Rabie, P. A., M. M. Welsch, N. Stone, and C. Derby. 2024. Novel approach to estimating avian mortality from vehicle–bird collisions on U.S. roads. Journal of Field Ornithology 95(3):1. https://doi.org/10.5751/JFO-00498-950301

Ornithological Methods

Novel approach to estimating avian mortality from vehicle–bird collisions on U.S. roads

Enfoque novedoso para estimar la mortalidad de aves debida a colisiones con vehículos en rutas de EE.UU.

Paul A. Rabie[1], *Melissa M. Welsch*[1], *Nancy Stone*[1] *and* *Clayton Derby*[1]

ABSTRACT. Bird population declines are an important ecosystem issue, and mortality from human-derived sources—including collisions with vehicles—is a contributing factor. Current knowledge of bird collisions with vehicles is based on detections of roadside casualties by on-the-ground searchers. We present an estimate of annual vehicle–bird collisions (hereafter collisions) based on counts of collisions by drivers. From 30 December 2020 to 12 January 2022, drivers recorded 125 collisions and 2,265,126 driven km. Nationwide annual collision rates in the USA were estimated by multiplying our modeled per-km collision rates with the U.S. Department of Transportation's annual vehicle mileage data. The resulting estimated annual collision rate for unpaved rural two-lane and paved rural two-lane roads combined was notably higher than for other categories: 60 collisions per million km driven (95% confidence interval [CI] 42–85) compared with paved rural multi-lane (12 [95% CI 6–25]) and urban/suburban (14 [95% CI 4–44]) roads. The predicted annual collision rate for U.S. Fish and Wildlife Service regions was highest in the Pacific (95 collisions per million km driven [95% CI 47–195]) and lowest in the Pacific Southwest (eight collisions per million km driven [95% CI 1–61]; no collisions were recorded in the Southeast [limited sampling]). We estimated total number of vehicle–bird collisions in the continental USA to be 96 million birds per year (95% CI 59–200). Our results are based only on light-duty trucks and sedans, and so could be refined with a more representative sample of vehicle types. Nevertheless, our nationwide estimates are useful to help prioritize broad-scale efforts to slow or reverse population declines. Our work suggests vehicle–bird collision risk is highest on two-lane roads and for small birds, and research to identify mitigation measures to reduce vehicle–bird collision rates might be most useful on two-lane roads.

RESUMEN. La disminución de las poblaciones de aves es un problema ecológico importante, y la mortalidad debido a la actividad humana, incluyendo las colisiones con vehículos, es un factor que contribuye con esto. El conocimiento actual sobre colisiones de aves con vehículos se basa en la detección en terreno de aves atropelladas. Presentamos una estimación anual de colisiones vehículo-ave (en adelante, colisiones) basada en los recuentos de colisiones por conductores. Desde el 30 de diciembre de 2020 hasta el 12 de enero de 2022, los conductores registraron 125 colisiones y 2.265.126 km recorridos. Las tasas de colisión anuales a nivel nacional en EE.UU. se estimaron mediante la multiplicación de nuestras tasas modeladas de colisión por km con los datos anuales de kilometraje vehicular del Departamento de Transporte de EE.UU. La tasa de colisión anual estimada para carreteras rurales de dos carriles no pavimentadas y pavimentadas combinadas fue notablemente mayor que para otras categorías: 60 colisiones por millón de km recorridos (intervalo de confianza (IC) del 95%: 42–85) en comparación con carreteras rurales multicarril pavimentadas (12 (IC del 95%: 6–25)) y carreteras urbanas/suburbanas (14 (IC del 95%: 4–44)). La tasa de colisión anual predicha para las regiones del Servicio de Pesca y Vida Silvestre de EE.UU. fue más alta en el Pacífico (95 colisiones por millón de km recorridos (IC del 95%: 47–195)) y más baja en el Suroeste del Pacífico (ocho colisiones por millón de km recorridos (IC del 95%: 1–61)); no se registraron colisiones en el Sudeste (muestreo limitado). Estimamos que el número total de colisiones vehículo-ave en los EE.UU. continentales es de 96 millones de aves por año (IC del 95%: 59–200). Nuestros resultados se basan solo en camionetas ligeras y sedanes, por lo que podrían mejorarse con una muestra más representativa de tipos de vehículos. No obstante, nuestras estimaciones a nivel nacional son útiles para ayudar a priorizar los esfuerzos a gran escala para frenar o revertir la disminución de las poblaciones. Nuestro trabajo sugiere que el riesgo de colisión vehículo-ave es más alto en carreteras de dos carriles y para aves pequeñas, y la investigación para identificar medidas de mitigación para reducir las tasas de colisión vehículo-ave podría ser más útil en carreteras de dos carriles.

Key Words: *automobiles; bird mortality; birds; estimate; miles driven; road type; roadkill; two-lane road; USA; vehicles*

INTRODUCTION

Bird populations in North America have decreased by an estimated 29% since 1970 (Rosenberg et al. 2019). Seventy species have lost two-thirds of their population size in the last 50 yr and are expected to lose an additional half of their population in the next 50 yr (North American Bird Conservation Initiative (NABCI) 2022). Thirty-eight bird families have experienced declines, with the majority of losses occurring from New World American sparrow (Emberizidae), wood warbler (Parulidae), and blackbird (Icteridae) families (Correl et al. 2019, Rosenberg et al. 2019), and these taxa are largely insectivorous (Tallamy and Shriver 2021).

There are several known human-related sources of bird mortality—both direct and indirect causes, including predation by cats (*Felis catus*), collisions with objects, habitat loss, incidental loss from agricultural practices (e.g., pesticide effects or nest destruction by grazing cattle [*Bos taurus*]), direct killing of birds

---

[1] Western EcoSystems Technology, Inc.

(e.g., poaching, crop damage reduction), and climate change (Loss et al. 2013*a*, *b*, Stanton et al. 2018, Dinkins et al. 2019, Rosenberg et al. 2019, Bateman et al. 2020, Saunders et al. 2020, 2022, Swanson et al. 2020, NABCI 2022). Indirect sources of bird mortality (e.g., habitat change or climate change) may account for a larger fraction of observed bird population declines than direct sources (Bateman et al. 2020, Saunders et al. 2020, U.S. Fish and Wildlife Service (USFWS) 2023), but direct sources of mortality are cumulatively important and more amenable to management interventions (Loss et al. 2015).

