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A previously published model of avian electrocution risk, “the 2014 model,” was developed by comparing power poles that electrocuted birds (electrocution poles; including 21 golden eagle Aquila chrysaetos electrocutions) to poles not known to have electrocuted birds (comparison poles). The 2014 model produces pole-specific risk index scores between 0 and 1. The scores rank relative risk so electric utilities can maximize conservation benefits per dollar spent by focusing retrofitting on poles with greatest risk. Although the 2014 model was created from a study population of birds and poles in southern California, the 2014 model has potential to be used in managing a target population of raptors including golden eagles throughout the western United States. Use beyond southern California is only appropriate if the study population is similar enough to the target population for the 2014 model to predict risk effectively. To evaluate similarity, we examined five sources of evidence. Two were the relative consistency in electrical safety codes for power poles and body sizes of golden eagles in the study and target populations. Three more were consistency in structure-specific factors associated with 1) golden eagle electrocutions in other studies, 2) other avian electrocutions, and 3) previously unreported golden eagle electrocutions. We found that although the study population in the 2014 model included relatively few golden eagles, data were sufficient to create a model that can be applied to a target population throughout the western United States. The model can also be useful in helping determine equivalencies between pole types if utilities seek to compare benefits of retrofitting small numbers of high-risk poles to large numbers of low-risk poles.
Can a Predictive Model of Avian Electrocution Risk from Southern California be Useful in Guiding Power Pole Retrofitting for Golden Eagles Throughout the Western United States?

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A previously published model of avian electrocution risk, “the 2014 model,” was developed by comparing power poles that electrocuted birds (electrocution poles; including 21 golden eagle Aquila chrysaetos electrocutions) to poles not known to have electrocuted birds (comparison poles). The 2014 model produces pole-specific risk index scores between 0 and 1. The scores rank relative risk so electric utilities can maximize conservation benefits per dollar spent by focusing retrofitting on poles with greatest risk. Although the 2014 model was created from a study population of birds and poles in southern California, the 2014 model has potential to be used in managing a target population of raptors including golden eagles throughout the western United States. Use beyond southern California is only appropriate if the study population is similar enough to the target population for the 2014 model to predict risk effectively. To evaluate similarity, we examined five sources of evidence. Two were the relative consistency in electrical safety codes for power poles and body sizes of golden eagles in the study and target populations. Three more were consistency in structure-specific factors associated with 1) golden eagle electrocutions in other studies, 2) other avian electrocutions, and 3) previously unreported golden eagle electrocutions. We found that although the study population in the 2014 model included relatively few golden eagles, data were sufficient to create a model that can be applied to a target population throughout the western United States. The model can also be useful in helping determine equivalencies between pole types if utilities seek to compare benefits of retrofitting small numbers of high-risk poles to large numbers of low-risk poles.

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Introduction

Extrapolating research results beyond their original scope of inference can be problematic because it is often impossible to know whether the underlying data structure and assumptions match (Tacha et al. 1982; Ellison 1996). However, research on wildlife habitats and behaviors are frequently extrapolated because repeating studies can be prohibitively expensive, result in delayed conservation actions, and be unnecessary when systems are similar. To address whether extrapolation is appropriate, Tacha et al. (1982) recommended defining a study population from which statistical inference is drawn and a target population to which inference will be applied, and carefully considering relationships between the two. Such comparisons can be accomplished via statistical methods in meta-analyses (Normand 1999) or Bayesian statistics (Ellison 1996) when raw data are available. Inference to biological significance can proceed in comparison-based assessments of independent datasets when raw data are unavailable. If patterns are consistent across datasets, then the original research may be extrapolated to the target population.

Dwyer et al. (2014) described a predictive model of avian electrocution risk for overhead distribution power lines (hereafter, “the 2014 model”). The 2014 model was developed by visiting 213 power poles where birds had been electrocuted (electrocution poles) and 248 poles where no electrocutions were known (comparison poles). Electrocution poles were randomly sampled from 440 poles that had electrocuted a bird and were still in service in southern California. Comparison poles were selected by placing random locations throughout the study area and then evaluating the nearest pole to each location. At each pole, Dwyer et al. (2014) collected information on numbers of jumpers, primary conductors, the presence of grounding, and the surrounding habitat. Variables were deliberately simple so the model could be used beyond the study population (Dwyer et al. 2014).

