

# Composition or encounter? Decomposing the altitude and night-time damage premiums in wildlife strikes to civil aircraft in the United States

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## Abstract

Damaging wildlife strikes to civil aircraft are commoner above 500 ft and at night, patterns usually attributed to the animals involved. Using the FAA National Wildlife Strike Database (354,564 reports, 1990–2026), damage probabilities were directly standardised to a common taxon mix under three standard populations, separately for aircraft up to and above 5,700 kg. Standardisation removed 66 to 80% of the night excess in lighter and 65 to 95% in heavier aircraft, leaving 1.07 (1.001–1.15) and 1.04 (0.99–1.09). How much remains is not settled: it varies with the coding of the outcome (1.04 to 1.10 and 0.97 to 1.04) and with whether unidentified birds are treated as composition, and intervals that resample airports include 1. Composition removed less of the altitude excess, where ratios stayed at 1.90 to 2.30 and 1.70 to 2.33 and the association held within individual taxa. Among heavier aircraft it weakened once recorded airspeed was held: on airspeeds present on both sides of 500 ft the ratio fell from 1.50 to 1.10 to 1.24, and to 1.14 on 10-kt bins. Damage probability levelled off above 1,500 ft in lighter aircraft but not in heavier ones. Airspeed is recorded selectively and species identification depends on damage and height, so collision energy and the selective reporting of strikes at altitude cannot be separated here. Hazard assessments for climb and approach corridors should not rest on species presence alone.

Keywords: bird strike; wildlife hazard management; aviation safety; direct standardisation; flight altitude; airspeed

## Introduction

Whether a wildlife strike damages an aircraft depends first on the animal. Dolbeer et al. (2000) ranked species groups in the FAA National Wildlife Strike Database (NWSD) by the share of strikes causing damage and showed that the most frequently struck species are not the most hazardous. DeVault et al. (2011) extended the ranking to 77 species and related the probability of damage to body mass; DeVault et al. (2016, 2018) and Ross et al. (2025) carried the approach off the airport and forward to recent years, and Rafe and Das (2026) again found body mass dominant in an ordered-probit model of the 1990–2025 record. Costs follow the same gradient (Anderson et al. 2015; Altringer et al. 2021).

Two further patterns are reported alongside the species ranking. Strikes above 500 ft above ground level

are more likely to cause damage than strikes at or below it (Dolbeer 2006, 2011; Dolbeer et al. 2026), and the FAA's most recent serial report notes a rising rate of damaging strikes during climb and approach above 1,500 ft (Dolbeer et al. 2026). Some taxa are struck mainly after dark: white-tailed deer (*Odocoileus virginianus*) at night and dusk (Biondi et al. 2011), and bats almost exclusively at night (Biondi et al. 2013). Dolbeer and Begier (2025) argue that strikes during climb and approach, which occur beyond the airport boundary, need management approaches distinct from those available on the airfield.

We refer to the higher damage rate above 500 ft as the altitude premium and to the higher damage rate at night as the night premium. Both are usually presented as marginal tables pooled over all animals, and a marginal table cannot distinguish two explanations. Under the first, composition, altitude and darkness change which animals can be struck; large birds and mammals are over-represented among them, and damage is commoner for that reason alone. Under the second, encounter, a strike with the same animal is more damaging at altitude or at night, because closing speed and therefore collision energy are higher, because crews have less opportunity to avoid the animal, or because minor strikes at altitude go unnoticed and unreported. The distinction matters for management. If composition explains the patterns, the relevant lever is which species use the airfield and its approaches. If it does not, height and light condition carry information about the outcome of a strike beyond the identity of the animal.

Several studies have modelled damage on the NWSD with height, airspeed and animal size as joint predictors. Avrenli and Dempsey (2014) found height, bird size and number of birds struck associated with engine failure, and Misra et al. (2022) ranked strike height, airspeed, bird size and aircraft mass among the strongest predictors of damage in a machine-learning model. Such models show that height predicts damage when size is included, but they do not separate how much of the marginal height or night premium is due to the mix of animals and how much remains within taxa, and they do not examine the premium against the variable most likely to carry it, airspeed. Metz et al. (2020) review the physical basis: impact energy scales with the square of relative velocity.

This study decomposes both premiums directly. It asks how much of each is removed when damage probabilities are standardised to a common taxon mix, whether the altitude premium persists within individual taxa, and how far recorded airspeed and phase of flight account for what remains.

## Methods

### Data

The analysis uses the NWSD, a voluntary reporting system for wildlife strikes to civil aircraft in the United States (Dolbeer et al. 2018, 2026), in the public export of 6 September 2026, aggregated with an open pipeline into freeze 2026-09-07. The export holds 354,564 reports, of which 22,210 (6.26%) are coded as damaging; incident years span 1990 to 2026, with 2026 incomplete. Table S1 traces the reports from the export to each analysis. Eight report identifiers occur twice, all from one species code mapped to two names in the species table; 1 of them falls within the aircraft classes analysed and was kept; removing it lowers the total and heavier-class counts and one stratum count by one report and changes no standardised or within-taxon estimate.

The record is incomplete and reporting is not independent of outcome. About 47% of strikes were reported in 2009–2013 (Dolbeer 2015), damaging strikes are reported more completely than minor ones (Dolbeer and Wright 2009), pilot reports under-represent small birds (Linnell et al. 1999), and species identification from remains has improved over the period (Dove et al. 2008).

Outcome. A report was counted as damaging if DAMAGE\_LEVEL was minor (M), undetermined severity (M?), substantial (S) or destroyed (D). The M? code records damage whose severity was not determined. DAMAGE\_LEVEL is blank on 125,096 reports, which were counted as non-damaging: the FAA's separate INDICATED\_DAMAGE flag is 0 on 125,095 of them and 1 on 1. Of the 8,911 M? reports, 3 carry INDICATED\_DAMAGE = 0. Online Resource 1 (Table S2) repeats every decomposition under four codings of the outcome.

Aircraft classes. Reports were split by the FAA mass class AC\_MASS into lighter aircraft (classes 1–2, up to 5,700 kg) and heavier aircraft (classes 3–5, above 5,700 kg), analysed separately throughout (Table 1). Mass class is not type of operation: 9,744 heavier-class reports list an operator coded BUSINESS, and scheduled carriers appear in the lighter class (Cape Air alone 463 reports). The 100,409 reports without a mass class (28.3% of the export, 0.19% damaging) were excluded.

Table 1 Aircraft mass classes, report counts and damage rates

| Mass class              | Definition  | Reports | Damaging | Damage rate |
|-------------------------|-------------|---------|----------|-------------|
| All records             | —           | 354,564 | 22,210   | 6.26%       |
| Lighter, up to 5,700 kg | AC_MASS 1–2 | 30,418  | 7,219    | 23.73%      |
| Heavier, above 5,700 kg | AC_MASS 3–5 | 223,737 | 14,797   | 6.61%       |
| Mass not recorded       | excluded    | 100,409 | 194      | 0.19%       |

Strata. Animals were grouped from the leading characters of the FAA SPECIES\_ID, two-character prefixes taking precedence: deer (1G), bats (1C), other mammals (1), waterfowl (J), raptors (K), owls (R), gulls and terns (NE), shorebirds (N), pigeons and doves (O), songbirds (Y, Z) and herons and egrets (I). Identified species outside these prefixes (for example chimney swift, common nighthawk, American coot, sandhill crane and double-crested cormorant) formed an Other identified stratum. Unidentified birds were split by the size carried in their code (small, medium, large, and size not recorded). Unidentified animals were retained, not dropped, because identification is associated with body size and with damage.

Contrasts. Two contrasts were examined: reports above 500 ft against reports at or below 500 ft, where the lower side includes strikes on the ground; and Night against Day as coded by the reporter. Dawn (665 lighter-class reports, 18.35% damaging) and Dusk (1,337, 30.29%) were not assigned to either side; assigning dusk to night or dawn to day is examined as a sensitivity analysis. Reports without a recorded height or light condition were excluded from the corresponding contrast; height was not recorded on 80,108 reports (31.5% of the two classes).

## Estimation

For each contrast a 2×2 table was built per stratum, keeping strata with at least 30 reports on each side. The primary measure was the directly standardised risk ratio: the damage probability on each side was standardised to a common stratum distribution and the two standardised probabilities were divided. The risk ratio is collapsible, so the change from the crude to the standardised ratio can be attributed to composition given the chosen standard. Because that attribution depends on the standard, three were used: the combined stratum sizes, the exposed side (above 500 ft or night) and the baseline side. Confidence intervals were obtained by the delta method with the standard held fixed; all 95% intervals use  $z = 1.96$ . The share of the crude excess risk removed by standardisation,  $(\text{crude RR} - \text{standardised RR}) / (\text{crude RR} - 1)$ , carries a 95% percentile interval from a parametric bootstrap in which each stratum's damaging count was redrawn from a binomial distribution with the observed rate (2,000

replicates, seed 20260917). This bootstrap ignores clustering of reports within events and airports, so its intervals are optimistic. For the night contrast, where the residual is close to 1, a second bootstrap resampled airports rather than reports (1,000 replicates, the same seed), applying the 30-report rule again inside each replicate; reports with no airport code form their own cluster.

Mantel–Haenszel odds ratios with Robins–Breslow–Greenland intervals and Tarone-corrected Breslow–Day tests are reported as familiar summaries. They were not used to measure composition, because the odds ratio is not collapsible and a crude and an adjusted odds ratio can differ without confounding (Greenland et al. 1999).

### Mechanism of the altitude premium

Three further stratifications examined what remains of the altitude premium after composition.

*Airspeed.* Recorded airspeed was grouped into bands (below 80, 80–119, 120–159, 160–199, 200–249 and 250 kt or more), and, within reports on which airspeed was recorded, the altitude contrast was standardised on stratum  $\times$  airspeed band, keeping cells with at least 10 reports on each side. Because high airspeeds occur almost only above 500 ft, the retained cells cover a narrower range of airspeeds than the subset as a whole; the comparison with standardisation on stratum alone was therefore made on the same retained cells (the common support), and repeated with the aircraft mass class (AC\_MASS 1 to 5) added to the cross-classification. Delta-method intervals over many small cells are optimistic.

A 40-kt band is wide enough to leave a systematic difference in recorded airspeed between the two sides of 500 ft (Table S3), so two further checks were run (Table S4). The contrast was repeated on 10-kt bins, which reduce the difference remaining inside a retained cell, averaged over cells, to less than half a knot, and each report was reweighted by the inverse probability that an airspeed had been recorded, estimated per stratum, side and damage status on the height-recorded reports. Every airspeed result is an association among reports that carry a recorded airspeed on overlapping bands, not an estimate for all reports with a recorded height. Airspeed was recorded on 70% of lighter-class and 60% of heavier-class reports with a recorded height. Airspeed lies between height and collision energy rather than beside them, so this stratification is not an adjustment for confounding. Nor does it identify a mediated effect: recording of airspeed depends on damage, height and the circumstances of the strike, and that selection can also act within airspeed bands. What it measures is how much of the altitude association remains among strikes reported at similar airspeeds. SPEED is the indicated airspeed entered by the reporter, not a measured closing speed, so it stands for collision energy only approximately.