Nationwide mortality estimates can be useful to help prioritize broad-scale efforts to slow or reverse population declines. Researchers have estimated effects of some human-related sources of direct bird mortality (Banks 1979, Erickson et al. 2005, Loss et al. 2015). According to a summary compiled by USFWS (2023), the largest direct source of bird mortality is predation by cats, estimated to cause 1.3–3.7 billion deaths per year (Loss et al. 2013*b*), followed by collisions with buildings (365–988 million; Loss et al. 2014*a*) and collisions with vehicles (89–340 million; Loss et al. 2014*b*). The USFWS is the federal agency responsible for protecting much of the country's fauna and flora and associated habitats (USFWS 2024). Additional sources with estimates include poison (72 million; USFWS 2023), collisions with electrical lines and communication towers (8–57.3 million and 6.6 million, respectively; Longcore et al. 2012, Loss et al. 2014*c*), oil pit entrapment (500,000–1 million; Trail 2006) and collisions with land-based wind energy turbines (140,000–328,000; Loss et al. 2013*a*). In addition, Machtans et al. (2013) estimated that 16–42 million birds die annually from collisions with buildings in Canada.

There is a robust literature for the top two sources of human-related bird mortality: cat predation on birds and bird–building collisions (e.g., Marra and Santella 2016 and Klem 2021, respectively). Our study focused on the third-highest estimated direct mortality source, bird collisions with vehicles (vehicle–bird collisions [VBCs]), about which less is known. van der Ree et al. (2015) summarized potential effects of roads on the surrounding ecosystem, including habitat loss and degradation, movement barriers, deterrence or attraction of wildlife, the creation of habitat or corridors for movement, and collision mortality. There are about 6.71 million km of U.S. public highways as of 2020 (U. S. Department of Transport [USDOT] 2014*a*, Statistica 2023) and at least US$120 billion has been designated for future U.S. roadway system expansion (American Society of Civil Engineers 2021), indicating an increasing occurrence of roads and likely VBCs.

Roads may be attractive to birds in several ways, putting them in proximity to vehicles for collisions. Areas adjacent to a road may have different vegetation, more favorable habitat, food resources, shelter, or perching opportunities compared with surrounding areas (Linsdale 1929, Milton et al. 2015). Erritzoe et al. (2003) and Bishop and Brogan (2013) noted that road-associated habitat may provide food in the form of human trash, spilt grain, road-killed animals, insects, earthworms, and prey detected from adjacent power lines, in addition to providing a source for grit, salt, drinking water, and bathing puddles.

In a review of 16 studies from eight countries on general effects of roads and traffic on 194 bird species, there was no overall strong negative effect (Rytwinski and Fahrig 2015). However, VBCs are an additive source of mortality for birds and may decrease already fragmented or declining populations (Bujoczek et al. 2011). The negative effects of VBCs for humans may include bodily harm and vehicular damage from some collisions plus reduced population size of species that are important for ecosystem services, such as food crop pollination and insect control (van der Ree et al. 2015, Klem 2021).

Understanding where, when, and why VBCs occur can help transportation planners avoid high-risk areas and create effective mitigation actions (Gunson and Teixeira 2015). Only four North American continent-wide estimates of VBCs are known, and all rely on a meta-analysis of individual, smaller-scale studies recorded in scientific literature, and all are based on roadside searcher data (i.e., observers traveled along roads and detected dead birds). The most comprehensive of these studies to date, Loss et al. (2014*b*), estimated that 89–340 million birds per year are killed by vehicles in the USA. Banks (1979) estimated that 57.2 million (10.2–374.5 million) birds were killed per year on U. S. roads in 1972, based on the rate calculated by Hodson and Snow (1965, as cited in Banks 1979). Erickson et al. (2005) updated the estimate by Banks (1979) to about 80 million birds based on road and vehicle data from 1997–1998. Bishop and Brogan (2013) estimated that 13.8 million VBC casualties occurred annually in Canada during the 4-mo breeding season.

Due to our familiarity with bird conservation issues from our work at an environmental and statistical consulting company (Company), we identified a unique opportunity to study VBCs using real-time human observation and normal driving routines. Our study used driver-reported VBCs from Company employees, who collectively drive over 6 million work-related km per year throughout the USA. The objective of this study was to estimate VBC rates by road type and region and extrapolate an annual VBC fatality estimate for the continental USA based on our collision rate data and USDOT mileage data. The USDOT collects mileage data as part of its responsibility to oversee the U. S. transportation system (USDOT 2022*a*). Our estimates provide an up-to-date point of comparison with existing estimates and are the first to be based on data collected specifically for this purpose and over a continental USA scale.

METHODS

Primary participants in our study were Company employees that regularly drove light-duty trucks and sedans for field data collection activities on other projects. Other interested Company employees also participated with their personal vehicles. All employees working for the Company as of December 2020 were eligible to participate, and participants self-selected into our study. Monthly data reporting (see "Field methods") was incentivized by offering participants chances to win prizes for timely data submission.

Field methods

Data collection

Each participant received instructions, datasheets for recording odometer readings and VBCs, and a removable sticker to place on the dashboard of their vehicle to remind them and other potential drivers to record VBCs. Each participant provided their name, vehicle's starting odometer reading, vehicle make and model, and license plate number.

Data collection occurred from 30 December 2020 to 12 January 2022. When a participant noticed that they had struck a bird, they stopped at a safe location (e.g., highway exit, roadside pullout, or their destination) as soon as possible to record strike details. Data collected included date, location (county and state), type of road (unpaved rural two-lane [e.g., gravel], paved rural two-lane, paved rural multi-lane [e.g., interstate], urban/suburban), bird size (i.e., large [at least 30 cm in length from head to tail], small [less than 30 cm in length]), bird guild (e.g., passerine, waterfowl, raptor), species (or best identification possible). At the end of each month, participants reported their current odometer reading, approximate proportion of monthly km driven in each U.S. state, approximate proportion of km driven during daylight, and approximate proportion of km on each road type (unpaved rural two-lane, paved rural two-lane, paved rural multi-lane, or urban/suburban) for the previous month. Total km for each participant each month were known exactly; monthly km per state, km during daylight hours, and km per road type were approximated by multiplying each participant's monthly km by their estimated proportion of km in each driving category.