Golden eagles *Aquila chrysaetos* are affected by electrocution throughout much of their range. For example, the United States Fish and Wildlife Service (USFWS) estimates 504 golden eagles are
electrocuted in the United States annually (95% credible interval: 124–1,494; USFWS 2016a), accounting for 26% of annual anthropogenic mortality. We focus on golden eagles because of interest from the USFWS in using the 2014 model to standardize compensatory mitigation requirements under the 1940 Bald and Golden Eagle Protection Act (as amended, USFWS 2021b) as an offset for permitted incidental take. Application of the 2014 model to species other than golden eagles is addressed in the discussion. The USFWS defines take of golden eagles as actions to “pursue, shoot, shoot at, poison, wound, kill, capture, trap, collect, or molest or disturb” (USFWS 2009; 2016b) and incidental take as take “associated with but not the purpose of a [lawful] activity” (USFWS 2009). Incidental take, such as specific limited impacts during commercial activities, may be authorized by the USFWS if that incidental take is offset elsewhere (2016b). Preventing electrocutions of golden eagles by retrofitting power poles is a primary mechanism of conservation (USFWS 2016a; Mojica et al. 2018; Bedrosian et al. 2020). For example, the USFWS uses retrofitting high-risk poles as a primary compensatory mitigation tool to offset permitted incidental take of golden eagles (about 17 poles/bird) or nests (about 98 poles /nest; USFWS 2016b). Using the 2014 model to identify high-risk poles is a potential mechanism of transparently prioritizing mitigation for incidental take permits and utility retrofitting programs (Dwyer et al. 2014; Harness and Dwyer 2015). The 2014 model may also be useful as a mechanism for determining equivalencies between pole types (i.e., determining how many low-risk poles yields an equivalent conservation benefit to one high risk pole). Using the 2014 model to select poles and determine equivalencies will be possible only if it is appropriate to extrapolate the 2014 model beyond the study population.

The 2014 model included a relatively small proportion of golden eagle electrocutions (21 of 213; 10%). Data from so few individuals seems intuitively inadequate to extrapolate across the western United States. Extrapolation may be appropriate however, because avian electrocution risk is largely a function of pole configuration and bird size (APLIC 2006; APLIC 2018). Regarding pole configuration, General Order 95 (GO-95) specifies regulations for power line configurations in California (State of California 2018), and the National Electrical Safety Code (NESC) specifies standards of power pole construction elsewhere in the United States (IEEE Standards Association 2017). The two codes are similar in many of the features that influence avian electrocution risk. For example, GO-95 specifies “11.5 inches” (29.2 cm) of horizontal separation required between distribution conductors carrying up to 7.5 kV. The NESC specifies “12.0 inches” (30.5 cm) of horizontal separation between distribution conductors carrying up to 8.7 kV. Given the >102-cm
carpal-to-carpal spread of a golden eagle’s wings, the 0.7 cm difference in codes is inconsequential.

Regarding bird size, golden eagles are consistently among the largest birds across North American landscapes (Katzner et al. 2020).

Although extrapolation seems appropriate based on pole configuration and bird size, we questioned whether additional supporting data were available. We attempted to answer that by comparing electrocution risk defined by the 2014 model to three independent sources of data. These were 1) structure configurations (poles, pylons, and towers) associated with golden eagle electrocutions described in global scientific literature, 2) structure configurations associated with other avian electrocutions, and 3) pole configurations associated with previously unpublished golden eagle electrocution data from satellite-tagged golden eagles in the western United States. If, across these datasets, more complex structures are associated with greater electrocution rates, as they are in the 2014 model, then it will be reasonable to conclude that the 2014 model is broadly applicable. If data are inconsistent, then we will conclude it is inappropriate to extrapolate the 2014 model.

Methods

Following Tacha et al. (1982), we defined two study populations; 1) golden eagles, and 2) power poles in the service area where the 2014 model was developed. We defined golden eagles and power poles in the western United States outside of the study populations as target populations. Following convention within the electric industry, we defined a structure as any construction supporting a power line, including poles, pylons, and towers. Pylons and towers tend to be constructed of conductive concrete or steel. Poles specifically indicate cylindrical structures usually constructed of non-conductive wood in the United States.

