showed significant results in one group comparison. The comparison showed that damaging strikes were less likely to occur at altitudes between 2,501 and 3,000 feet AGL. Lastly, a significant association was observed between time of day and strike severity (χ^2 (1) = 28.856, $p < 0.001$, Phi = -0.132). The Bonferroni post-hoc test was conducted. It showed significant results in two group comparisons with helicopters more likely to experience damaging strikes during the day and less likely at night.

Table 7

Chi-Square Tests of Independence for Strike Severity

Variable	χ^2	df	p	Effect Size	Significant Post Hoc Findings
Sky Condition	1.852	2	0.396	—	—
Phase of Flight	3.856	2	0.145	—	—
Airspeed	1.953	1	0.162	—	—
Bird Size	258.872	2	< .001	Cramer's V = 0.395	Medium and large birds more likely – damaging strikes Small birds more likely – non-damaging strikes
Altitude	11.789	5	0.038	Cramer's V = 0.084	2,501–3,000 ft less likely – damaging strikes
Time of Day	28.856	1	< .001	$\Phi = -0.132$	Day more likely – damaging strikes Night less likely – damaging strikes

Note. χ^2 = chi-square statistic; df = degrees of freedom; Φ and Cramer's V represent effect size estimates. Post hoc comparisons were conducted using Sidak or Bonferroni adjustments where applicable.

Binary Logistical Regression

For the binary logistic regression, 1,676 valid cases were analyzed to assess the predictive value of selected variables on strike severity (damaging vs. non-damaging). Because the analysis is based on reported wildlife strike events, the model evaluates predictors of damage outcomes conditional on a strike occurring rather than predictors of overall wildlife strike occurrence. The Omnibus Tests of Model Coefficients were significant ($p < 0.001$, $\chi^2 = 285.322$), indicating that the model provided a better fit than the null model and warrants further model evaluation. Model fit was assessed using three tests: Cox & Snell $r^2 = 0.157$ and Nagelkerke $r^2 = 0.268$. Pseudo-R^2 values in logistic regression are typically lower than R^2 values reported in linear regression models and should therefore be interpreted differently. In observational studies involving complex phenomena influenced by multiple interacting factors, values within this range are commonly reported and are generally considered acceptable indicators of model explanatory power (Menard, 2002; Hosmer et al., 2013).

The Hosmer and Lemeshow test yielded a non-significant result (*p* = .627), indicating adequate model fit. In addition to statistical significance, effect sizes were evaluated using odds ratios (*OR*) and corresponding 95% confidence intervals (CI). Several predictors demonstrated statistically significant effects on the likelihood of a damaging strike. Specifically, strikes occurring during the climb phase were associated with significantly lower odds of damage (*OR* = 0.455, 95% CI [0.218, 0.951], *p* = .036), indicating a protective effect relative to the reference phase. In contrast, aircraft operating at speeds between 51–100 knots exhibited significantly higher odds of damage (*OR* = 3.314, 95% CI [1.075, 10.219], *p* = .037), suggesting an increased risk under these conditions.

Bird size emerged as a significant predictor. Strikes involving small birds were associated with reduced odds of damage (*OR* = 0.550, *p* = .009), while medium-sized birds showed a substantially greater reduction in odds (*OR* = 0.081, *p* < .001), both relative to the reference category. These findings indicate that larger birds are disproportionately associated with damaging strike outcomes. Collectively, these results provide an interpretable assessment of predictor influence beyond statistical significance alone (see Table 8).

Table 8

Predictor and Significance Value (p)

Predictor	Predictor Level	p-value	Odds Ratio (OR)	95% CI
Phase of Flight	Climb	.036	0.455	[0.218, 0.951]
Airspeed	51–100 kts	.037	3.314	[1.075, 10.219]
Bird Size	Small	< .001	0.550	[0.351, 0.863]
Bird Size	Medium	.009	0.081	[0.051, 0.128]

Note. Odds ratios (OR) greater than 1 indicate increased likelihood of a damaging strike, while values less than 1 indicate decreased likelihood. The reference categories are phase of flight (all other phases), airspeed (other speed groups), and bird size (large birds). Time of day and large bird size were excluded from the final model due to unstable parameter estimates and quasi-complete separation. Only statistically significant predictors are shown.

The model correctly predicted 97.8% of non-damaging strikes (FALSE), but only 16.9% of damaging strikes (TRUE). The overall prediction accuracy was 84.7%, reflecting a high prediction rate for non-damaging cases but limited effectiveness in identifying damaging events. While the model's overall performance appears acceptable, it is largely driven by the high prediction rate for non-damaging strikes, whereas the model’s ability to predict damaging strikes, the primary focus of this research remains limited.