Data processing

Study data were summarized into three data sets. The km per road type for each participant and month were summarized in a first data set (hereafter, "reporting categories data set") based on data reported by participants. To facilitate alignment with road type categories used by the USDOT (2021), a second data set (hereafter, "USDOT categories data set") was created containing categories that could be mapped to USDOT annual mileage data for 2020 (USDOT 2021), following the schema in Table 1. The sample unit for these data sets was monthly km per road type per participant. For a third data set ("USFWS region data set"), km per state for each participant and month were aggregated into km per USFWS region (USFWS 2010; Fig. 1). The sample unit for this USFWS region data set was number of monthly km per USFWS region per participant. The USFWS regions were chosen to be a meaningful grouping because wildlife management policies are organized at this level, and we anticipated too few data points to use state for a predictor in our analyses. Alaska and Hawaii were excluded from our study and were also excluded from the 2020 USDOT categories data set, along with mileage data from U.S. territories.

Table 1. Road-type schema for comparison among road-type categories collected in the Vehicle–Bird Collision Study, U.S. Department of Transportation (USDOT) road-type categories, and road-type categories used in the analysis.

Road category for analysis	Description based on road type reporting categories	Corresponding USDOT road type categories
Urban	Urban/suburban	Urban: total
Paved rural multi-lane	Paved rural multi-lane	Rural: interstate, rural: other freeways and expressways, rural: other principal arterial
Rural other	Paved rural two-lane, unpaved rural two-lane	Rural: minor arterial, rural: major collector, rural: minor collector, rural: local

Fig. 1. Management regions of the U.S. Fish and Wildlife Service used to stratify data in the Vehicle–Bird Collision Study.

Statistical analysis

We estimated collision rates (collisions per vehicle km) from our data using generalized linear mixed models (glmm). We were interested in variation in collision rates among geographic regions and road types, but our data lacked resolution to estimate both simultaneously; consequently, we conducted separate analyses to address each question. Finally, we used USDOT vehicle mileage estimates and our estimated collision rates to estimate total collision-related bird fatalities in the USA.

We used the glmmTMB package (v1.1.2.3; Brooks et al. 2017) in the R statistical software (v4.1.2; R Core Team 2021) to fit a generalized linear mixed model with a negative binomial distribution to each of three data sets. Reporting categories and USDOT categories data sets were analyzed with count of collisions being the response variable and road type being a categorical variable. The USFWS region data set was analyzed, with count of collisions being the response variable and USFWS region being a categorical variable. For all three models, participant identity was used as a random effect because most of our study participants were working on specific projects, and each participant's km tended to accrue over a relatively small number of driving routes. Monthly km were an offset term in the models, transforming parameter estimates into collision rates (i.e., collisions per vehicle km).

The ggeffects R package (v1.1.1; Lüdecke 2018) was used to generate predictions with 95% confidence interal (CI) in terms of collisions per km per road type or USFWS region. For USDOT categories and USFWS region models, these collision rates were multiplied by USDOT annual mileage estimates to obtain per road type and per USFWS region estimates of VBCs for 2020. To obtain an annual estimate of VBC mortality for the continental USA, we used a road type model covariance matrix to generate 100,000 bootstrap replicates of fatality rate estimates, multiplied results to the USDOT vehicle mileage estimates, and summed results for a bootstrap distribution of mortality for the continental USA in 2020. We did not plan to test formally for differences in vehicle collision rates among road types or regions because our objective was to characterize VBC risk rather than to test hypotheses about differences in risk, but upon reviewing the estimates, we made a post hoc pairwise comparison of collision rates among the reporting categories of road types with a Bonferroni adjustment for multiple comparisons.

RESULTS

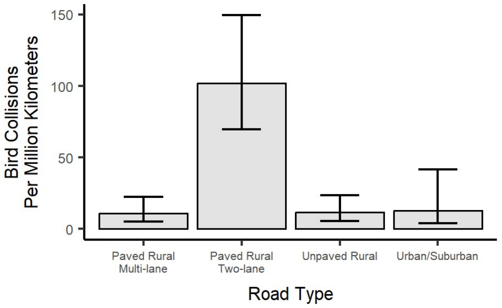
Eighty-nine participants drove 2,265,126 km and simultaneously monitored for collisions from 30 December 2020 to 12 January 2022 using 174 vehicles. About 35% of participants submitted monthly data for 10–12 mo, 40% for 4–9 mo, and 25% for 1–3 mo. Shorter durations were due to the seasonal nature of work duties. Data were recorded in all U.S. states except Alaska, Delaware, Hawaii, Massachusetts, Rhode Island, and Vermont.

One hundred and twenty-five VBCs were recorded, including 29 large birds and 96 small birds, for a total raw collision rate of 55.2 birds per million km driven (12.8 large birds and 42.4 small birds per million km driven, respectively). Thirty bird species were collision casualties, with the most common being Horned Lark (*Eremophila alpestris*; 14 casualties), Mourning Dove (*Zenaida macroura*; 10), Ring-necked Pheasant (*Phasianus colchicus*; 10), House Sparrow (*Passer domesticus*; 9), and American Robin (*Turdus migratorius*; 8), along with 23 casualties of unknown small birds. There were four or fewer casualties of all other species reported; the full species list is provided in Append. 1.