*Phase of flight.* Strikes on the ground roll differ from strikes in flight. The contrast was therefore repeated on airborne reports only (excluding the ground height band, the take-off run, landing roll, taxi and parked phases, and reports without a recorded phase), with 1–500 ft as the baseline, standardised on stratum and on stratum  $\times$  phase of flight. The night contrast was also standardised on stratum  $\times$  phase of flight. Phase of flight describes the circumstances of the strike and is not itself caused by darkness, but night strikes during the ground roll may also be less often noticed, so this stratification can absorb a detection effect as well as a circumstantial one.

Stratifications that cross the stratum with a second variable (airspeed band, phase of flight, mass class) keep cells with at least 10 reports on each side; reports with no recorded phase form their own category in the night  $\times$  phase stratification. The stratification on stratum  $\times$  decade keeps cells with at least 30 reports on each side. Common-support comparisons pool the retained cells back to strata without a further size threshold.

*Number of animals struck.* The altitude contrast was repeated for reports of a single animal and of two or more, since a flock changes the encounter rather than the animal (Table S11).

*Height bands.* The standardised damage probability was computed for each of the five height bands (ground, 1–500, 501–1,500, 1,501–3,000 and above 3,000 ft) over the strata that reach 30 reports in every band, with one set of weights for all five, so that the bands can be read as one profile. Comparing each band with the band below it on its own strata and weights, as in earlier versions of this work, gives a different sequence and is reported in the Online Resource. Requiring presence in all five bands excludes ground-concentrated strata, so the profile was also computed over the strata present in the three lowest bands.

#### Taxon-level replication and identification

The altitude contrast was repeated within taxa with at least 100 reports on each side of 500 ft. FAA codes that are a prefix of another code in the record were treated as group codes and reported separately from leaf codes. Each taxon's estimate is a Mantel–Haenszel odds ratio across the two mass classes, which were not pooled. Counts of intervals excluding 1 are unadjusted; the number surviving a Holm correction is also given.

Within-taxon estimates are conditional on the species having been identified, and identification may depend on both damage and height: remains of a damaging strike are more likely to be collected and sent for identification. For each class and contrast, the probability that a report carried an identified species was computed by damage status on each side, and the ratio of ratios  $\psi = [P(\text{id} \mid \text{damage, exposed})/P(\text{id} \mid \text{no damage, exposed})] / [P(\text{id} \mid \text{damage, baseline})/P(\text{id} \mid \text{no damage, baseline})]$  was used as a sensitivity factor: if identification selects on damage and side by the same factor in every taxon, the observed within-taxon odds ratio is inflated by exactly  $\psi$ . The marginal  $\psi$  is not an estimate of that factor for any taxon, because it also carries composition;  $\psi$  computed within FAA size classes over the non-mammal strata varies from 1.15 to 2.53. Within-taxon odds ratios are therefore divided by several fixed factors as scenarios rather than corrected by one, and also by the factor computed for the taxon's own FAA size class. Each taxon here carries a single size code. As a complementary check, the altitude contrast was also computed within the four unidentified-bird strata, which no species-level identification can select into or out of by taxon. The direction in which identification shifts these odds ratios depends on assumptions that this record cannot test, so they are reported as a separate line of evidence and not as a bound.

#### Sensitivity analyses and analysis history

The decomposition was repeated over identified strata only; with the grouping used in the preprint of this work, in which identified species outside the listed prefixes and all unidentified birds formed one stratum; standardised on stratum  $\times$  decade; and under four codings of the outcome (Online Resource 1, Tables S2, S5). The analysis was not pre-registered. It developed over successive versions of a preprint: the measure of composition was changed from odds ratios to standardised risk ratios, the three standards and the stratum definitions above were adopted, and the airspeed, phase, height-band and identification analyses were added in response to reviews. All versions of the analysis are reported in this paper or its Online Resource.

## Software and use of AI tools

All quantities were computed in Python from the deposited freeze by `build_r7.py`, which refuses to produce the manuscript unless the analysis table reproduces the independently exported per-family tables cell by cell. A generative AI assistant (Claude, Anthropic) was used to draft and revise text and to write analysis code; all analyses and statements were checked by the author, who is responsible for the content.

## Results

### Night

In the lighter class the marginal damage rate was 27.87% at night against 21.88% by day. Over the 14 strata the crude risk ratio was 1.29; standardised to the combined stratum mix it was 1.07 (95% CI 1.001–1.15), and 1.06 to 1.10 across the three standards, removing 66 to 80% of the excess (Table 2). Deer account for most of what standardisation removes: they are struck disproportionately at night and damage the aircraft in most strikes (Tables S6, S7). With phase of flight also held constant the ratio was 0.98 (0.92–1.05), against 1.07 (1.01–1.13) on the same cells with the stratum alone.

In the heavier class the crude ratio was 1.16; standardised it was 1.04 (0.99–1.09), 1.01 to 1.06 across standards, removing 65 to 95% of the excess, and 1.02 (0.96–1.08) on stratum  $\times$  phase of flight. Restricted to identified strata a residual remained in both classes (1.10, 1.001–1.22; 1.15, 1.07–1.23). In the heavier class the work is done by the strata rather than by the phase: medium and large unidentified birds made up 23.7% of night strikes against 9.9% of day strikes, and adding phase of flight moved the ratio from 1.02 to 1.02 on the same cells, although the phase distribution differs strongly (64.6% of night strikes on approach against 33.4%). In the lighter class phase of flight does change the estimate. With the preprint grouping, the heavier-class night ratio was 1.14 (1.09–1.19). Counting dusk as night gave 1.02 to 1.09 and 1.01 to 1.04 across standards, and counting dawn as day 1.07 to 1.11 and 1.00 to 1.05 (Table S5). Under the four codings of the outcome the night ratio ranged from 1.04 to 1.10 in the lighter class and 0.97 to 1.04 in the heavier class (Table S2), so what is left of the night premium depends on how blank and undetermined severity grades are treated. Resampling airports rather than reports widens the intervals on the primary estimates to 0.96–1.27 (2,145 airports) and 0.95–1.13 (1,389); neither residual is distinguishable from 1 once strikes are clustered by airport.

Table 2 Crude and directly standardised risk ratios (95% CI) under three standard populations. Combined: stratum sizes on both sides; exposed: night or above 500 ft; baseline: day or at or below 500 ft. Share removed = (crude – standardised)/(crude – 1), negative when composition masks the association

| Contrast                             | strata | crude |                          | exposed              | baseline             | share removed,<br>combined<br>(bootstrap<br>95% CI) | identified<br>strata only,<br>combined |
|--------------------------------------|--------|-------|--------------------------|----------------------|----------------------|-----------------------------------------------------|----------------------------------------|
|                                      |        | RR    | combined                 |                      |                      |                                                     |                                        |
| Night vs day, lighter                | 14     | 1.29  | 1.07<br>(1.001–<br>1.15) | 1.10 (1.06–<br>1.15) | 1.06 (0.97–<br>1.16) | 75% (55 to<br>102)                                  | 1.10<br>(1.001–<br>1.22)               |
| Night vs day, heavier                | 16     | 1.16  | 1.04 (0.99–<br>1.09)     | 1.01 (0.97–<br>1.05) | 1.06 (0.99–<br>1.12) | 77% (53 to<br>112)                                  | 1.15 (1.07–<br>1.23)                   |
| Above vs at/below 500 ft,<br>lighter | 13     | 2.25  | 2.14 (2.03–<br>2.24)     | 1.90 (1.81–<br>1.99) | 2.30 (2.18–<br>2.43) | 9% (5 to 13)                                        | 2.48 (2.34–<br>2.63)                   |

| Contrast                             | strata | crude<br>RR | combined             | exposed              | baseline             | share<br>removed,<br>combined<br>(bootstrap<br>95% CI) | identified<br>strata only,<br>combined |
|--------------------------------------|--------|-------------|----------------------|----------------------|----------------------|--------------------------------------------------------|----------------------------------------|
| Above vs at/below 500 ft,<br>heavier | 14     | 2.00        | 2.13 (2.04–<br>2.22) | 1.70 (1.63–<br>1.77) | 2.33 (2.22–<br>2.44) | -12% (-18 to<br>-6)                                    | 2.65 (2.51–<br>2.80)                   |

### Altitude: composition

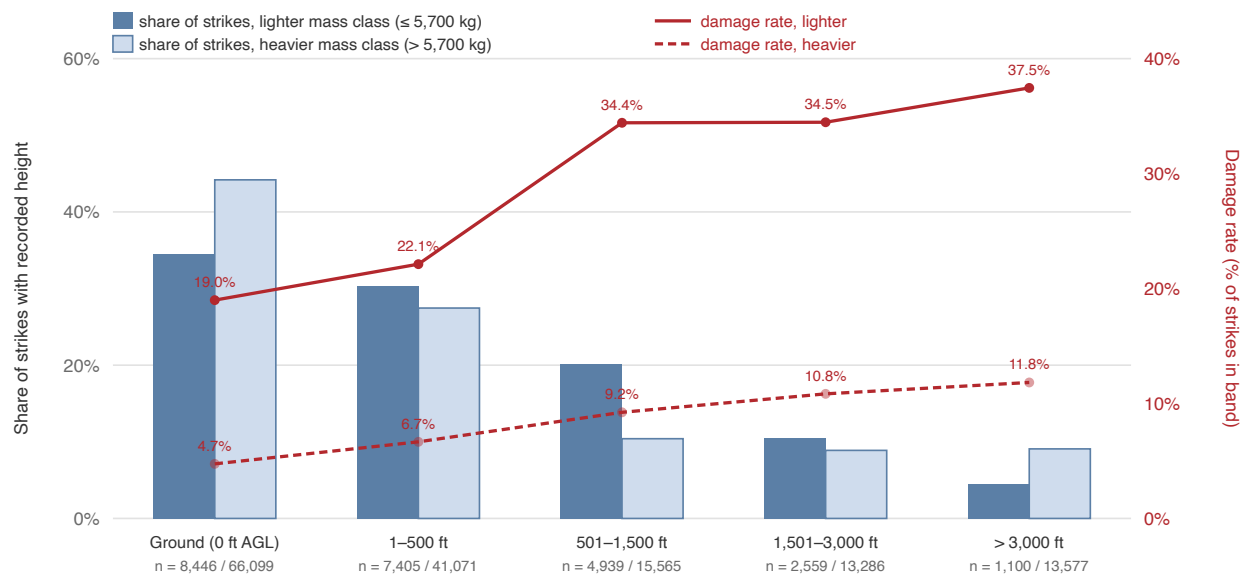


Fig. 1 Strikes concentrate at or below 500 ft while the damage rate rises with height. Bars show each class's share of strikes with a recorded height; lines show the damage rate within the band (lighter class solid, heavier dashed). Counts below each band are lighter / heavier

The marginal damage rate rose with height in both classes (Fig. 1): from 20.45% at or below 500 ft to 34.82% above it in the lighter class, and from 5.48% to 10.57% in the heavier class. Standardisation left most of this premium in place. Standardised risk ratios were 1.90 to 2.30 in the lighter class and 1.70 to 2.33 in the heavier class across the three standards (Table 2). The share removed was -4 to 28% in the lighter and -33 to 30% in the heavier class; negative values mean that the animals struck at low height are, on balance, more damaging than those struck higher, so composition partly masks the premium. The per-stratum tables are in Tables S8 and S9. Groups struck almost only at low height could not enter any stratum: deer (0 and 1,035 reports); other mammals (0 and 322 reports); owls (12 and 140 reports) (above and at or below 500 ft) in the lighter class, and other mammals (1 and 1,336 reports); deer (0 and 352 reports) in the heavier class.