Utility structure types associated with electrocutions

We reviewed published studies to identify whether there were patterns in configurations associated with golden eagle electrocutions by searching for key words *Aquila chrysaetos*, electrocution, golden eagle, and power line in the Institute for Scientific Information (ISI) Web of Sciences databases (Mojica et al. 2018). We reviewed publications these searches returned for data relating structure configuration to golden eagle electrocutions; data relating structure configuration to electrocutions of other birds, and citations containing additional data.
Google Earth assessment of power poles that electrocuted a satellite-tagged golden eagle

Previously published studies describing utility structures associated with electrocutions are potentially biased. Detection, scavenging, and search biases can influence which species and individuals are documented (Cartron et al. 2000; Dwyer and Mannan 2007; Lasch et al. 2010; Harness et al. 2013; Gális et al. 2019). Preconceptions about which structures are dangerous, and assumptions of electrocution as the cause of death can lead to confirmation bias (Harness et al. 2013; Demeter et al. 2018).

Satellite telemetry can create data unaffected by these biases (Dwyer et al. 2020b). The USFWS is using satellite telemetry of golden eagles to track movements and mortality in the central and southwest United States (Murphy et al. 2017; Murphy et al. 2019; Dwyer et al. 2020b). The dataset includes locations for 14 golden eagle electrocutions identified by USFWS personnel or their designees when visiting locations where GPS tracks terminated in Arizona, Colorado, New Mexico, Oklahoma, Texas, and Utah in the United States, and northern Chihuahua in Mexico. The GPS data are accompanied by photographs and non-technical descriptions of some of the poles involved. We used these data to assess the 2014 model, but to be useful, we needed configuration data for every pole involved so we could evaluate them consistently. We also needed configuration data for adjacent poles so we could identify how configurations of electrocution poles compared to poles across the landscape. We used Google Earth and Google Street View imagery to generate the necessary data. Google Earth imagery has been used to infer electrocution as a cause of death for osprey Pandion haliaetus (Klaassen et al. 2014) and assess golden eagle perching on poles (Dwyer et al. 2020b), but to our knowledge has not previously been used to assess the level of pole-specific detail in the 2014 model. For that reason, documenting the effectiveness of using Google Earth was a secondary objective of this study. To evaluate whether Google Earth imagery was effective, we used blind assessments of poles. Specifically, one author (EKM) held the USFWS pole descriptions and images while the other author (JFD) viewed the poles in Google Earth so we could compare remote sensing assessments to USFWS photos and descriptions. JFD navigated in Google Earth to each of the GPS waypoints provided for the electrocutions, and then following Dwyer et al. (2020b), identified whether a pole was visible within 30 m of the GPS point. If so, we assumed the pole, or the nearest pole if > one was present, was where the electrocution occurred. JFD examined poles in each Google Earth and Google Street View image available (typically 2-3, taken 1-3 years apart) to infer configurations and populate the 2014 model for the electrocution pole and four nearest poles. We followed Dwyer et al. (2020b) in assessing the four nearest poles because those
were within approximately 100 m, so likely would have provided a perched golden eagle with a similar view of the landscape. We compared configurations of poles where electrocutions occurred those of adjacent poles to identify configurations associated with electrocutions given the pole types across the landscape.

Because the level of detail visible in Google Earth was limited, we categorized poles as tangent, intersection, and equipment (Figure 1). Tangent poles supported conductors only and were constructed in relatively straight lines. Conductors are the long wires connecting poles to one another. Intersection poles supported conductors and jumpers where lines crossed or connected. Jumpers are the short wires connecting conductors to one another or equipment. Equipment poles supported conductors, jumpers, and equipment. Equipment is any energized pole-mounted device other than conductors and jumpers. Equipment poles also sometimes supported jumpers connecting conductors to equipment. For analysis, we pooled intersection poles and equipment poles as non-tangent poles. This addressed small sample sizes of intersection poles and equipment poles. Pooling was reasonable because the presence of jumpers on both pole types made them functionally similar. We used a chi-square test to compare proportions of electrocution poles (tangent versus non-tangent) to proportions of nearby poles (tangent versus non-tangent) to test the null hypothesis that golden eagle electrocutions occurred in proportion to pole types. We considered results significant at $\alpha = 0.05$.