Collisions by road type

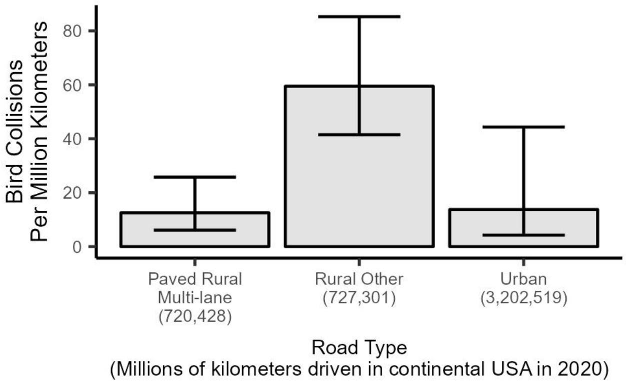
Of the reporting categories (Table 1), km driven during our study was about equal among paved rural multi-lane roads (690,603 km), paved rural two-lane roads (684,832 km), and unpaved rural two-lane roads (681,734 km), and fewer km were reported on urban/suburban roads (207,956 km). Respectively, VBCs by reporting category road type were 11, 100, 11, and three. Predicted collisions were significantly higher (all $p \leq 0.003$) for paved rural two-lane roads (102 collisions per million km driven [95% CI 70–150]) compared with paved rural multi-lane (11 [95% CI 5–22]), unpaved rural two-lane (12 [95% CI 6–24]), and urban/suburban (13 [95% CI 4–42]) road types, and collision rates did not differ among other road types (Fig. 2).

Fig. 2. Estimated annual bird collisions per million km driven by reporting category in the Vehicle–Bird Collision Study, 30 December 2020–12 January 2022. Error bars show 95% confidence intervals.



When data were reorganized into USDOT categories (Table 1), the predicted annual VBC rate for the rural other category (60 collisions per million km driven [95% CI 42–85]) was much higher than for paved rural multi-lane (12 [95% CI 6–25]) and urban (14 [95% CI 4–44]) road types (Fig. 3).

Fig. 3. Estimated annual bird collisions per million km among U.S. Department of Transportation (USDOT) road categories in the Vehicle–Bird Collision Study, 30 December 2020–12 January 2022. Error bars show 95% confidence intervals.



Collisions by U.S. Fish and Wildlife Service region

Participants drove in every USFWS region in the continental USA, with total km per region ranging from 20,308 (Southeast) to 799,780 (Midwest; Table 2). Vehicle–bird collisions were recorded in every region except the Southeast and ranged from one collision in the Pacific Southwest to 47 in the Midwest. Among regions where collisions occurred, the predicted annual VBC rate was highest in the Pacific (95 collisions per million km driven [95% CI 47–195]) and lowest in the Pacific Southwest (eight collisions per million km driven [95% CI 1–61], Fig. 4).

Nationwide estimate

The estimated number of bird collisions with vehicles in the continental USA was 96 million birds per year (95% CI 59–200).

DISCUSSION

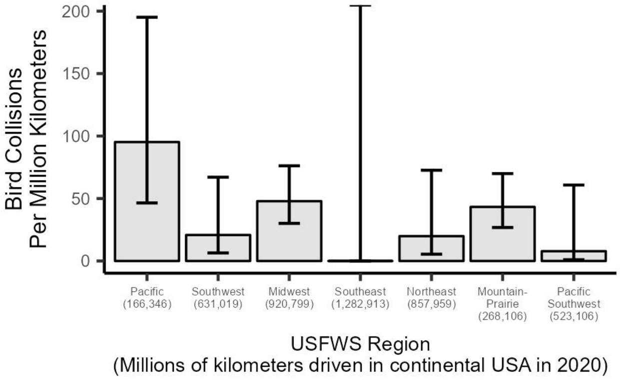
Overall vehicle-bird collision estimate

Our estimated annual continental USA VBC fatality rate, 96 million (95% CI 59–200 million) casualties, is slightly lower than, but on the same order of magnitude, as that calculated by Loss et al. (2014*b*), which was 89–340 million casualties per year and which also included collision casualties from commercial trucks and motorcycles. Our estimate is also comparable to that of Banks (1979), who estimated 10.2–374.5 million annual casualties on U. S. roads per year and is higher than the 80 million annual casualties estimated by Erickson et al. (2005). Our estimate does not account for imperfect detection by observers and so may underestimate VBCs. Our driving data also undersampled some of the USFWS regions, which could lead to bias (of unknown direction) in our estimate.

Table 2. Total kilometers driven, bird collisions, and composition for U.S. Fish and Wildlife Service (USFWS) regions in the Vehicle–Bird Collision Study, 30 December 2020–12 January 2022. USFWS Region 7 (Alaska and Hawaii) was not included in our analysis.

USFWS region (region number)	Total km driven	Bird collisions	Species composition of collisions
Pacific (1)	209,168	28	California Quail, Cliff Swallow, Dark-eyed Junco, Eurasian Collared Dove, European Starling, Horned Lark, House Sparrow, Lesser Nighthawk, Mourning Dove, Red-winged Blackbird, unknown dove, unknown small bird, unknown sparrow, White-crowned Sparrow
Southwest (2)	180,052	7	Eastern Meadowlark, Horned Lark, Killdeer, Mourning Dove, Ring-necked Pheasant, unknown small bird
Midwest (3)	799,780	47	American Robin, Barn Swallow, Brown-headed Cowbird, Common Grackle, Dickcissel, Eastern Kingbird, European Starling, Horned Lark, House Sparrow, Mourning Dove, Northern Flicker, Red-tailed Hawk, Red-winged Blackbird, Ring-necked Pheasant, unknown small bird, unknown sparrow, Vesper Sparrow, Yellow-rumped Warbler
Southeast (4)	20,308	0	Not applicable
Northeast (5)	133,247	3	American Robin, Barn Swallow, European Starling
Mountain-Prairie (6)	781,840	39	American Robin, Bank Swallow, Barn Swallow, Cassin's Sparrow, Chestnut-collared Longspur, Cliff Swallow, Horned Lark, House Sparrow, Killdeer, Mourning Dove, Red-winged Blackbird, Ring-necked Pheasant, Sharp-tailed Grouse, unknown blackbird, unknown small bird, unknown swallow, Vesper Sparrow, Western Kingbird, Western Meadowlark
Pacific Southwest (8)	140,732	1	Red-tailed Hawk

Fig. 4. Estimated annual bird collisions per million km among U.S. Fish and Wildlife Service (USFWS) regions in the Vehicle–Bird Collision Study, 20 December 2020–12 January 2022. Note that no collisions were recorded in the USFWS Southeast region. Error bars show 95% confidence intervals.