Unidentified birds carry about half of the standardisation weight (49% and 55%). Over identified strata alone, the crude ratios were larger (3.24 and 3.53), standardisation removed 29 to 44% and 29 to 54% of the excess, and residual ratios of 2.24 to 2.59 and 2.17 to 2.79 remained. Measured differences in composition therefore account for part of the premium but not for most of it, under all three standards, with

and without the unidentified strata, with the preprint grouping and when standardised on stratum  $\times$  decade (1.86 to 2.21 and 1.77 to 2.40; Table S5). Under the four codings of the outcome the standardised ratio ranged from 2.02 to 2.29 and 1.83 to 2.13 (Table S2). The strata are coarse, so composition within them is not held constant; the taxon-level analysis below addresses that.

#### Altitude: airspeed, phase of flight and height bands

Recorded airspeed accounted for much of the residual premium in heavier aircraft and less of it in lighter aircraft (Table 3). Among heavier-class reports with a recorded airspeed, the premium standardised on stratum was 1.66 (1.58–1.74) over all such reports. The retained cells contain 2,362 fewer reports above 500 ft than the airspeed-recorded subset, and 2,140 reports at 250 kt or more are excluded because such airspeeds hardly occur at or below 500 ft; on the remaining common support the premium standardised on stratum alone was 1.50 (1.42–1.58), and standardised on stratum  $\times$  airspeed band it fell to 1.16 (1.06–1.28), 1.10 to 1.24 across the three standards, with the interval including 1 under the baseline standard (1.10, 0.99–1.22). Adding the mass class to the cross-classification gave 1.17 to 1.19. Computed inside each FAA mass class separately, the ratio on stratum  $\times$  airspeed band was 1.20 (1.04–1.39) for class 3 and 1.17 (1.07–1.28) for class 4, against 1.62 and 1.40 on the stratum alone; class 5 carries only 383 reports in the retained cells and cannot resolve it (1.05, 0.55–1.99; Table S10). In the lighter class the corresponding ratios were 1.61 on the common support and 1.44 (1.35–1.53) on stratum  $\times$  airspeed band. These results apply to airspeeds represented on both sides of 500 ft; the fastest strikes, almost all above 500 ft, cannot be compared in this way. Airspeed is recorded more often for damaging strikes at low height, so this comparison conditions on a selected subset, and the selection may operate within bands as well as between them. Two checks bear on how much this matters (Table S4). Over the bands holding at least 100 reports on each side, a 40-kt band still separates the two sides of 500 ft by +4.7 to +9.6 kt of mean recorded airspeed in the heavier class (Table S3); on 10-kt bins, where that difference falls to 0.1 kt, the ratio is 1.14 (1.03–1.27) against 1.33 on the same reports standardised on stratum alone. Reweighting each report by the inverse probability that an airspeed was recorded moves the stratum-only ratio to 1.89 and the airspeed-stratified ratio to 1.41 (1.30–1.52), so the drop is not produced by selection into recording alone. In the lighter class the corresponding pairs are 1.42 and 1.33 on 10-kt bins and 2.01 and 1.81 reweighted. The airspeed-recorded subset is itself selected: at or below 500 ft airspeed was recorded on 65% of damaging and 52% of non-damaging heavier-class reports, against 78% and 78% above 500 ft (lighter class 68% and 59% below, 88% and 86% above), which lowers the crude premium in that subset. The comparison of interest is therefore within the common support, between the two stratifications.

Excluding the ground roll reduced the premium without removing it. Among airborne reports, with 1–500 ft as the baseline, the ratio standardised on stratum was 1.54 (1.47–1.62) in the lighter and 1.62 (1.54–1.69) in the heavier class; adding phase of flight gave 1.43 and 1.54. Among airborne reports with a recorded airspeed, on the common support, standardising on stratum gave 1.40 and 1.39, and adding airspeed band gave 1.29 (1.22–1.38) and 1.19 (1.07–1.31).

The number of animals struck also matters. For reports of a single animal the altitude ratio standardised on stratum was 2.18 in the lighter and 2.35 in the heavier class; for reports of two or more it was 1.72 and 1.73, although the crude ratios run the other way (2.62 and 2.94; Table S11). Flocks are struck disproportionately by the strata that damage aircraft most, which is composition, and the residual altitude association within strata is smaller for them than for single animals.

Table 3 The altitude premium (above 500 ft against at or below 500 ft; for airborne subsets, against 1–500 ft) standardised on stratum, on stratum  $\times$  airspeed band and on stratum  $\times$  phase of flight. Cross-

classified cells need at least 10 reports on each side; common support means the reports in the cells retained by the stratum  $\times$  airspeed band cross-classification

| Class   | Reports                                              | Standardised<br>on                     | strata | above /<br>below    | crude<br>RR | standardised<br>RR, combined<br>(95% CI) | range over<br>three<br>standards |
|---------|------------------------------------------------------|----------------------------------------|--------|---------------------|-------------|------------------------------------------|----------------------------------|
| Lighter | All with a<br>recorded height                        | stratum                                | 13     | 8,586 /<br>14,354   | 2.25        | 2.14<br>(2.03–2.24)                      | 1.90 to 2.30                     |
| Lighter | Airspeed<br>recorded,<br>common support              | stratum                                | 13     | 6,765 /<br>8,302    | 1.62        | 1.61<br>(1.53–1.70)                      | 1.52 to 1.70                     |
| Lighter | Airspeed<br>recorded,<br>common support              | stratum $\times$<br>airspeed<br>band   | 36     | 6,765 /<br>8,302    | 1.62        | 1.44<br>(1.35–1.53)                      | 1.31 to 1.57                     |
| Lighter | Airborne, 1–500<br>ft baseline                       | stratum                                | 13     | 8,565 /<br>7,225    | 1.63        | 1.54<br>(1.47–1.62)                      | 1.48 to 1.62                     |
| Lighter | Airborne, 1–500<br>ft baseline                       | stratum $\times$<br>phase of<br>flight | 33     | 8,372 /<br>6,958    | 1.61        | 1.43<br>(1.35–1.52)                      | 1.32 to 1.60                     |
| Lighter | Airborne,<br>airspeed<br>recorded,<br>common support | stratum                                | 13     | 6,751 /<br>5,675    | 1.41        | 1.40<br>(1.33–1.48)                      | 1.35 to 1.46                     |
| Lighter | Airborne,<br>airspeed<br>recorded,<br>common support | stratum $\times$<br>airspeed<br>band   | 36     | 6,751 /<br>5,675    | 1.41        | 1.29<br>(1.22–1.38)                      | 1.23 to 1.38                     |
| Heavier | All with a<br>recorded height                        | stratum                                | 14     | 42,427 /<br>105,482 | 2.00        | 2.13<br>(2.04–2.22)                      | 1.70 to 2.33                     |
| Heavier | Airspeed<br>recorded,<br>common support              | stratum                                | 14     | 30,816 /<br>51,648  | 1.53        | 1.50<br>(1.42–1.58)                      | 1.33 to 1.61                     |
| Heavier | Airspeed<br>recorded,<br>common support              | stratum $\times$<br>airspeed<br>band   | 43     | 30,816 /<br>51,648  | 1.53        | 1.16<br>(1.06–1.28)                      | 1.10 to 1.24                     |
| Heavier | Airborne, 1–500<br>ft baseline                       | stratum                                | 14     | 42,239 /<br>41,007  | 1.59        | 1.62<br>(1.54–1.69)                      | 1.52 to 1.72                     |
| Heavier | Airborne, 1–500<br>ft baseline                       | stratum $\times$<br>phase of<br>flight | 30     | 40,101 /<br>40,815  | 1.53        | 1.54<br>(1.47–1.61)                      | 1.45 to 1.64                     |
| Heavier | Airborne,<br>airspeed<br>recorded,<br>common support | stratum                                | 14     | 30,307 /<br>30,876  | 1.31        | 1.39<br>(1.31–1.47)                      | 1.31 to 1.46                     |
| Heavier | Airborne,<br>airspeed<br>recorded,<br>common support | stratum $\times$<br>airspeed<br>band   | 42     | 30,307 /<br>30,876  | 1.31        | 1.19<br>(1.07–1.31)                      | 1.10 to 1.28                     |

The shape differed between classes (Table 4). Requiring a stratum to be present in all five bands excludes the ground-concentrated groups, deer among them, so the profile describes taxa that are struck at every height rather than the whole strike mix. Over the 8 strata present in all five bands, the standardised

damage probability in lighter aircraft rose from 11.11% on the ground to 21.90% at 1–500 ft and 32.37% at 501–1,500 ft, and then changed little (34.01% and 36.03%). In heavier aircraft, over 12 strata, it rose in every band, from 4.77% to 16.12%, with band-to-band ratios of 1.26 to 1.43 and no sign of levelling off. Comparing each band with the one below it on its own strata and weights gives a different sequence, in which the heavier-class steps decline from 1.46 to 1.20 (Table S12). Over the 10 lighter-class strata present in the three lowest bands, which include gulls and pigeons, the first three points are 10.56%, 21.94% and 33.82%, so the rise to 1,500 ft does not depend on the stricter filter.

Table 4 Standardised damage probability by height band, over the strata that reach 30 reports in every band, with one set of weights for all five bands. Lighter class: Other identified, Raptors, Songbirds, Unidentified bird, large, Unidentified bird, medium, Unidentified bird, size not recorded, Unidentified bird, small and Waterfowl. Heavier class: Bats, Gulls & terns, Other identified, Pigeons & doves, Raptors, Shorebirds, Songbirds, Unidentified bird, large, Unidentified bird, medium, Unidentified bird, size not recorded, Unidentified bird, small and Waterfowl

| Class   | Height band    | reports | standardised damage % (95% CI) | ratio to the band below |
|---------|----------------|---------|--------------------------------|-------------------------|
| Lighter | Ground         | 4,923   | 11.11 (10.15–12.06)            | —                       |
| Lighter | 1–500 ft       | 5,673   | 21.90 (20.89–22.91)            | 1.97                    |
| Lighter | 501–1,500 ft   | 4,572   | 32.37 (31.18–33.55)            | 1.48                    |
| Lighter | 1,501–3,000 ft | 2,423   | 34.01 (32.37–35.66)            | 1.05                    |
| Lighter | Above 3,000 ft | 1,061   | 36.03 (33.39–38.67)            | 1.06                    |
| Heavier | Ground         | 62,450  | 4.77 (4.58–4.96)               | —                       |
| Heavier | 1–500 ft       | 40,375  | 6.61 (6.38–6.85)               | 1.39                    |
| Heavier | 501–1,500 ft   | 15,483  | 8.97 (8.48–9.45)               | 1.36                    |
| Heavier | 1,501–3,000 ft | 13,243  | 11.26 (10.60–11.92)            | 1.26                    |
| Heavier | Above 3,000 ft | 13,553  | 16.12 (14.97–17.28)            | 1.43                    |

#### Within taxa

The inclusion rule was met by 23 taxa: 14 leaf codes (Table 5) and 9 group codes (Table S13). The odds ratio of damage above against at or below 500 ft exceeded 1 in all 22 taxa for which it was defined, and its interval excluded 1 in 17 (10 of 13 leaf codes); 13 survived a Holm correction. The median was 2.86 over all taxa and 4.74 over leaf codes. For the yellow-rumped warbler no damaging report at or below 500 ft exists, so the ratio is undefined. For seven taxa the estimate rests on fewer than 10 damaging reports on one side (European starling, sparrows, chimney swift, perching birds (y), Brazilian free-tailed bat, cedar waxwing and microbats), and their asymptotic intervals are too narrow. The intervals of European starling, sparrows, rock pigeon, Brazilian free-tailed bat and microbats include 1, and for European starling, sparrows and rock pigeon the two mass classes point in opposite directions (Table S14). A Breslow–Day test rejects homogeneity between the classes for 5 taxa (gulls, sparrows, hawks, blackbirds and mallard), so the count of 22 describes the pooled direction and not a uniform within-class effect. The mourning dove (*Zenaida macroura*) illustrates the pattern: its strikes were damaging in 3.82% of reports at or below 500 ft and 17.53% above (odds ratio 5.31, 95% CI 3.41–8.27).