Discussion and Conclusions

The purpose of this study was to examine the frequency, severity, and contributing factors of wildlife strikes involving helicopters and to identify operational and environmental variables associated with damaging events. Specifically, the study aimed to determine how factors such as bird size, altitude, time of day, airspeed, phase of flight, and sky condition influence the likelihood that a reported wildlife strike results in aircraft damage. Importantly, the analytical framework focuses on factors associated with damage severity among reported strike events rather than modeling the overall probability of wildlife strike occurrence. By analyzing a decade of helicopter wildlife strike data (2013-2022), this research sought to address a gap in the literature, which has largely focused on fixed-wing aircraft, and to provide insights relevant to current rotorcraft operations. While the present analysis focuses on helicopter wildlife strike data, the findings may offer preliminary insights for emerging AAM operations. These aircraft are expected to operate in similar low-altitude environments where most wildlife strikes occur and from distributed infrastructure where formal wildlife hazard management programs may not be required under current FAA regulations. By analyzing a decade of helicopter wildlife strike data (2013–2022), this research sought to fill a gap in the literature, which has largely focused on fixed-wing aircraft, and provide insights relevant to current helicopter operations as well as emerging AAM platforms.

The analysis of helicopter wildlife strikes revealed that altitude, time of day, and bird size are significant factors in determining the likelihood of damaging bird strikes. Studies have shown that larger-bodied animals are more likely to be involved in damaging wildlife strikes, highlighting body mass as a key risk factor (Dolbeer et al., 2024; Mendonca et al., 2024; Pfeifer et al., 2018). Large and medium-sized birds were found to be more likely to cause damaging strikes when encountered by helicopters, while small-sized birds were more commonly involved in non-damaging strikes. This finding is also consistent with the FAA's 2024 wildlife-strike report (Dolbeer et al., 2024), which notes that while small birds are the most frequently struck species, they rarely cause significant damage. For example, Mourning doves were the most frequently struck species by civil aircraft in the USA from 1990 to 2019, but they are not the primary cause of damaging events. In contrast, medium-sized birds, such as Waterfowl (ducks and geese), account for only 5% of strikes yet are responsible for 28% of damaging strikes.

Time of day also influenced strike vulnerability in ways that reflect ecological patterns and broader industry trends. Helicopters were more likely to experience damaging strikes during daylight hours, consistent with FAA findings that over 60% of bird strikes occur during the day (Dolbeer et al., 2024). This alignment suggests that diurnal bird activity, combined with higher helicopter movements and visibility conditions, contributes to increased daytime exposure. However, the occurrence of a comparable number of damaging nighttime strikes indicates that nocturnal conditions also present meaningful risk, likely shaped by differences in species behavior, reduced visibility, and limited detection capability. Overall, the day night distribution of damaging strikes underscores that wildlife hazards persist throughout the entire operational day, reinforcing the need for mitigation strategies that address both diurnal and nocturnal environments rather than focusing exclusively on daytime operations.

Altitude also emerged as a significant factor influencing the likelihood of damage. The majority of damaging strikes occurred at lower altitudes, particularly within the 0-1,500 ft AGL band, where helicopter operations frequently intersect with high concentrations of bird activity. This pattern is consistent with prior research. Dolbeer (2006) reported that approximately 66% of damaging strikes to civil aircraft occur at or below 500 ft AGL, and that the overall probability of a bird strike decreases by roughly 32% for every 1,000 ft of altitude gained. In the present analysis, damaging strikes became progressively less common above 2,000 ft, and helicopters operating above 2,500 ft experienced few damaging encounters, reflecting the reduced presence of birds at higher elevations. Collectively, these findings reinforce that the highest risk zones for helicopter wildlife strikes are concentrated below 1,500 ft, where aircraft operations and bird activity most frequently overlap, while risk decreases substantially at higher altitudes.

In addition to these variables, the binary logistic regression model identified time of day, phase of flight, and speed groups as significant predictors of damaging strikes; however, the model's predictive power was limited, with a low sensitivity of 16.9%In contrast, the chi-square tests revealed significant associations between strike severity and variables such as bird size, time of day, and altitude. This distinction underscores the complementary nature of the two analytical methods. While chi-square tests are effective for detecting relationships among variables, binary logistic regression offers a more precise approach for estimating the likelihood of damaging outcomes based on multiple predictors simultaneously during helicopter operations. Using both methods strengthens the analytical framework and provides a more comprehensive understanding of the factors contributing to strike severity, increasing the robustness of the findings.

While prior research has emphasized the importance of analyzing wildlife strike data to improve overall aviation safety (Dolbeer et al., 2024; Mendonca et al., 2024; Metz et al., 2020), much of this work has focused on fixed-wing aircraft, with limited attention to rotorcraft operations. This study addresses that gap by examining the frequency, severity, and contributing factors of wildlife strikes involving helicopters, which is an area of increasing relevance given the anticipated growth of AAM systems. By identifying operational and environmental predictors such as bird size, time of day, altitude, airspeed, and phase of flight, the findings contribute to a better understanding of the risk landscape faced by rotorcraft-specific risks. These insights not only inform the development of targeted mitigation strategies for current helicopter operations but also support proactive safety planning for emerging AAM platforms, which share similar low-altitude, urban flight profiles and operational characteristics.