Our estimate is consistent with others that put vehicles as one of the top three sources of bird mortality, yet less than the combined 365 million–3.7 billion casualty range estimated for building collisions and cat predation (Loss et al. 2013*b*, 2014*a*). All three continental USA VBC estimates are greater than those attributed to commercial infrastructure, including electrical lines, communication towers, oil pits, and wind energy turbines (Trail 2006, Longcore et al. 2012, Loss et al. 2013*a*, 2014*c*, Erickson et al. 2014). Considering the large population declines for birds, conservation efforts should consider all sources of mortality, even ones for which no estimate of mortality is available, including habitat loss, agricultural practices, and climate change (Loss et al. 2015).

Road type and region effects

Paved rural two-lane roadways were associated with fatality rates several-fold higher than those on paved rural multi-lane roads, unpaved roads, or urban/suburban roads. A reason for this is not clear but could be related to shoulder width and roadside mowing regimes, which would affect proximity of potential bird habitat (e.g., grass) to moving vehicles. Speed of travel may interact with shoulder width because vehicles go faster on paved rural two-lane roads compared with unpaved rural roads, and paved rural two-lane roads have narrower shoulders than rural multi-lane roads. Also, there could be a difference in bird density between rural roads and urban roads (Finnis 1960). Finally, there may be a difference in detectability among road types based on vehicle speed or how busy a road is (Erritzoe et al. 2003). Bishop and Brogan (2013) considered two-lane and four-lane rural roads and determined that the VBC rate was an order of magnitude lower on two-lane roads with low seasonal traffic volume compared with rates on two-lane and four-lane roads with comparatively high seasonal volume. Their result suggests that traffic volume may be also an important predictor of VBC rates.

The "rural other" USDOT category, which included paved rural two-lane roads, comprised about half of all rural km driven (50.3%) and 15.7% of all km driven on U.S. roads in 2020 (USDOT 2021), indicating new knowledge in this area would apply to a large proportion of U.S. traffic in areas that birds tend to occupy. Given the higher fatality estimate calculated for paved rural two-lane roads compared with other road types (Figs. 2 and 3), future work should identify features specific to paved rural two-lane roads that are correlated with VBC rates. Such features may include shoulder width, mowing regimes, and traffic volume.

The USFWS Pacific region had a higher rate of collisions compared with other regions, but CIs for estimates overlapped across all regions (Fig. 4). González-Suárez et al. (2018), in a VBC study of roadways within Brazil, also identified variation in VBC rates based on geographical location. Collision rates may vary regionally, possibly at finer scales than our data can resolve, depending on local abundance and species composition of bird communities, and road-adjacent habitat conditions.

Species composition

Small birds made up the majority of VBCs in this study, possibly because population sizes of small bird species are often greater than those of large bird species (Partners in Flight 2020). González-Suárez et al. (2018) reported lower mortality rates for species having a more threatened conservation status (based on global International Union for Conservation of Nature's (IUCN) Red List of Threatened Species status reported by the authors) and presumably a smaller population size, also suggesting VBCs may, at least in part, occur proportionally to species abundance.

The five species accounting for most casualties in this study are all relatively abundant species. Horned Lark was the most frequently documented VBC species in our study; it was also the most common casualty species for both known multi-study meta-analyses of bird collisions with wind turbines (Loss et al. 2013*a*, Erickson et al. 2014) and is a relatively abundant species that is estimated to have a breeding population of 73 million in the USA (Partners in Flight 2020). Horned Larks tend to occur in areas of short grass and barren ground (Beason 2020), which road shoulders and mowed grass borders provide, especially in the U. S. Great Plains where part of our survey effort occurred. Passerines were the most commonly found casualty in Canadian studies reviewed by Bishop and Brogan (2013), whereas Loss et al. (2014*b*) noted that Barn Owl (*Tyto alba*), Common Raven (*Corvus corax*), Canada Jay (*Perisoreus canadensis*), Black-billed Magpie (*Pica hudsonia*), and European Starling (*Sturnus vulgaris*) all had a proportional representation of at least 5% in the studies used in their analysis.

Of 70 bird species identified in the 2022 State of the Birds report (produced by the U.S. Committee of the NABCI to document bird population trends) that experienced a two-thirds population decline in the last 50 yr (NABCI 2022), Chestnut-collared Longspur (*Calcarius ornatus*) comprised two casualties in our study. At least 8.8% of our study casualties were of New World sparrow (Emberizidae), wood warbler (Parulidae), and blackbird (Icteridae) families (four, one, and six individuals, respectively; Append. 1) that were previously identified to have relatively large population declines, although we note that 23 individuals were small birds and two more were unknown sparrows, meaning the impact to these taxa may be understated here. House Sparrow, a non-native species, accounted for nine small bird casualties, fourth highest by species.

Given the ubiquity of the House Sparrow, its non-protected status, and its susceptibility to collision demonstrated in this and other studies, local populations of House Sparrows could be a focus of future species-specific VBC studies for learning more about how bird life history and behavior affects susceptibility to collisions with vehicles for a passerine species. Although the house sparrow is not a focus of conservation as it is a non-native species in the USA, similar to some native passerine species, its population is also declining in the USA, especially in highly developed landscapes (Berigan et al. 2020). House Sparrow was reported to be the species most frequently killed on roads in mainland Europe and England (Erritzoe et al. 2003) and an area of Wisconsin (Finnis 1960). House Sparrow could be a model species from which derived knowledge could be applied to passerine species of conservation concern; this may be important because most declining bird populations in North America are represented by passerine species (Rosenberg et al. 2019). This could be a first step to identifying important variables related to species and life history that are correlates of VBCs, which could shape future conservation strategies. Additionally, as new driver-assisted self-driving vehicle technology becomes more prevalent, these research endeavors could be carried out by specially programmed self-driving vehicles equipped with sensors and cameras.

Study design

This study was the first to collect data about VBCs based on driver observations instead of observers looking for dead birds along the road. This approach increased the physical safety of data collection (e.g., observers were not walking along sides of roads near moving vehicles) and eliminated biases due to removal of carcasses by scavengers, injured individuals moving away from search areas (crippling bias), and inclusion of birds killed by other sources and assumed to be VBCs. This study also included a full calendar year, decreasing the potential for seasonal bias, whereas studies performed during expected peak VBC seasons were extrapolated to unsurveyed seasons that may have fewer VBCs (e.g., non-breeding seasons), potentially resulting in an inflated value; this was a potential influence for the estimate by Loss et al. (2014*b*).