Table 5 Damage above 500 ft against at or below 500 ft within FAA leaf codes. Counts and Wilson intervals pool both mass classes; the odds ratio is Mantel–Haenszel across the two classes with a Robins–Breslow–Greenland interval, unadjusted for multiplicity. The last column divides the odds ratio by 2.0, one of the identification-selection scenarios in the text

| Taxon                                                      | FAA code | n above | damage %<br>(95% CI) | n below | damage %<br>(95% CI) | MH OR<br>(95% CI)      | OR ÷<br>2.0 |
|------------------------------------------------------------|----------|---------|----------------------|---------|----------------------|------------------------|-------------|
| Mourning dove ( <i>Zenaida macroura</i> )                  | 02205    | 154     | 17.5<br>(12.3–24.3)  | 4,848   | 3.8<br>(3.3–4.4)     | 5.31<br>(3.41–8.27)    | 2.66        |
| European starling ( <i>Sturnus vulgaris</i> )              | YL001    | 130     | 6.9<br>(3.7–12.6)    | 3,258   | 4.3<br>(3.7–5.1)     | 1.54<br>(0.76–3.13)    | 0.77        |
| Rock pigeon ( <i>Columba livia</i> )                       | 02111    | 112     | 15.2<br>(9.7–23.0)   | 2,095   | 12.8<br>(11.4–14.3)  | 1.16<br>(0.68–1.99)    | 0.58        |
| Red-tailed hawk ( <i>Buteo jamaicensis</i> )               | K3302    | 184     | 62.0<br>(54.8–68.7)  | 1,883   | 20.3<br>(18.5–22.2)  | 4.91<br>(3.52–6.86)    | 2.46        |
| Canada goose ( <i>Branta canadensis</i> )                  | J2204    | 496     | 70.2<br>(66.0–74.0)  | 1,311   | 47.8<br>(45.1–50.5)  | 2.76<br>(2.21–3.46)    | 1.38        |
| Turkey vulture ( <i>Cathartes aura</i> )                   | K1002    | 518     | 72.4<br>(68.4–76.1)  | 516     | 40.1<br>(36.0–44.4)  | 3.38<br>(2.58–4.41)    | 1.69        |
| American robin ( <i>Turdus migratorius</i> )               | Z6007    | 437     | 14.9<br>(11.8–18.5)  | 505     | 3.8<br>(2.4–5.8)     | 4.79<br>(2.81–8.14)    | 2.39        |
| Chimney swift ( <i>Chaetura pelagica</i> )                 | T1002    | 325     | 2.5<br>(1.3–4.8)     | 586     | 0.2<br>(0.0–1.0)     | 14.46<br>(1.83–114.05) | 7.23        |
| Mallard ( <i>Anas platyrhynchos</i> )                      | J2109    | 203     | 62.1<br>(55.2–68.5)  | 497     | 24.1<br>(20.6–28.1)  | 4.74<br>(3.33–6.76)    | 2.37        |
| Brazilian free-tailed bat ( <i>Tadarida brasiliensis</i> ) | 1C2201   | 129     | 0.8<br>(0.1–4.3)     | 335     | 0.6<br>(0.2–2.2)     | 1.36<br>(0.12–15.18)   | 0.68        |
| Bald eagle ( <i>Haliaeetus leucocephalus</i> )             | K3201    | 103     | 75.7<br>(66.6–83.0)  | 334     | 34.4<br>(29.5–39.7)  | 5.06<br>(3.00–8.53)    | 2.53        |
| Cedar waxwing ( <i>Bombycilla cedrorum</i> )               | ZD102    | 120     | 9.2<br>(5.2–15.7)    | 203     | 2.0<br>(0.8–5.0)     | 4.78<br>(1.47–15.59)   | 2.39        |
| White-headed gull complex ( <i>Larus spp.</i> )            | NE141    | 104     | 40.4<br>(31.5–50.0)  | 187     | 21.4<br>(16.1–27.8)  | 2.36<br>(1.39–4.00)    | 1.18        |
| Yellow-rumped warbler ( <i>Setophaga coronata</i> )        | ZS009    | 124     | 3.2<br>(1.3–8.0)     | 103     | 0.0<br>(0.0–3.6)     | —                      | —           |

Identification depended on damage and height. In heavier aircraft a damaging strike above 500 ft carried an identified species in 0.51 of reports and a non-damaging one in 0.19, against 0.69 and 0.54 at or below 500 ft, a ratio of ratios  $\psi$  of 2.01 (lighter class 1.95; Table S13). Computed within FAA size classes over the non-mammal strata,  $\psi$  ranges from 1.15 to 2.53 (lighter aircraft, animals coded large and heavier aircraft, animals coded medium; Table S15), so no single factor describes the selection. Pooling the two mass classes, the factor is 1.72 for animals coded small, 2.50 for medium and 1.66 for large. Dividing every within-taxon odds ratio by a fixed factor as a scenario, the ratio remained above 1 in 19 of 22

taxa at 1.5, 16 at 2.0 and 14 at 2.5, and its lower confidence limit in 11, 9 and 7 respectively; the leaf-code median of 4.74 falls to 3.16, 2.37 and 1.90. Dividing each taxon by the factor of its own size class instead leaves 16 of 22 above 1 and 9 with a lower limit above 1. Across factors from 1.00 to 2.50 the two counts run 1.00: 22 and 17; 1.25: 21 and 15; 1.50: 19 and 11; 1.75: 18 and 10; 2.00: 16 and 9; 2.25: 15 and 7; 2.50: 14 and 7, so no count of surviving taxa should be read as a property of the data alone. Within unidentified birds the altitude odds ratio was above 1 in every size stratum of both classes (1.25 to 3.17; Table S16) and increased from small to large birds. These strata cannot be selected by species-level identification, but the size code carried by an unidentified bird can itself depend on damage and height, so the gradient is consistent both with heavier birds causing more damage and with damage-dependent size coding.

## Outcome coding

Restricting to reports with an explicit DAMAGE\_LEVEL, recoding M? as no damage, or removing M? reports changed the size of the Mantel–Haenszel estimates but not the direction of any contrast. On the standardised ratios the altitude results are stable (2.02 to 2.29 and 1.83 to 2.13) and the night results are not (1.04 to 1.10 and 0.97 to 1.04; Table S2).

## Discussion

The two premiums behave differently. The night premium is largely a matter of what is struck, and in lighter aircraft also of the phase of flight: standardised to a common mix of strata, the damage ratio is close to 1 in both classes. How much is left is not established. The residual moves with the coding of the outcome, it is larger among identified strata, and intervals that resample airports rather than reports include 1 in both classes. In lighter aircraft this is mainly deer, in line with the nocturnal and crepuscular pattern of deer strikes (Biondi et al. 2011) and with the dependence of mammal strikes on species behaviour (Schwarz et al. 2014). In heavier aircraft the premium falls away once unidentified birds are separated by size, and adding phase of flight changes little; birds struck at night are more often medium or large. Among identified strata a residual of 10–15% remains in both classes, and the heavier-class residual changes sign between codings of the outcome. Night adds little information about the outcome of a strike beyond the animal struck, and how little cannot be pinned down with this record.

Composition does not explain the altitude premium in full. Holding the mix of strata constant removes 29 to 44% (lighter) and 29 to 54% (heavier) of it among identified taxa and less when unidentified birds are included; the strata are coarse, so finer composition within them is not held constant, but the premium also appears within individual taxa and within every size class of unidentified birds. Part of it reflects the difference between strikes on the ground roll and strikes in flight, but a clear premium remains among airborne reports.

Among heavier aircraft the association weakens substantially once airspeed is held constant. Within an airspeed band, a strike above 500 ft was 1.10 to 1.24 times as likely to damage the aircraft as a strike below it, against 1.50 times on the same reports without regard to airspeed, and under one of the three standards the difference was not distinguishable from none; the pattern is the same inside FAA mass classes 3 and 4, while class 5 is too small to resolve. This is consistent with the collision-energy account: height is associated with higher airspeed during climb and approach, and impact energy scales with the square of relative velocity (Metz et al. 2020). It is not a demonstration of it. The recorded airspeed is the indicated airspeed the reporter entered rather than a closing speed, it is recorded more often when a strike causes damage, and the same selection may act inside airspeed bands, so this stratification describes where the association is weaker rather than isolating a mechanism. In heavier aircraft the

standardised damage probability continues to rise through every height band, and the FAA's own series shows a rising rate of damaging strikes above 1,500 ft (Dolbeer et al. 2026); both fit an effect that grows with height rather than a threshold at 500 ft. The airspeed comparisons exclude the fastest strikes, which occur almost only at altitude and are likely to be the most damaging. In lighter aircraft the premium is concentrated between the ground and 1,500 ft and airspeed accounts for less of it. Lighter aircraft fly at lower airspeeds (94% of their strikes with a recorded airspeed were below 160 kt, against 68% in heavier aircraft), so the bands discriminate less; the remaining difference may also reflect aircraft type, the taxa met near small airfields, or reporting.

Reporting is the main alternative explanation. A non-damaging strike at altitude may go unnoticed, whereas a strike on the runway is more likely to be seen or found, which would inflate the altitude premium without any change in damage. Selection of this kind is demonstrably present: identification of the species, which requires remains, depends on damage and height by factors of 1.15 to 2.53 across size classes, and a factor of 2 would halve the typical within-taxon odds ratio. The premium nevertheless persists among unidentified birds, which identification cannot select by taxon, and within taxa under every scenario up to 1.5. Whether the residual reflects collision energy or the selective reporting of strikes at altitude is not settled here, and the two are not mutually exclusive.

These results bear on management. Species identity remains the main lever on the airfield, where most strikes occur. In climb and approach corridors, reported damage is more likely than the mix of animals alone predicts, and the excess is concentrated where airspeeds are higher. Hazard assessments for these corridors, which Dolbeer and Begier (2025) identify as the part of the problem airport wildlife programmes cannot reach, should therefore weight strikes by the phase and speed at which they occur, and not only by the species present.