Implications for Practice

Developing a predictive model for damaging bird strikes is feasible, but it requires more comprehensive data, a wider range of variables, and a broader base of case studies. Much of the existing research is outdated and does not reflect current environmental or operational conditions. For instance, Dolbeer's (2006) frequently cited study on bird strikes and altitude is nearly two decades old, limiting its applicability given the changes in bird populations and migratory behaviors. Similarly, Washburn et al. (2013) conducted a more targeted study on helicopters and bird strike patterns, but their analysis relied on data from 1990 to 2011. These limitations underscore a pressing need to update the research that captures recent trends and to support the development of a reliable predictive model.

From an operational standpoint, several practices can help helicopter and AAM operators reduce the risk of wildlife strikes. Flight planning should account for seasonal bird migration patterns. Doing so can significantly reduce the likelihood of encountering flocks in flight paths. Additionally, operators should consider limiting nighttime operations when operationally feasible, as reduced visibility may limit the ability to visually detect and avoid birds as suggested by MacKinnon (2004), should minimize nighttime operations, as limited visibility increases the chances of a strike. Altitude management also plays a critical role, as the 0-1,500 ft AGL band is particularly prone to bird activity. Finally, reducing airspeed to below 100 knots during approach phases can lessen the impact severity if a strike occurs (Mendonca & Keller, 2022).

Delimitations and Limitations of the Study

Several delimitations were applied to focus the scope of this study. First, the analysis was limited to civil helicopter wildlife strike events reported in the FAA NWSD between 2013 and 2022. Fixed-wing aircraft, UAS, and other aircraft categories were excluded to ensure the findings remained specific to rotorcraft operational environments. Second, strike severity was operationalized using a binary classification (damaging vs. non-damaging) rather than differentiating between levels of damage severity or economic impact. This approach was adopted to facilitate statistical modeling and maintain consistency with the structure of the NWSD damage reporting fields. Third, the analysis focused on operational and environmental variables (e.g., altitude, phase of flight, airspeed, time of day, sky condition, and bird size). Spatial variables such as airport location, regional wildlife management practices, and specific habitat characteristics were intentionally excluded to emphasize broader operational patterns rather than site-specific risk factors. Additionally, birds were categorized by general size classes (small, medium, large) rather than species-level identification to examine general risk patterns associated with strike severity.

A number of limitations should be considered when interpreting the results. First, the FAA NWSD relies largely on voluntary reporting, which raises concerns regarding data completeness and potential reporting bias. Minor strikes or events perceived as operationally insignificant may be underreported, potentially influencing the observed distribution of wildlife strike events. Second, the dataset does not include operational exposure metrics such as helicopter flight hours, mission type, or altitude-specific operational activity. As a result, the analysis reflects patterns in reported strike events rather than normalized strike rates. Third, the logistic regression model demonstrated limited sensitivity in predicting damaging strikes, which may be partly attributable to the class imbalance present in the dataset, where non-damaging strikes substantially outnumber damaging events. This low sensitivity substantially limits the model's practical utility for identifying high-risk damaging events, which are of primary importance in aviation safety contexts. Additionally, this imbalance may bias classification performance toward the majority class. Future research should consider techniques such as resampling methods or cost-sensitive modeling approaches to improve predictive performance for rare but critical outcomes. Finally, the statistical analysis includes methodological limitations. Although post hoc analyses (e.g., Sidak and Bonferroni adjustments) were conducted for selected variables, they were not systematically applied across all categorical predictors, limiting the ability to fully interpret category-level differences. This constraint should be considered when interpreting the strength and specificity of associations identified in the chi-square analyses. In addition, the logistic regression analysis did not include detailed diagnostics such as multicollinearity assessments (e.g., variance inflation factors) or additional model calibration metrics (e.g., ROC curves or AUC), which could further inform model performance and predictive reliability.

In conclusion, developing a reliable predictive model for damaging bird strikes in helicopter operations is feasible; however, it requires more comprehensive data, a broader range of variables, and additional case studies to improve accuracy and practical applicability. To mitigate wildlife strike risk, helicopter and AAM operators should incorporate bird migration patterns into flight planning, consider limiting nighttime operations when operationally feasible, and adopt strategies that reduce exposure to low-altitude environments where most strikes occur. As shown in Table 6, approximately 75% of all strikes and 82% of damaging strikes occur between 0 and 1,500 ft AGL. Accordingly, operational measures such as managing altitude profiles, reducing approach speeds (e.g., below 100 knots when feasible), and increasing pilot awareness during low-altitude phases of flight may help reduce strike risk and associated damage. While this study provides valuable insights, further research is needed to identify additional predictors and refine predictive models to support more effective risk management.

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