To further validate the Google Earth assessment, we repeated it with a dataset provided by Powder River Energy Corporation (PRECorp, Gillette, WY; Bedrosian et al. 2020). The PRECorp data included GPS locations for 345 golden eagle electrocutions reported by customers or found by electricians. These locations likely included many of the biases described above but were useful in evaluating the technique because each datapoint was accompanied by a detailed pole description. We evaluated a random selection of 14 locations to match the sample size from the USFWS, and analyzed PRECorp data separate from USFWS data.

**Results**

**Structure types associated with golden eagle electrocutions**

Excluding Dwyer et al. (2014), we identified 10 publications that quantified relationships between golden eagle electrocutions and some aspect of structure configuration (Table 1). Each reported more electrocutions on more complex structures. Simpler structures typically involved few, if any, jumpers, equipment, or grounding. We also identified 23 peer-reviewed scientific
publications that quantified relationships between electrocution rates for birds other than golden eagles and some aspect of structure configuration (Table 2). Of these, 21 reported more electrocutions on more complex structures than on tangent structures. Many reported electrocutions of various species, often including eagle species, such as bald eagles *Haliaeetus leucocephalus* (Harness and Wilson 2001), Bonelli’s eagles *Aquila fasciata* (Tintó et al. 2010; Guil et al. 2011), chaco eagles *Buteogallus coronatus* (Sarasola et al. 2020), eastern imperial eagles *Aquila heliacal* (Gális et al. 2019), Spanish imperial eagles *Aquila adalberti* (Janss and Ferrer 2001; Guil et al. 2011), steppe eagles *Aquila nipalensis* (Matsyna et al. 2011; Dixon et al. 2019), tawny eagles *Aquila rapax* (Harness et al. 2013), and white-tailed eagles *Haliaeetus albicilla* (Demeter et al. 2018). Across species, electrocutions were associated with more complex structures. One study only evaluated tangent structures and found greater risk with shorter crossarms (Benson 1981). Shorter crossarms placed conductors closer together, similar to how separations are reduced with increased pole complexity. Another study reported electrocutions only on equipment poles. In that study, tangent poles were assumed lower risk based on prior knowledge (Kemper et al. 2020).

We did not find a single study indicating tangent structures were equally dangerous or more dangerous to golden eagles specifically, or to birds generally, than non-tangent structures. Patterns illustrating the risk-relationship between equipment and grounding were particularly apparent in India, Hungary, and Mongolia (Harness et al. 2013; Demeter et al. 2018; Dixon et al. 2019) where nearly all configurations, including tangents, involved grounded structures. Tangent structures in those locations were associated with increased numbers of electrocutions, but even then, intersection and equipment structures had greater numbers.

**Google Earth assessment of power poles that electrocuted a golden eagle**

We evaluated 28 electrocution poles including 14 from the USFWS (hereafter USFWS poles; Table 3) and 14 from PRECorp (hereafter PRECorp poles; Table 4). Each pole and some wires and equipment were visible in at least one Google Earth image (Figure 1). Grounding was not consistently identifiable. When we could confirm grounding present or absent, we report that assessment only. When we could not confirm grounding, we report scores with grounding present (PR) and with grounding absent (AB) so readers can see the role grounding plays in electrocution risk.

In assessing USFWS poles, at seven poles (50%) it was not possible to compare risk scores from remote sensing to known pole configurations because known configurations were not provided
(n = 5), the GPS location was midway between two poles with different configurations (n = 1), or the structure was a transmission pole not suitable for the 2014 model (n = 1). Of the remaining poles, our identification matched the reported configuration in six cases (86%). For one, the USFWS reported three transformers where it was clear in Google Earth there was only one. We concluded the USFWS assessment was incorrect.