## Limitations

The NWSD is voluntary and every count is a lower bound. Reporting, identification and the recording of height and airspeed all depend on damage; the analyses above measure some of these dependencies but do not remove them. Height was not recorded on 31.5% of reports and airspeed on a further share, and those reports were excluded, not imputed. TIME\_OF\_DAY was taken as reported and not reconciled with date and location. Standardisation holds constant only the variables standardised on, and only as coarsely as the strata are defined; airport, season, aircraft type within a mass class and the number of animals struck were not considered and may carry part of the residual. The airspeed and phase analyses condition on fields that are themselves recorded selectively, so they describe subsets of the record rather than identifying mechanisms. The identification factor  $\psi$  is a scenario, not an estimated correction: computed within size classes it ranges from 1.15 to 2.53. Standardised ratios depend on the standard population, which is why three were reported, and they describe this record, not other assemblages. The mass classes combine differences in airframe and in type of operation. There is no exposure denominator, so none of the figures is a risk per movement. The bootstrap ignores clustering. The analysis was not pre-registered and was revised after review, as described in Methods.

## Conclusions

Measured differences in composition remove most of the night-time damage premium in United States wildlife strikes, though the size of the remainder depends on the coding of the outcome and on the treatment of unidentified birds. They remove much less of the altitude premium, which persists within taxa and among unidentified birds. The altitude association weakens substantially once recorded airspeed is held constant; how much of what remains reflects collision energy and how much the selective report-

ing of strikes at altitude cannot be separated in this record. Wildlife hazard assessments for climb and approach should account for the speed at which strikes occur and not rely on species presence alone.

## Statements and Declarations

**Funding** No funding was received for conducting this study.

**Competing interests** The author operates FlightFinder (himaxym.com), a website that publishes aviation-safety statistics, including wildlife-strike statistics derived from the database analysed here. The author declares no other financial or non-financial interests.

**Ethics approval** Not applicable. The study uses publicly released reports of wildlife strikes; no animals were handled.

**Author contributions** DK conceived the study, compiled and analysed the data, and wrote the manuscript.

**Data and code availability** The freeze analysed here, including `wildlife_analysis_cube.csv` from which every new analysis is computed, and the scripts that produce every number and table in this paper (`emit_cube.py`, `build_r7.py`, `r7_stats.py`, the manuscript templates and `make_figure1.mjs`) are archived on Zenodo under CC BY 4.0 at <https://doi.org/10.5281/zenodo.22820124>. A preprint of an earlier version of this work is available at <https://doi.org/10.32942/X2C67R>.

## References

- Altringer L, Navin J, Begier MJ, Shwiff SA, Anderson A (2021) Estimating wildlife strike costs at US airports: a machine learning approach. *Transp Res D Transp Environ* 97:102907. <https://doi.org/10.1016/j.trd.2021.102907>
- Anderson A, Carpenter DS, Begier MJ, Blackwell BF, DeVault TL, Shwiff SA (2015) Modeling the cost of bird strikes to US civil aircraft. *Transp Res D Transp Environ* 38:49–58. <https://doi.org/10.1016/j.trd.2015.04.027>
- Avrenli KA, Dempsey BJ (2014) Statistical analysis of aircraft–bird strikes resulting in engine failure. *Transp Res Rec* 2449:14–23. <https://doi.org/10.3141/2449-02>
- Biondi KM, Belant JL, Martin JA, DeVault TL, Wang G (2011) White-tailed deer incidents with U.S. civil aircraft. *Wildl Soc Bull* 35:303–309. <https://doi.org/10.1002/wsb.46>
- Biondi KM, Belant JL, DeVault TL, Martin JA, Wang G (2013) Bat incidents with U.S. civil aircraft. *Acta Chiropt* 15:185–192. <https://doi.org/10.3161/150811013X667984>
- DeVault TL, Belant JL, Blackwell BF, Seamans TW (2011) Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. *Wildl Soc Bull* 35:394–402. <https://doi.org/10.1002/wsb.75>
- DeVault TL, Blackwell BF, Seamans TW, Belant JL (2016) Identification of off airport interspecific avian hazards to aircraft. *J Wildl Manage* 80:746–752. <https://doi.org/10.1002/jwmg.1041>
- DeVault TL, Blackwell BF, Seamans TW, Begier MJ, Kougher JD, Washburn JE, Miller PR, Dolbeer RA (2018) Estimating interspecific economic risk of bird strikes with aircraft. *Wildl Soc Bull* 42:94–101. <https://doi.org/10.1002/wsb.859>
- Dolbeer RA (2006) Height distribution of birds recorded by collisions with civil aircraft. *J Wildl Manage* 70:1345–1350. [https://doi.org/10.2193/0022-541X\(2006\)70\[1345:HDOBRB\]2.0.CO;2](https://doi.org/10.2193/0022-541X(2006)70[1345:HDOBRB]2.0.CO;2)

Dolbeer RA (2011) Increasing trend of damaging bird strikes with aircraft outside the airport boundary: implications for mitigation measures. *Hum-Wildl Interact* 5:235–248. <https://doi.org/10.26077/dnvb-x958>

Dolbeer RA (2015) Trends in reporting of wildlife strikes with civil aircraft and in identification of species struck under a primarily voluntary reporting system, 1990–2013. Special report submitted to the Federal Aviation Administration, Washington, DC

Dolbeer RA, Begier MJ (2025) Bird strikes during climb and approach: a need for innovative management strategies. *Hum-Wildl Interact* 19:13. <https://doi.org/10.26077/n3c0-1p74>

Dolbeer RA, Begier MJ, Miller PR, Weller JR, Major W (2026) Wildlife strikes to civil aircraft in the United States, 1990–2025. Serial Report 32. Federal Aviation Administration and U.S. Department of Agriculture, Washington, DC. [https://www.faa.gov/airports/airport\\_safety/wildlife/arp-Wildlife-Strike-Report-1990-2025.pdf](https://www.faa.gov/airports/airport_safety/wildlife/arp-Wildlife-Strike-Report-1990-2025.pdf)

Dolbeer RA, Begier MJ, Weller JR (2018) The National Wildlife Strike Database: a scientific foundation to enhance aviation safety. *Proc Vertebr Pest Conf* 28:152–157. <https://doi.org/10.5070/v42811027>

Dolbeer RA, Wright SE (2009) Safety management systems: how useful will the FAA National Wildlife Strike Database be? *Hum-Wildl Confl* 3:167–178. <https://doi.org/10.26077/kt7q-b287>

Dolbeer RA, Wright SE, Cleary EC (2000) Ranking the hazard level of wildlife species to aviation. *Wildl Soc Bull* 28:372–378

Dove CJ, Rotzel NC, Heacker M, Weigt LA (2008) Using DNA barcodes to identify bird species involved in birdstrikes. *J Wildl Manage* 72:1231–1236. <https://doi.org/10.2193/2007-272>

Greenland S, Robins JM, Pearl J (1999) Confounding and collapsibility in causal inference. *Stat Sci* 14:29–46. <https://doi.org/10.1214/ss/1009211805>

Linnell MA, Conover MR, Ohashi TJ (1999) Biases in bird strike statistics based on pilot reports. *J Wildl Manage* 63:997–1003. <https://doi.org/10.2307/3802814>

Metz IC, Ellerbroek J, Mühlhausen T, Kügler D, Hoekstra JM (2020) The bird strike challenge. *Aerospace* 7:26. <https://doi.org/10.3390/aerospace7030026>

Misra S, Toppo I, Mendonca FAC (2022) Assessment of aircraft damage due to bird strikes: a machine learning approach. *Int J Sustain Aviat* 8:136–151. <https://doi.org/10.1504/IJSA.2022.122328>

Rafe A, Das S (2026) Do aviation hazard rankings overlook conservation-concern birds in U.S. wildlife strikes, 1990–2025? SSRN preprint. <https://doi.org/10.2139/ssrn.7032498>

Ross CD, Schank M, Begier MJ, Blackwell BF, DeVault TL (2025) Assessing relative hazard, risk, and seasonal differences of wildlife–aircraft collisions. *Wildl Soc Bull* 49:e1609. <https://doi.org/10.1002/wsb.1609>

Schwarz KB, Belant JL, Martin JA, DeVault TL, Wang G (2014) Behavioral traits and airport type affect mammal incidents with U.S. civil aircraft. *Environ Manage* 54:908–918. <https://doi.org/10.1007/s00267-014-0345-4>

# Online Resource 1

## Composition or encounter? Decomposing the altitude and night-time damage premiums in wildlife strikes to civil aircraft in the United States

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European Journal of Wildlife Research — supplementary tables. All values are computed from freeze 2026-09-07 (<https://doi.org/10.5281/zenodo.22820124>) by `build_r7.py`. Odds ratios for single strata carry Woolf 95% intervals and are undefined (—) where a cell is empty; proportions carry Wilson intervals. Strata with fewer than 30 reports on either side of a contrast are omitted; cross-classified cells need at least 10 reports on each side.

Table S1 Report flow from the public export to each analysis

| Step                                               | Reports | Damaging |
|----------------------------------------------------|---------|----------|
| Reports in the export                              | 354,564 | 22,210   |
| With an FAA mass class                             | 254,155 | 22,016   |
| Lighter: all reports                               | 30,418  | 7,219    |
| Lighter: height recorded                           | 24,449  | 6,236    |
| Lighter: in a stratum kept by the height contrast  | 22,940  | 5,208    |
| Lighter: height and airspeed recorded              | 17,146  | 4,844    |
| Lighter: common support of stratum × airspeed band | 15,067  | 3,885    |
| Lighter: night or day recorded                     | 25,872  | 6,114    |
| Lighter: in a stratum kept by the night contrast   | 25,600  | 6,083    |
| Lighter: strata present in all five height bands   | 18,652  | 4,434    |
| Heavier: all reports                               | 223,737 | 14,797   |
| Heavier: height recorded                           | 149,598 | 10,358   |
| Heavier: in a stratum kept by the height contrast  | 147,909 | 10,053   |
| Heavier: height and airspeed recorded              | 89,946  | 7,296    |
| Heavier: common support of stratum × airspeed band | 82,464  | 6,070    |
| Heavier: night or day recorded                     | 156,395 | 10,282   |
| Heavier: in a stratum kept by the night contrast   | 156,395 | 10,282   |
| Heavier: strata present in all five height bands   | 145,104 | 9,692    |