Caveats

Our estimates do not account for imperfect observer detection, (i.e., ability of drivers to detect collisions), variation in detection between observers, non-random selection of participants (most observers were biologists working on avian studies and may have been inclined to drive in a way to avoid bird collisions), non-random use of U.S. roads, and relatively limited representation of vehicle types (none of the vehicles represented in our study was larger than a light-duty truck). If imperfect observer detection and non-random selection of participants were accounted for, the estimates could increase, whereas a wider suite of vehicle types may cause our estimate to increase or decrease. Collision detection was potentially subject to participant error; participants indicated they were "very certain" about 83% of the recorded collisions. Vehicle types other than sedans and light trucks (e.g., single-unit and combination trucks with more than two axles, buses, and motorcycles) account for just 17% of rural km and 11% of total km driven in the USA in 2020 (USDOT 2014*b*, 2022*b*) but if collision rates increase with vehicle size, those km could account for a substantial fraction of continental USA VBC risk. To the extent that our data do not represent the actual U.S. mileage, our estimate may be biased.

We recognize that estimates describing how collision rates vary by season are of interest, but seasonal phenology is highly location dependent, and we did not have enough data to make reliable inference to the seasonality of collision risk.

CONCLUSION

Our study provided a novel method to estimate VBCs and indicated that paved rural two-lane roads may pose a greater collision risk for birds than other road types. By using vehicle drivers recording collision data in near-real time, this method eliminated biases associated with searching for dead birds along roadsides in addition to seasonal bias associated with studies that do not last a full year. Future research should focus on identifying variables contributing to collision risk on paved rural two-lane roads, collecting more data in less-supported regions of our study, especially Northeast and Southeast USFWS regions, and determining if vehicle type is an important variable for VBCs. In addition, research on House Sparrows could be a starting point for identifying passerine-specific characteristics of VBC vulnerability. Collectively, these future research topics could provide conservation assistance for birds susceptible to collisions with vehicles, much like current research and conservation efforts are underway for bird and building collisions (e.g., Elmore et al. 2021, Klem 2021).

Acknowledgments:

We would like to thank all WEST employees who voluntarily participated in our study for their devotion to recording vehicle–bird collisions and tracking their miles. We would not have a study without them. We would also like to thank John Lloyd for his insightful review and Andrea Palochak for her expert help in preparing our manuscript for publication.

Data Availability:

The data sets generated during the current study are available from the lead author by request.

LITERATURE CITED

American Society of Civil Engineers. 2021. Report card for America's infrastructure: roads. American Society of Civil Engineers, Reston, Virginia, USA. https://infrastructurereportcard.org/cat-item/roads-infrastructure/

Banks, R. C. 1979. Human related mortality of birds in the United States. Special Scientific Report No. 215. U.S. Department of the Interior, Fish and Wildlife Service, Washington, D.C., USA.

Bateman, B. L., C. Wilsey, L. Taylor, J. Wu, G. S. LeBaron, and G. Langham. 2020. North American birds require mitigation and adaptation to reduce vulnerability to climate change. Conservation Science and Practice 2(8): e242. https://doi.org/10.1111/csp2.242

Beason, R. C. 2020. Horned Lark (*Eremophila alpestris*), version 1.0. In S. M. Billerman, editor. Birds of the world, Cornell Lab of Ornithology, Ithaca, New York, USA. https://doi.org/10.2173/bow.horlar.01

Berigan, L. A., E. I. Greig, and D. N. Bonter. 2020. Urban House Sparrow (*Passer domesticus*) populations decline in North America. The Wilson Journal of Ornithology 132:248-258. https://doi.org/10.1676/1559-4491-132.2.248

Bishop, C., and J. Brogan. 2013. Estimates of avian mortality attributed to vehicle collisions in Canada. Avian Conservation and Ecology 8:2. https://doi.org/10.5751/ACE-00604-080202

Brooks, M. E., K. K. Kristensen, K. J. van Benthem, A. Magnusson, C. W. Berg, A. Nielsen, H. J. Skaug, M. Maechler, and B. M. Bolker. 2017. glmmTMB balances speed and flexibility among packages for zero-inflated generalized linear mixed modeling. The R Journal 9:378-400. https://doi.org/10.32614/RJ-2017-066

Bujoczek, M., M. Ciach, and R. Yosef. 2011. Road-kills affect avian population quality. Biological Conservation 144 (3):1036-1039. https://doi.org/10.1016/j.biocon.2010.12.022

Correll, M. D., E. H. Strasser, A. W. Green, and A. O. Panjabi. 2019. Quantifying specialist avifaunal decline in grassland birds of the Northern Great Plains. Ecosphere 10: e02523. https://doi.org/10.1002/ecs2.2523

Dinkins, M. F., L. D. Igl, J. A. Shaffer, D. H. Johnson, A. L. Zimmerman, B. D. Parkin, C. M. Goldade, and B. R. Euliss. 2019. The effects of management practices on grassland birds—Horned Lark (*Eremophila alpestris*). Version 1.1. Chapter U in D. H. Johnson, L. D. Igl, J. A. Shaffer, and J. P. DeLong, editors. The effects of management practices on grassland birds. U.S. Geological Survey Professional Paper 1842. https://doi.org/10.3133/pp1842U

Elmore, J. A., S. B. Hager, B. J. Cosentino, T. J. O'Connell, C. S. Riding, M. L. Anderson, M. H. Bakermans, T. J. Boves, D. Brandes, E. M. Butler, N. L. Cagle, R. Calderón-Parra, A. P. Capparella, A. Chen, K. Cipollini, A. A. T. Conkey, T. A. Contreras, R. I. Cooper, C. E. Corbin, R. L. Curry, J. J. Dosch, K. L. Dyson, E. E. Fraser, R. A. Furbush, N. D. G. Hagemeyer, K. N. Hopfensperger, D. Klem, Jr., E. A. Lago, A. S. Lahey, C. S. Machtans, J. M. Madosky, T. J. Maness, K. J. McKay, S. B. Menke, N. Ocampo-Peñuela, R. Ortega-Álvarez, A. L. Pitt, A. Puga-Caballero, J. E. Quinn, A. M. Roth, R. T. Schmitz, J. L. Schnurr, M. E. Simmons, A. D. Smith, C. W. Varian-Ramos, E. L. Walters, L. A. Walters, J. T. Weir, K. Winnett-Murray, I. Zuria, J. Vigliotti, and S. R. Loss. 2021. Correlates of bird collisions with buildings across three North American countries. Conservation Biology 35:654-665. https://doi.org/10.1111/cobi.13569