Limiting our assessment to these seven poles, three (43%) electrocutions involved three-phase poles, five (71%) involved intersection or equipment poles (non-tangent poles), and two (29%) involved poles with grounding above the lowest energized component. The total count exceeds seven because some poles included combinations of factors. Overall, six poles (86%) where satellite-tagged golden eagles were electrocuted had one or more risk factors predicted by the 2014 model. Considering electrocution and comparison poles together, five electrocutions occurred across nine non-tangent poles, and two electrocutions occurred across 26 tangent poles (data from seven electrocution poles and four adjacent poles at each location). Electrocutions were significantly more likely on non-tangent poles than on tangent poles (X² = 9.57, df = 1, P = 0.002).

Stated another way, proactively retrofitting the nine non-tangent poles in the dataset would have prevented 71% of electrocutions. Retrofitting all 15 non-tangent poles and tangent poles with grounding above the lowest conductor would have prevented 87% of electrocutions. In contrast, proactively retrofitting all 20 tangent poles without grounding above the lowest conductor would have prevented only one (13%) electrocution. Accounting for the distribution of pole types on the landscape, electrocutions occurred at a rate 8.0 times greater on intersection and equipment poles, and on tangent poles with grounding above the lowest energized conductor than on tangent poles without grounding above the lowest energized conductor.

In assessing PRECorp poles, we correctly identified the electrocution pole in all 14 cases but did not correctly identify configurations for three. In two of those, crossarm-mounted lightning arresters were not visible in Google Earth, and in one, switches were not visible, leading to underestimates of the number of jumpers in each case. After correcting those errors, 12 of 14 electrocutions occurred on three-phase poles (86%), and 10 of 14 (71%) occurred on equipment or intersection poles (one also included grounding above the lowest conductor). Only four (29%) occurred on tangent poles, and only one (7%) on a single-phase tangent pole. Six of 56 (11%) nearby poles were equipment or intersection poles; 50 (89%) were tangent poles. We did not detect grounding above the lowest energized conductor on any adjacent pole. Overall, 10 electrocutions occurred across 16 non-tangent poles, and four occurred across 54 tangent poles (data from 14
Electrocution poles and four adjacent poles at each electrocution pole. Electrocutions were more likely to occur on non-tangent poles than on tangent poles ($X^2 = 23.41, df = 1, P < 0.001$).

Proactively retrofitting all 16 non-tangent PRECorp poles would have prevented 71% of electrocutions. In contrast, proactively retrofitting all 54 tangent poles would have prevented only four (29%) electrocutions. Accounting for the distribution of pole types on the landscape, electrocutions occurred at a rate 8.4 times greater on intersection poles, equipment poles, and poles with grounding above the lowest energized conductor than on tangent poles without grounding above the lowest energized conductor.

**Discussion**

We evaluated if the 2014 model might be too biased by geography and sample size to be useful in determining retrofitting priorities for golden eagles outside the study population. We could not test that quantitatively, so we considered similarities in pole construction practices and golden eagle sizes, consistency between the 2014 model’s variables and structure-specific factors identified as influential in other studies, and new data from satellite-tagged electrocuted golden eagles. We found high levels of consistency, suggesting the 2014 model can be extrapolated. Although our focus was on golden eagles, consistency with studies of other electrocuted birds suggests that our conclusions may also apply to other species.

The 2014 model has potential for widespread use, but also has limitations. One practical limitation is that correctly identifying grounding on poles is essential to generating accurate results. Google Earth imagery will likely be insufficient for identifying grounding, so users may need to physically visit poles to correctly determine whether a path to ground is present. Another limitation is that the 2014 model’s input variables are deliberately simple to make the model accessible to a wide range of users (Dwyer and Harness 2012). Although the choice for simplicity was deliberate, it nevertheless results in a weakness wherein the model considers the number of conductors but not their arrangement.

We used Google Earth imagery to develop risk index scores. The approach was mostly successful, but the resolution of the imagery was insufficient to see pole ground wires. The resolution was often sufficient to see where neutral wires were attached, and thus to infer whether grounding was likely. In an actual retrofitting program questions regarding grounding would be resolved through visiting and evaluating poles being evaluated. We also failed to detect lightning arresters on two poles and switches on one where golden eagles were electrocuted, leading to
incorrectly low risk index scores. Again, in a mitigation program this would be resolved through visiting and evaluating poles in person. Despite these errors, most electrocution locations were correctly associated with equipment poles. Given these patterns, we conclude that using Google Earth to characterize poles was effective but imperfect.