Table S2 Crude and directly standardised risk ratios under four codings of the outcome: the primary definition (DAMAGE\_LEVEL in M, M?, S, D, with a blank grade counted as no damage); reports carrying an explicit DAMAGE\_LEVEL only; M? recoded as no damage; and M? reports removed

| Contrast                          | Outcome definition         | strata | crude RR | standardised RR, combined (95% CI) | range over three standards |
|-----------------------------------|----------------------------|--------|----------|------------------------------------|----------------------------|
| Night vs day, lighter             | primary definition         | 14     | 1.29     | 1.07 (1.001–1.15)                  | 1.06 to 1.10               |
| Night vs day, lighter             | explicit DAMAGE_LEVEL only | 14     | 1.24     | 1.04 (0.97–1.11)                   | 1.02 to 1.07               |
| Night vs day, lighter             | M? recoded as no damage    | 14     | 1.43     | 1.10 (1.004–1.20)                  | 1.10 to 1.10               |
| Night vs day, lighter             | M? reports removed         | 13     | 1.43     | 1.08 (0.99–1.17)                   | 1.05 to 1.12               |
| Night vs day, heavier             | primary definition         | 16     | 1.16     | 1.04 (0.99–1.09)                   | 1.01 to 1.06               |
| Night vs day, heavier             | explicit DAMAGE_LEVEL only | 16     | 1.06     | 0.97 (0.92–1.01)                   | 0.94 to 0.98               |
| Night vs day, heavier             | M? recoded as no damage    | 16     | 1.19     | 0.98 (0.92–1.05)                   | 0.97 to 1.00               |
| Night vs day, heavier             | M? reports removed         | 16     | 1.20     | 0.99 (0.92–1.05)                   | 0.97 to 1.00               |
| Above vs at/below 500 ft, lighter | primary definition         | 13     | 2.25     | 2.14 (2.03–2.24)                   | 1.90 to 2.30               |
| Above vs at/below 500 ft, lighter | explicit DAMAGE_LEVEL only | 13     | 2.14     | 2.02 (1.93–2.12)                   | 1.82 to 2.17               |
| Above vs at/below 500 ft, lighter | M? recoded as no damage    | 13     | 2.10     | 2.08 (1.94–2.23)                   | 1.82 to 2.27               |
| Above vs at/below 500 ft, lighter | M? reports removed         | 11     | 2.25     | 2.29 (2.14–2.44)                   | 2.02 to 2.46               |
| Above vs at/below 500 ft, heavier | primary definition         | 14     | 2.00     | 2.13 (2.04–2.22)                   | 1.70 to 2.33               |
| Above vs at/below 500 ft, heavier | explicit DAMAGE_LEVEL only | 14     | 1.82     | 1.92 (1.84–2.00)                   | 1.59 to 2.08               |
| Above vs at/below 500 ft, heavier | M? recoded as no damage    | 14     | 1.82     | 1.83 (1.72–1.94)                   | 1.51 to 1.98               |
| Above vs at/below 500 ft, heavier | M? reports removed         | 14     | 1.87     | 2.04 (1.92–2.17)                   | 1.60 to 2.24               |

Table S3 Mean recorded indicated airspeed above and at or below 500 ft within each 40-kt band, over reports with a recorded height and airspeed. A band that still separates the two sides by several knots does not hold airspeed constant

| Class   | Airspeed band | above 500 ft, n | mean kt | at or below, n | mean kt | difference |
|---------|---------------|-----------------|---------|----------------|---------|------------|
| Lighter | <80           | 375             | 69.1    | 4,368          | 58.0    | +11.2      |
| Lighter | 80-119        | 3,143           | 99.1    | 4,020          | 93.9    | +5.1       |
| Lighter | 120-159       | 3,029           | 128.4   | 1,169          | 127.9   | +0.5       |
| Lighter | 160-199       | 578             | 171.5   | 103            | 166.8   | +4.7       |
| Lighter | 200-249       | 284             | 213.1   | 21             | 212.5   | +0.7       |
| Lighter | 250+          | 53              | 259.9   | 3              | 258.3   | +1.6       |
| Heavier | <80           | 4               | 44.2    | 1,460          | 54.1    | -9.9       |
| Heavier | 80-119        | 161             | 106.5   | 11,682         | 99.7    | +6.8       |
| Heavier | 120-159       | 9,448           | 140.4   | 38,308         | 135.8   | +4.7       |
| Heavier | 160-199       | 8,926           | 174.2   | 4,797          | 167.5   | +6.7       |
| Heavier | 200-249       | 9,185           | 214.2   | 450            | 204.5   | +9.6       |
| Heavier | 250+          | 5,478           | 256.0   | 47             | 257.7   | -1.6       |

Table S4 The altitude contrast on the airspeed-recorded reports under four treatments of airspeed: 40-kt bands as in Table 3 of the manuscript, 10-kt bins, and both after reweighting each report by the inverse probability that an airspeed was recorded (estimated per stratum, side of the contrast and damage status on the height-recorded reports)

| Class   | Comparison                                           | cells or strata | above / below   | crude RR | standardised RR, combined (95% CI) |
|---------|------------------------------------------------------|-----------------|-----------------|----------|------------------------------------|
| Lighter | 40-kt bands: stratum, common support                 | 13              | 6,765 / 8,302   | 1.62     | 1.61 (1.53–1.70)                   |
| Lighter | 40-kt bands: stratum × band                          | 36              | 6,765 / 8,302   | 1.62     | 1.44 (1.35–1.53)                   |
| Lighter | 10-kt bins: stratum, common support                  | 10              | 6,139 / 6,113   | 1.41     | 1.42 (1.35–1.50)                   |
| Lighter | 10-kt bins: stratum × bin                            | 74              | 6,139 / 6,113   | 1.41     | 1.33 (1.25–1.42)                   |
| Lighter | 40-kt bands reweighted for recording: stratum        | 13              | 7,788 / 13,121  | 2.01     | 2.01 (1.91–2.11)                   |
| Lighter | 40-kt bands reweighted for recording: stratum × band | 36              | 7,788 / 13,121  | 2.01     | 1.81 (1.70–1.92)                   |
| Heavier | 40-kt bands: stratum, common support                 | 14              | 30,816 / 51,648 | 1.53     | 1.50 (1.42–1.58)                   |
| Heavier | 40-kt bands: stratum × band                          | 43              | 30,816 / 51,648 | 1.53     | 1.16 (1.06–1.28)                   |
| Heavier | 10-kt bins: stratum, common support                  | 12              | 25,143 / 44,351 | 1.33     | 1.33 (1.25–1.40)                   |
| Heavier | 10-kt bins: stratum × bin                            | 97              | 25,143 / 44,351 | 1.33     | 1.14 (1.03–1.27)                   |
| Heavier | 40-kt bands reweighted for recording: stratum        | 14              | 38,912 / 96,308 | 1.91     | 1.89 (1.81–1.98)                   |
| Heavier | 40-kt bands reweighted for recording: stratum × band | 43              | 38,912 / 96,308 | 1.91     | 1.41 (1.30–1.52)                   |

Table S5 Directly standardised risk ratios (95% CI) under alternative stratifications and contrast definitions: identified strata only; the preprint grouping (identified species outside the listed prefixes and all unidentified birds in one stratum); stratum × decade; and, for the night contrast, stratum × phase of flight, dusk counted as night, and dawn counted as day

| Contrast              | Stratification    | strata | crude RR | combined (95% CI) | exposed (95% CI) | baseline (95% CI) |
|-----------------------|-------------------|--------|----------|-------------------|------------------|-------------------|
| Night vs day, lighter | stratum (primary) | 14     | 1.29     | 1.07 (1.001–1.15) | 1.10 (1.06–1.15) | 1.06 (0.97–1.16)  |

| Contrast                          | Stratification                      | strata | crude RR | combined (95% CI) | exposed (95% CI)  | baseline (95% CI) |
|-----------------------------------|-------------------------------------|--------|----------|-------------------|-------------------|-------------------|
| Night vs day, lighter             | identified strata only              | 10     | 1.91     | 1.10 (1.001–1.22) | 1.17 (1.12–1.23)  | 1.08 (0.94–1.23)  |
| Night vs day, lighter             | preprint grouping                   | 10     | 1.29     | 1.07 (0.998–1.15) | 1.11 (1.06–1.16)  | 1.05 (0.96–1.16)  |
| Night vs day, lighter             | stratum × decade                    | 36     | 1.52     | 1.16 (1.10–1.23)  | 1.11 (1.06–1.16)  | 1.20 (1.12–1.28)  |
| Night vs day, lighter             | stratum × phase of flight           | 58     | 1.36     | 0.98 (0.92–1.05)  | 0.94 (0.90–0.98)  | 1.01 (0.92–1.10)  |
| Night vs day, lighter             | stratum; night and dusk against day | 14     | 1.31     | 1.05 (0.995–1.10) | 1.09 (1.05–1.14)  | 1.02 (0.96–1.10)  |
| Night vs day, lighter             | stratum; night against day and dawn | 14     | 1.30     | 1.08 (1.01–1.16)  | 1.11 (1.06–1.15)  | 1.07 (0.97–1.17)  |
| Night vs day, heavier             | stratum (primary)                   | 16     | 1.16     | 1.04 (0.99–1.09)  | 1.01 (0.97–1.05)  | 1.06 (0.99–1.12)  |
| Night vs day, heavier             | identified strata only              | 12     | 1.48     | 1.15 (1.07–1.23)  | 1.19 (1.12–1.27)  | 1.13 (1.04–1.23)  |
| Night vs day, heavier             | preprint grouping                   | 12     | 1.16     | 1.14 (1.09–1.19)  | 1.16 (1.11–1.21)  | 1.13 (1.06–1.20)  |
| Night vs day, heavier             | stratum × decade                    | 52     | 1.14     | 1.08 (1.03–1.14)  | 1.03 (0.98–1.07)  | 1.11 (1.04–1.18)  |
| Night vs day, heavier             | stratum × phase of flight           | 104    | 1.16     | 1.02 (0.96–1.08)  | 0.96 (0.91–1.000) | 1.06 (0.98–1.14)  |
| Night vs day, heavier             | stratum; night and dusk against day | 16     | 1.17     | 1.03 (0.99–1.07)  | 1.01 (0.97–1.05)  | 1.04 (0.99–1.09)  |
| Night vs day, heavier             | stratum; night against day and dawn | 16     | 1.14     | 1.03 (0.98–1.08)  | 1.00 (0.96–1.05)  | 1.05 (0.99–1.11)  |
| Above vs at/below 500 ft, lighter | stratum (primary)                   | 13     | 2.25     | 2.14 (2.03–2.24)  | 1.90 (1.81–1.99)  | 2.30 (2.18–2.43)  |
| Above vs at/below 500 ft, lighter | identified strata only              | 9      | 3.24     | 2.48 (2.34–2.63)  | 2.24 (2.13–2.36)  | 2.59 (2.42–2.77)  |
| Above vs at/below 500 ft, lighter | preprint grouping                   | 9      | 2.25     | 2.27 (2.16–2.38)  | 2.08 (1.99–2.19)  | 2.38 (2.26–2.52)  |
| Above vs at/below 500 ft, lighter | stratum × decade                    | 33     | 2.13     | 2.06 (1.96–2.16)  | 1.86 (1.77–1.95)  | 2.21 (2.10–2.32)  |
| Above vs at/below 500 ft, heavier | stratum (primary)                   | 14     | 2.00     | 2.13 (2.04–2.22)  | 1.70 (1.63–1.77)  | 2.33 (2.22–2.44)  |
| Above vs at/below 500 ft, heavier | identified strata only              | 10     | 3.53     | 2.65 (2.51–2.80)  | 2.17 (2.07–2.29)  | 2.79 (2.63–2.95)  |
| Above vs at/below 500 ft, heavier | preprint grouping                   | 10     | 2.00     | 2.32 (2.23–2.42)  | 1.98 (1.90–2.06)  | 2.46 (2.35–2.58)  |
| Above vs at/below 500 ft, heavier | stratum × decade                    | 43     | 2.06     | 2.19 (2.10–2.29)  | 1.77 (1.70–1.85)  | 2.40 (2.28–2.51)  |