Erickson, W. P., G. D. Johnson, and D. P. Young, Jr. 2005. A summary and comparison of bird mortality from anthropogenic causes with an emphasis on collisions. General Technical Report PSW-GTR-191. U.S. Department of Agriculture, Washington, D.C., USA. https://www.fs.usda.gov/psw/publications/documents/psw_gtr191/psw_gtr191_1029-1042_erickson.pdf

Erickson, W. P., M. M. Wolfe, K. J. Bay, D. H. Johnson, and J. L. Gehring. 2014. A comprehensive analysis of small-passerine fatalities from collision with turbines at wind energy facilities. PLoS ONE 9:e107491. https://doi.org/10.1371/journal.pone.0107491

Erritzoe, J., T. D. Mazgajski, and L. Rejt. 2003. Bird casualties on European roads—a review. Acta Ornithologica 38:77-93. https://doi.org/10.3161/068.038.0204

Finnis, R. G. 1960. Road casualties among birds. Bird Study 7:21-32. https://doi.org/10.1080/00063656009475957

González-Suárez, M., l. Z. Ferreira, and C. Grilo. 2018. Spatial and species-level predictions of road mortality risk using trait data. Global Ecology and Biogeography 27(9):1093-1105. https://doi.org/10.1111/geb.12769

Gunson K., and F. Z. Teixeira. 2015. Road–wildlife mitigation planning can be improved by identifying the patterns and processes associated with wildlife–vehicle collisions. Chapter 13 in R. van der Ree, D. J. Smith, and C. Grilo, editors. Handbook of road ecology. Wiley, Minneapolis, Minnesota, USA. https://doi.org/10.1002/9781118568170.ch13

Klem, D. 2021. Solid air: invisible killer: saving billions of birds from windows. Hancock House Publishers, Surrey, British Columbia, Canada.

Linsdale, J. M. 1929. Roadways as they affect bird life. The Condor 31:143-145. https://doi.org/10.2307/1362978

Longcore, T., C. Rich, P. Mineau, B. MacDonald, D. G. Bert, L. M. Sullivan, E. Mutrie, S. A. Gauthreaux, Jr., M. L. Avery, R. L. Crawford, A. M. Manville II, E. R. Travis, and D. Drake. 2012. An estimate of avian mortality at communication towers in the United States and Canada. PLoS ONE 7: e34025. https://doi.org/10.1371/journal.pone.0034025

Loss, S. R., T. Will, and P. P. Marra. 2013a. Estimates of bird collision mortality at wind facilities in the contiguous United States. Biological Conservation 168:201-209. https://doi.org/10.1016/j.biocon.2013.10.007

Loss, S. R., T. Will, and P. P. Marra. 2013b. The impact of free-ranging domestic cats on wildlife of the United States. Nature Communications 4: 1396. https://doi.org/10.1038/ncomms2380

Loss, S. R., T. Will, and P. P. Marra. 2014a. Bird–building collisions in the United States: estimates of annual mortality and species vulnerability. The Condor 116:8-23. https://doi.org/10.1650/CONDOR-13-090.1

Loss, S. R., T. Will, and P. P. Marra. 2014b. Estimation of bird–vehicle collision mortality on U.S. roads. Journal of Wildlife Management 78:763-771. https://doi.org/10.1002/jwmg.721

Loss, S. R., T. Will, and P. P. Marra. 2014c. Refining estimates of bird collision and electrocution mortality at power lines in the United States. PLoS ONE 9:e101565. https://doi.org/10.1371/journal.pone.0101565

Loss, S. R., T. Will, and P. P. Marra. 2015. Direct mortality of birds from anthropogenic causes. Annual Review of Ecology, Evolution, and Systematics 46:99-120. https://doi.org/10.1146/annurev-ecolsys-112414-054133

Lüdecke, D. 2018. ggeffects: tidy data frames of marginal effects from regression models. Journal of Open Source Software 3: 772. https://doi.org/10.21105/joss.00772

Machtans, C. S., C. H. Wedeles, and E. M. Bayne. 2013. A first estimate for Canada of the number of birds killed by colliding with building windows. Avian Conservation Ecology 8(2):6. http://dx.doi.org/10.5751/ACE-00568-080206

Marra, P. P., and C. Santella. 2016. Cat wars: the devastating consequences of a cuddly killer. Princeton University Press, Princeton, New Jersey, USA.

Milton, S. J., W. R. J. Dean, L. E. Sielecki, and R. van der Ree. 2015. The function and management of roadside vegetation. Chapter 46 in R. van der Ree, D. J. Smith, and C. Grilo, editors. Handbook of road ecology. Wiley, Minneapolis, Minnesota, USA. https://doi.org/10.1002/9781118568170.ch46

North American Bird Conservation Initiative (NABCI). 2022. The state of the birds, United States of America. North American Bird Conservation Initiative, Washington, D.C., USA. https://www.stateofthebirds.org/2022/

Partners in Flight. 2020. Population estimates database, version 3.1. https://pif.birdconservancy.org/population-estimates-database/

R Core Team. 2021. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Rosenberg, K. V., A. M. Dokter, P. J. Blancher, J. R. Sauer, A. C. Smith, P. A. Smith, J. C. Stanton, A. Panjabi, L. Helft, M. Parr, and P. P. Marra. 2019. Decline of the North American avifauna. Science 366:120-124. https://doi.org/10.1126/science.aaw1313

Rytwinski, T., and L. Fahrig. 2015. The impacts of roads and traffic on terrestrial animal populations. Chapter 28 in R. van der Ree, D. J. Smith, and C. Grilo, editors. Handbook of road ecology. Wiley, Minneapolis, Minnesota, USA. https://doi.org/10.1002/9781118568170.ch28