Table S6 Damage by stratum, night against day, lighter mass class

| Stratum                              | Night, n | damage % (95% CI) | Day, n | damage % (95% CI) | OR (95% CI)       |
|--------------------------------------|----------|-------------------|--------|-------------------|-------------------|
| Unidentified bird, small             | 2,313    | 6.8 (5.8–7.9)     | 3,785  | 6.6 (5.8–7.4)     | 1.04 (0.84–1.28)  |
| Unidentified bird, size not recorded | 1,242    | 14.0 (12.2–16.1)  | 2,584  | 10.6 (9.5–11.8)   | 1.37 (1.12–1.68)  |
| Songbirds                            | 424      | 13.4 (10.5–17.0)  | 2,501  | 6.0 (5.1–7.0)     | 2.45 (1.77–3.39)  |
| Unidentified bird, medium            | 1,090    | 33.1 (30.4–36.0)  | 1,429  | 35.5 (33.0–38.0)  | 0.90 (0.76–1.06)  |
| Raptors                              | 45       | 31.1 (19.5–45.7)  | 2,396  | 45.8 (43.8–47.8)  | 0.53 (0.28–1.01)  |
| Gulls & terns                        | 177      | 25.4 (19.6–32.3)  | 1,733  | 25.6 (23.6–27.7)  | 0.99 (0.70–1.42)  |
| Waterfowl                            | 664      | 67.6 (64.0–71.1)  | 713    | 52.6 (48.9–56.2)  | 1.88 (1.51–2.34)  |
| Pigeons & doves                      | 109      | 14.7 (9.2–22.5)   | 1,218  | 10.8 (9.1–12.6)   | 1.43 (0.81–2.50)  |
| Deer                                 | 585      | 89.2 (86.5–91.5)  | 251    | 88.0 (83.5–91.5)  | 1.12 (0.71–1.79)  |
| Unidentified bird, large             | 225      | 60.9 (54.4–67.0)  | 425    | 68.0 (63.4–72.3)  | 0.73 (0.52–1.03)  |
| Other identified                     | 130      | 48.5 (40.0–57.0)  | 464    | 36.0 (31.8–40.5)  | 1.67 (1.13–2.48)  |
| Shorebirds                           | 89       | 15.7 (9.6–24.7)   | 367    | 9.0 (6.5–12.4)    | 1.89 (0.96–3.70)  |
| Hérons & egrets                      | 31       | 58.1 (40.8–73.6)  | 298    | 17.1 (13.3–21.8)  | 6.71 (3.09–14.55) |
| Other mammals                        | 194      | 25.3 (19.7–31.8)  | 118    | 17.8 (11.9–25.7)  | 1.56 (0.88–2.77)  |

Table S7 Damage by stratum, night against day, heavier mass class

| Stratum                              | Night, n | damage % (95% CI) | Day, n | damage % (95% CI) | OR (95% CI)       |
|--------------------------------------|----------|-------------------|--------|-------------------|-------------------|
| Unidentified bird, small             | 13,984   | 1.9 (1.7–2.1)     | 23,841 | 2.1 (1.9–2.3)     | 0.90 (0.78–1.05)  |
| Songbirds                            | 6,730    | 3.2 (2.8–3.7)     | 25,684 | 1.7 (1.5–1.9)     | 1.95 (1.65–2.30)  |
| Unidentified bird, size not recorded | 10,160   | 3.3 (2.9–3.6)     | 13,920 | 2.3 (2.0–2.5)     | 1.47 (1.26–1.72)  |
| Unidentified bird, medium            | 11,333   | 7.9 (7.4–8.4)     | 8,905  | 10.3 (9.7–10.9)   | 0.75 (0.68–0.82)  |
| Raptors                              | 296      | 14.2 (10.7–18.6)  | 7,385  | 18.0 (17.2–18.9)  | 0.75 (0.54–1.05)  |
| Gulls & terns                        | 1,091    | 14.6 (12.6–16.8)  | 6,253  | 14.2 (13.3–15.1)  | 1.03 (0.86–1.24)  |
| Pigeons & doves                      | 740      | 7.0 (5.4–9.1)     | 5,980  | 6.2 (5.6–6.9)     | 1.14 (0.84–1.54)  |
| Shorebirds                           | 1,439    | 5.2 (4.2–6.5)     | 3,093  | 3.2 (2.6–3.8)     | 1.68 (1.24–2.29)  |
| Waterfowl                            | 2,056    | 45.6 (43.5–47.8)  | 1,650  | 38.2 (35.9–40.6)  | 1.35 (1.19–1.55)  |
| Other identified                     | 895      | 14.4 (12.3–16.9)  | 2,042  | 12.3 (10.9–13.8)  | 1.20 (0.96–1.51)  |
| Unidentified bird, large             | 1,573    | 27.5 (25.3–29.7)  | 1,222  | 34.0 (31.4–36.7)  | 0.73 (0.62–0.86)  |
| Bats                                 | 1,633    | 0.9 (0.6–1.5)     | 232    | 1.7 (0.7–4.3)     | 0.53 (0.17–1.61)  |
| Owls                                 | 1,216    | 9.4 (7.9–11.1)    | 206    | 13.1 (9.2–18.4)   | 0.69 (0.44–1.07)  |
| Hérons & egrets                      | 279      | 24.0 (19.4–29.4)  | 1,074  | 12.5 (10.6–14.6)  | 2.22 (1.60–3.08)  |
| Other mammals                        | 834      | 4.3 (3.1–5.9)     | 355    | 1.1 (0.4–2.9)     | 3.96 (1.40–11.21) |
| Deer                                 | 230      | 72.6 (66.5–78.0)  | 64     | 62.5 (50.3–73.3)  | 1.59 (0.89–2.85)  |

| Stratum | Night, n | damage % (95% CI) | Day, n | damage % (95% CI) | OR (95% CI) |
|---------|----------|-------------------|--------|-------------------|-------------|
|---------|----------|-------------------|--------|-------------------|-------------|

Table S8 Damage by stratum, above 500 ft against at or below 500 ft, lighter mass class

| Stratum                              | Above 500 ft, n | damage % (95% CI) | At or below, n | damage % (95% CI) | OR (95% CI)        |
|--------------------------------------|-----------------|-------------------|----------------|-------------------|--------------------|
| Unidentified bird, small             | 2,852           | 8.0 (7.1–9.1)     | 3,238          | 6.3 (5.5–7.2)     | 1.29 (1.06–1.57)   |
| Songbirds                            | 551             | 17.8 (14.8–21.2)  | 2,332          | 4.9 (4.1–5.9)     | 4.17 (3.13–5.56)   |
| Unidentified bird, medium            | 1,389           | 40.7 (38.1–43.3)  | 1,079          | 25.6 (23.1–28.3)  | 1.99 (1.68–2.37)   |
| Raptors                              | 909             | 76.8 (73.9–79.4)  | 1,431          | 27.3 (25.1–29.7)  | 8.80 (7.25–10.67)  |
| Unidentified bird, size not recorded | 1,025           | 20.2 (17.9–22.8)  | 1,110          | 7.4 (6.0–9.1)     | 3.17 (2.42–4.16)   |
| Gulls & terns                        | 316             | 52.5 (47.0–58.0)  | 1,633          | 20.4 (18.5–22.4)  | 4.32 (3.36–5.56)   |
| Waterfowl                            | 669             | 75.0 (71.6–78.2)  | 832            | 49.0 (45.7–52.4)  | 3.12 (2.50–3.90)   |
| Pigeons & doves                      | 74              | 29.7 (20.5–40.9)  | 1,338          | 9.9 (8.4–11.7)    | 3.83 (2.26–6.51)   |
| Unidentified bird, large             | 449             | 73.1 (68.8–76.9)  | 186            | 49.5 (42.4–56.6)  | 2.77 (1.94–3.95)   |
| Other identified                     | 212             | 62.3 (55.6–68.5)  | 388            | 27.3 (23.1–32.0)  | 4.39 (3.07–6.27)   |
| Shorebirds                           | 32              | 43.8 (28.2–60.7)  | 457            | 7.4 (5.4–10.2)    | 9.68 (4.43–21.13)  |
| Hérons & egrets                      | 34              | 73.5 (56.9–85.4)  | 290            | 14.8 (11.2–19.4)  | 15.96 (6.97–36.52) |
| Bats                                 | 74              | 5.4 (2.1–13.1)    | 40             | 0.0 (0.0–8.8)     | —                  |

Table S9 Damage by stratum, above 500 ft against at or below 500 ft, heavier mass class

| Stratum                              | Above 500 ft, n | damage % (95% CI) | At or below, n | damage % (95% CI) | OR (95% CI)       |
|--------------------------------------|-----------------|-------------------|----------------|-------------------|-------------------|
| Unidentified bird, small             | 13,176          | 2.3 (2.0–2.5)     | 25,753         | 1.8 (1.7–2.0)     | 1.25 (1.08–1.45)  |
| Songbirds                            | 4,099           | 4.3 (3.7–5.0)     | 25,145         | 1.7 (1.5–1.9)     | 2.62 (2.20–3.14)  |
| Unidentified bird, medium            | 10,449          | 9.4 (8.9–10.0)    | 11,764         | 7.5 (7.1–8.0)     | 1.28 (1.17–1.41)  |
| Unidentified bird, size not recorded | 7,281           | 4.1 (3.7–4.6)     | 10,218         | 2.0 (1.8–2.3)     | 2.06 (1.72–2.47)  |
| Gulls & terns                        | 918             | 26.5 (23.7–29.4)  | 6,639          | 12.9 (12.1–13.8)  | 2.43 (2.06–2.86)  |
| Raptors                              | 958             | 54.3 (51.1–57.4)  | 6,518          | 12.9 (12.1–13.8)  | 7.99 (6.90–9.25)  |
| Pigeons & doves                      | 252             | 13.5 (9.8–18.3)   | 6,927          | 5.6 (5.1–6.2)     | 2.61 (1.80–3.81)  |
| Shorebirds                           | 253             | 18.6 (14.3–23.8)  | 4,243          | 2.6 (2.1–3.1)     | 8.65 (5.98–12.52) |
| Waterfowl                            | 1,798           | 54.6 (52.3–56.8)  | 1,988          | 33.9 (31.8–36.0)  | 2.35 (2.06–2.68)  |
| Unidentified bird, large             | 1,857           | 34.0 (31.9–36.2)  | 1,061          | 23.0 (20.6–25.6)  | 1.73 (1.45–2.05)  |
| Other identified                     | 832             | 23.9 (21.1–26.9)  | 1,676          | 9.5 (8.2–11.0)    | 2.98 (2.37–3.74)  |
| Owls                                 | 36              | 22.2 (11.7–38.1)  | 1,415          | 9.8 (8.3–11.4)    | 2.64 (1.18–5.91)  |
| Hérons & egrets                      | 112             | 46.4 (37.5–55.6)  | 1,242          | 13.1 (11.4–15.1)  | 5.74 (3.82–8.61)  |

| Stratum | Above 500 ft, n | damage % (95% CI) | At or below, n | damage % (95% CI) | OR (95% CI)      |
|---------|-----------------|-------------------|----------------|-------------------|------------------|
| Bats    | 406             | 1.5 (0.7–3.2)     | 893            | 0.9 (0.5–1.8)     | 1.66 (0.57–4.81) |