Saunders, S. P., N. L. Michel, B. L. Bateman, C. B. Wilsey, K. Dale, G. S. LeBaron, and G. M. Langham. 2020. Community science validates climate suitability projections from ecological niche modeling. Ecological Applications 30: e02128. https://doi.org/10.1002/eap.2128

Saunders, S. P., T. D. Meehan, N. L. Michel, B. L. Bateman, W. DeLuca, J. L. Deppe, J. Grand, G. S. LeBaron, L. Taylor, H. Westerkam, J. X. Wu, and C. B. Wilsey. 2022. Unraveling a century of global change impacts on winter bird distributions in the eastern United States. Global Change Biology 28:2221-2235. https://doi.org/10.1111/gcb.16063

Stanton, R. L., C. A. Morrissey, and R. G. Clark. 2018. Analysis of trends and agricultural drivers of farmland bird declines in North America: a review. Agriculture, Ecosystems and Environment 254:244-254. https://doi.org/10.1016/j.agee.2017.11.028

Statistica. 2023. Highway mileage within the United States from 1990 to 2020 (in million statute miles). Statistica Inc., New York, New York, USA. https://www.statista.com/statistics/183397/united-states-highway-mileage-since-1990/

Swanson, D. A., J. A. Shaffer, and L. D. Igl. 2020. The effects of management practices on grassland birds—Savannah Sparrow (*Passerculus sandwichensis*) (ver. 1.1, May 2023). Chapter FF in D. H. Johnson, L. D. Igl, J. A. Shaffer, and J. P. DeLong, editors. The effects of management practices on grassland birds. U.S. Geological Survey Professional Paper 1842. Washington, D.C., USA. https://doi.org/10.1093/ornithapp/duaa059

Trail, P. W. 2006. Avian mortality at oil pits in the United States: a review of the problem and efforts for its solution. Environmental Management 38:532-544. https://doi.org/10.1007/s00267-005-0201-7

U.S. Department of Transportation (USDOT). 2014a. Highway finance data collection: our nation's highways: 2011. USDOT, Federal Highway Administration, Highway Statistics, Washington, D.C., USA.https://www.fhwa.dot.gov/policyinformation/pubs/hf/pl11028/chapter1.cfm

USDOT. 2014b. Traffic monitoring guide. Appendix C. Vehicle types. Federal Highway Administration, Highway Statistics. Washington, D.C., USA. https://www.fhwa.dot.gov/policyinformation/tmguide/tmg_2013/vehicle-types.cfm

USDOT. 2021. Annual issues: functional system travel - 2020, annual vehicle - miles. Table VM-1. Federal Highway Administration, Highway Statistics. USDOT, Washington, D.C., USA. https://www.fhwa.dot.gov/policyinformation/statistics/2020/vm2.cfm

USDOT. 2022a. About DOT. USDOT, Washington, D.C., USA. https://www.transportation.gov/about

USDOT. 2022b. Annual issues: annual vehicle distance traveled in miles and related data - 2020 by highway category and vehicle type. Table VM-1. USDOT, Federal Highway Administration, Highway Statistics, Washington, D.C., USA. https://www.fhwa.dot.gov/policyinformation/statistics/2020/vm1.cfm

U.S. Fish and Wildlife Service. 2010. FWS National Regional Boundaries. U.S. Fish and Wildlife Service, Washington, D.C., USA. https://gis-fws.opendata.arcgis.com/datasets/fws::fws-national-regional-boundaries/explore

U.S. Fish and Wildlife Service. 2023. Threats to birds. U.S. Fish and Wildlife Service, Washington, D.C., USA. https://www.fws.gov/library/collections/threats-birds

U.S. Fish and Wildlife Service. 2024. Homepage. U.S. Fish and Wildlife Service, Washington, D.C. https://www.fws.gov/

van der Ree, R., D. J. Smith, and C. Grilo. 2015. The ecological effects of linear infrastructure and traffic: challenges and opportunities of rapid global growth. Chapter 1 in R. van der Ree, D. J. Smith, and C. Grilo, editors. Handbook of road ecology. Wiley, Minneapolis, Minnesota, USA. https://doi.org/10.1002/9781118568170.ch1

Appendix 1

Common Name	Scientific Name	Count
unknown small bird	Not applicable	23
Horned Lark	*Eremophila alpestris*	14
Mourning Dove	*Zenaida macroura*	10
Ring-necked Pheasant	*Phasianus colchicus*	10
House Sparrow	*Passer domesticus*	9
American Robin	*Turdus migratorius*	8
European Starling	*Sturnus vulgaris*	4
Barn Swallow	*Hirundo rustica*	3
California Quail	*Callipepla californica*	3
Killdeer	*Charadrius vociferus*	3
Red-winged Blackbird	*Agelaius phoeniceus*	3
White-crowned Sparrow	*Zonotrichia leucophrys*	3
Chestnut-collared Longspur	*Calcarius ornatus*	2
Cliff Swallow	*Petrochelidon pyrrhonota*	2
Dark-eyed Junco	*Junco hyemalis*	2
Red-tailed Hawk	*Buteo jamaicensis*	2
Sharp-tailed Grouse	*Tympanuchus phasianellus*	2
unknown sparrow	Not applicable	2
Vesper Sparrow	*Pooecetes gramineus*	2
Western Kingbird	*Tyrannus verticalis*	2
Western Meadowlark	*Sturnella neglecta*	2
Bank Swallow	*Riparia riparia*	1
Brown-headed Cowbird	*Molothrus ater*	1
Cassin's Sparrow	*Peucaea cassinii*	1
Common Grackle	*Quiscalus quiscula*	1
Dickcissel	*Spiza americana*	1
Eastern Kingbird	*Tyrannus tyrannus*	1
Eastern Meadowlark	*Sturnella magna*	1
Eurasian Collared Dove	*Streptopelia decaocto*	1
Lesser Nighthawk	*Chordeiles acutipennis*	1
Northern Flicker	*Colaptes auratus*	1
unknown blackbird	Not applicable	1
unknown dove	Not applicable	1
unknown swallow	Not applicable	1
Yellow-rumped Warbler	*Setophaga coronata*	1