Table S10 The altitude contrast within each FAA mass class separately, among reports with a recorded airspeed, on the cells retained by the stratum × airspeed band cross-classification

| Class   | AC_MASS | strata × band cells | above / below   | standardised RR on stratum, common support | standardised RR on stratum × airspeed band (95% CI) |
|---------|---------|---------------------|-----------------|--------------------------------------------|-----------------------------------------------------|
| Lighter | 1       | 24                  | 2,796 / 3,953   | 1.74                                       | 1.49 (1.37–1.63)                                    |
| Lighter | 2       | 26                  | 3,724 / 3,654   | 1.36                                       | 1.26 (1.14–1.40)                                    |
| Heavier | 3       | 25                  | 3,092 / 8,284   | 1.62                                       | 1.20 (1.04–1.39)                                    |
| Heavier | 4       | 36                  | 24,398 / 38,093 | 1.40                                       | 1.17 (1.07–1.28)                                    |
| Heavier | 5       | 7                   | 124 / 259       | 1.02                                       | 1.05 (0.55–1.99)                                    |

Table S11 The altitude contrast by the number of animals struck

| Class   | Animals struck | strata | above / below   | crude RR | standardised RR, combined (95% CI) |
|---------|----------------|--------|-----------------|----------|------------------------------------|
| Lighter | 1              | 12     | 7,927 / 11,393  | 2.25     | 2.18 (2.07–2.30)                   |
| Lighter | 2+             | 5      | 511 / 1,763     | 2.62     | 1.72 (1.50–1.96)                   |
| Heavier | 1              | 14     | 38,611 / 86,871 | 2.02     | 2.35 (2.23–2.47)                   |
| Heavier | 2+             | 11     | 3,754 / 18,212  | 2.94     | 1.73 (1.56–1.92)                   |

Table S12 Each height band against the band below it, each comparison standardised on its own strata and weights. This is the form used in earlier versions of this work; Table 4 of the manuscript instead reports one profile over strata present in every band

| Class   | Band against the band below           | strata | crude RR | standardised RR, combined (95% CI) | range over three standards |
|---------|---------------------------------------|--------|----------|------------------------------------|----------------------------|
| Lighter | 1–500 ft against ground               | 14     | 1.19     | 1.66 (1.57–1.76)                   | 1.50 to 1.98               |
| Lighter | 501–1,500 ft against 1–500 ft         | 11     | 1.59     | 1.50 (1.42–1.58)                   | 1.46 to 1.53               |
| Lighter | 1,501–3,000 ft against 501–1,500 ft   | 9      | 1.00     | 1.04 (0.98–1.09)                   | 1.03 to 1.04               |
| Lighter | above 3,000 ft against 1,501–3,000 ft | 8      | 1.08     | 1.08 (1.000–1.17)                  | 1.08 to 1.09               |
| Heavier | 1–500 ft against ground               | 14     | 1.51     | 1.46 (1.39–1.54)                   | 1.37 to 1.53               |
| Heavier | 501–1,500 ft against 1–500 ft         | 13     | 1.40     | 1.34 (1.26–1.42)                   | 1.31 to 1.35               |
| Heavier | 1,501–3,000 ft against 501–1,500 ft   | 13     | 1.17     | 1.24 (1.16–1.32)                   | 1.23 to 1.25               |
| Heavier | above 3,000 ft against 1,501–3,000 ft | 12     | 1.10     | 1.20 (1.13–1.28)                   | 1.20 to 1.21               |

Table S13 Damage above 500 ft against at or below 500 ft within the 9 FAA group codes meeting the inclusion rule (at least 100 reports on each side). Group codes pool several species and are excluded from the leaf-code medians in the main text

| Taxon              | FAA code | n above | damage % (95% CI) | n below | damage % (95% CI) | MH OR (95% CI)     |
|--------------------|----------|---------|-------------------|---------|-------------------|--------------------|
| Gulls              | NE1      | 924     | 30.7 (27.8–33.8)  | 5,344   | 14.8 (13.9–15.8)  | 2.51 (2.14–2.95)   |
| Sparrows           | ZX3      | 217     | 2.8 (1.3–5.9)     | 2,658   | 1.8 (1.4–2.4)     | 1.35 (0.56–3.30)   |
| Hawks              | K33      | 298     | 46.0 (40.4–51.6)  | 1,060   | 16.0 (14.0–18.4)  | 3.86 (2.88–5.16)   |
| Blackbirds         | ZT1      | 208     | 10.6 (7.1–15.5)   | 975     | 6.3 (4.9–8.0)     | 1.79 (1.06–3.02)   |
| Ducks              | J21      | 390     | 43.6 (38.8–48.6)  | 400     | 27.0 (22.9–31.6)  | 1.97 (1.45–2.69)   |
| Perching birds (y) | Y        | 264     | 4.5 (2.6–7.8)     | 459     | 1.3 (0.6–2.8)     | 2.95 (1.05–8.25)   |
| Geese              | J22      | 293     | 58.7 (53.0–64.2)  | 123     | 37.4 (29.4–46.2)  | 2.60 (1.65–4.08)   |
| New World vultures | K1       | 239     | 69.0 (62.9–74.6)  | 131     | 49.6 (41.2–58.1)  | 2.14 (1.35–3.39)   |
| Microbats          | 1C2      | 111     | 4.5 (1.9–10.1)    | 199     | 0.5 (0.1–2.8)     | 7.96 (0.59–107.50) |

Table S14 Class-specific odds ratios behind Table 5 and Table S13, the pooled Mantel–Haenszel estimate and the Breslow–Day test of homogeneity between the two classes. A dash marks a class with no damaging report at or below 500 ft

| Taxon                     | FAA code | lighter-class OR | heavier-class OR | MH OR (95% CI)      | Breslow–Day p |
|---------------------------|----------|------------------|------------------|---------------------|---------------|
| Gulls                     | NE1      | 3.54             | 2.07             | 2.51 (2.14–2.95)    | 0.002         |
| Mourning dove             | 02205    | 5.68             | 5.22             | 5.31 (3.41–8.27)    | 0.881         |
| European starling         | YL001    | 3.49             | 0.93             | 1.54 (0.76–3.13)    | 0.070         |
| Sparrows                  | ZX3      | 3.34             | 0.37             | 1.35 (0.56–3.30)    | 0.034         |
| Rock pigeon               | 02111    | 1.99             | 0.75             | 1.16 (0.68–1.99)    | 0.080         |
| Red-tailed hawk           | K3302    | 5.02             | 4.81             | 4.91 (3.52–6.86)    | 0.903         |
| Canada goose              | J2204    | 3.35             | 2.58             | 2.76 (2.21–3.46)    | 0.337         |
| Hawks                     | K33      | 5.87             | 2.67             | 3.86 (2.88–5.16)    | 0.010         |
| Blackbirds                | ZT1      | 3.50             | 1.17             | 1.79 (1.06–3.02)    | 0.047         |
| Turkey vulture            | K1002    | 3.53             | 3.28             | 3.38 (2.58–4.41)    | 0.790         |
| American robin            | Z6007    | 14.00            | 4.02             | 4.79 (2.81–8.14)    | 0.101         |
| Chimney swift             | T1002    | —                | 7.35             | 14.46 (1.83–114.05) | 0.338         |
| Ducks                     | J21      | 2.59             | 1.65             | 1.97 (1.45–2.69)    | 0.161         |
| Perching birds (y)        | Y        | 5.50             | 2.27             | 2.95 (1.05–8.25)    | 0.479         |
| Mallard                   | J2109    | 9.89             | 3.79             | 4.74 (3.33–6.76)    | 0.032         |
| Brazilian free-tailed bat | 1C2201   | —                | 1.36             | 1.36 (0.12–15.18)   | —             |
| Bald eagle                | K3201    | 3.98             | 5.99             | 5.06 (3.00–8.53)    | 0.451         |
| Geese                     | J22      | 3.31             | 2.22             | 2.60 (1.65–4.08)    | 0.391         |
| New World vultures        | K1       | 2.41             | 1.98             | 2.14 (1.35–3.39)    | 0.678         |
| Cedar waxwing             | ZD102    | —                | 3.29             | 4.78 (1.47–15.59)   | 0.228         |
| Microbats                 | 1C2      | —                | 2.85             | 7.96 (0.59–107.50)  | 0.385         |
| White-headed gull complex | NE141    | 1.40             | 2.52             | 2.36 (1.39–4.00)    | 0.499         |
| Yellow-rumped warbler     | ZS009    | —                | —                | —                   | —             |

Table S15 Proportion of reports carrying an identified species, by damage status and side of the contrast, for all animals and, within each FAA size class, for the non-mammal strata (everything outside deer, bats and other mammals), with the ratio of ratios  $\psi$  used as an identification-selection scenario

| Class   | Subset                                | damaging, exposed | not damaging,<br>exposed | damaging, baseline | not damaging,<br>baseline | $\psi$ |
|---------|---------------------------------------|-------------------|--------------------------|--------------------|---------------------------|--------|
| Lighter | all animals, above vs at/below 500 ft | 0.56              | 0.22                     | 0.80               | 0.61                      | 1.95   |
| Lighter | all animals, night vs day             | 0.61              | 0.26                     | 0.67               | 0.52                      | 1.81   |
| Lighter | non-mammal strata, size coded small   | 0.44              | 0.18                     | 0.60               | 0.59                      | 2.41   |
| Lighter | non-mammal strata, size coded medium  | 0.54              | 0.31                     | 0.71               | 0.73                      | 1.82   |
| Lighter | non-mammal strata, size coded large   | 0.71              | 0.62                     | 0.87               | 0.87                      | 1.15   |
| Heavier | all animals, above vs at/below 500 ft | 0.51              | 0.19                     | 0.69               | 0.54                      | 2.01   |
| Heavier | all animals, night vs day             | 0.51              | 0.31                     | 0.66               | 0.52                      | 1.32   |
| Heavier | non-mammal strata, size coded small   | 0.54              | 0.28                     | 0.69               | 0.61                      | 1.70   |
| Heavier | non-mammal strata, size coded medium  | 0.46              | 0.13                     | 0.66               | 0.48                      | 2.53   |
| Heavier | non-mammal strata, size coded large   | 0.63              | 0.32                     | 0.80               | 0.72                      | 1.78   |

Table S16 The altitude contrast within unidentified-bird strata. These strata are not selected by species-level identification, but the size code carried by an unidentified bird can itself depend on damage and height. Woolf 95% intervals

| Class   | Unidentified-bird<br>stratum | above 500 ft, n | damage % | at or below, n | damage % | OR (95% CI)      |
|---------|------------------------------|-----------------|----------|----------------|----------|------------------|
| Lighter | small                        | 2,852           | 8.03     | 3,238          | 6.33     | 1.29 (1.06–1.57) |
| Lighter | medium                       | 1,389           | 40.68    | 1,079          | 25.58    | 1.99 (1.68–2.37) |
| Lighter | large                        | 449             | 73.05    | 186            | 49.46    | 2.77 (1.94–3.95) |
| Lighter | size not recorded            | 1,025           | 20.20    | 1,110          | 7.39     | 3.17 (2.42–4.16) |
| Heavier | small                        | 13,176          | 2.26     | 25,753         | 1.81     | 1.25 (1.08–1.45) |
| Heavier | medium                       | 10,449          | 9.45     | 11,764         | 7.51     | 1.28 (1.17–1.41) |
| Heavier | large                        | 1,857           | 34.03    | 1,061          | 23.00    | 1.73 (1.45–2.05) |
| Heavier | size not recorded            | 7,281           | 4.11     | 10,218         | 2.04     | 2.06 (1.72–2.47) |