In the United States, determining how to prioritize poles for retrofitting is typically left to the discretion of electric utilities. In some cases, this is changing as the USFWS becomes involved through compensatory mitigation permitting. In such cases, the USFWS helps guide incidental take permittees and their utility partners to which poles can be retrofit to fulfill permit conditions. To create consistency and transparency in the process, the USFWS and electric industry need a mechanism of scaling the mitigation benefits of retrofitting various pole types. We describe what might be the least conservation-conservative equivalency, a highly conservation-conservative equivalency, and a middle ground for this scaling. The least conservation-conservative equivalency is to assume that all poles are equal so retrofitting any pole is equivalent. Clearly, not all pole configurations pose equal electrocution risk, and a 1:1 equivalency is inappropriate. A highly conservation-conservative equivalency might be to count pieces of equipment needed to retrofit a pole configuration that electrocutes a relatively large number of golden eagles. Typically, three-phase transformer banks are associated with high electrocution risk (citations in Tables 1, 2).

Retrofitting this configuration frequently requires 1 conductor cover or dead-end cover, 9 jumper covers, 3 lightning arrester covers, 3 cutout covers, and 3 bushing covers for a total of 19 pieces of retrofitting equipment. If this configuration is used as a baseline, then installation of 19 pieces of retrofitting equipment could be considered the equivalent of retrofitting one high risk pole regardless of how many poles the equipment is actually distributed across. Many intersection and equipment poles do not require as many pieces of equipment to retrofit however, so a 19:1 equivalency is probably also inappropriate. Equivalency between tangent poles and non-tangent poles appears to be somewhere between 1:1 and 19:1.

Our results may be useful in identifying a middle ground. In this study, electrocutions occurred 8.0-8.4 times more frequently on intersection poles, equipment poles, and poles with grounding above the lowest energized conductor (non-tangent poles) than on tangent poles without grounding above the lowest energized conductor. This ratio exceeds the ratio of 5.25:1 calculated by Mojica et al. (n.d.) in their assessment of electrocution data in Lehman et al. (2010). Because the Lehman et al. (2010) data were drawn exclusively from an oil and gas field where the density of non-tangent poles was unusually high, we suggest the ratio of 5.25:1 is informative in that case, but
not applicable across the entire western United States. Instead, we suggest the ratio of poles in Lehman et al. (2010) may indicate that the range in our findings should be refined to its low end of 8.0:1.

Using the 8.0:1 ratio, if the developer of a wind energy facility is required to retrofit 10 high risk poles (in the vernacular of the USFWS; Mojica et al. n.d.), then 10 non-tangent poles could be retrofitted, 80 tangent poles could be retrofitted, or the ratio could be applied to facilitate a mix of non-tangent and tangent poles. This would enable electric utilities to focus either on non-tangent poles or on circuits. Importantly, this does not imply that electric utilities cannot retrofit additional tangent poles if data exist indicating electrocutions are occurring on them in their service areas. If an electric utility knows that golden eagle electrocutions are occurring, then poles should be retrofitted regardless of whether funding from an external compensatory mitigation plan is available.

**Supplemental Materials**

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Figure 1. Examples of power poles that electrocuted golden eagles *Aquila chrysaetos* (2011-2019) as viewed in Google Earth at an eye height (Google Earth’s term for estimated height above ground) of 75 m. A) Three phase tangent. B) Three phase intersection. C) Three phase equipment. D) Three phase tangent with wires visible. E) Three phase intersection with wires visible. F) Single phase dead-end equipment. See APLIC (2006), Dwyer et al. (2014), and Dwyer et al. (2017) for ground-level views of various pole configurations.
Table 1. Original research associating power pole configuration with golden eagle *Aquila chrysaetos* electrocutions (excluding Dwyer et al. 2014).

| Publication1 | Location       | Finding regarding pole design and golden eagle electrocutions                                                                 | Consistent?a |
|-------------|---------------|-----------------------------------------------------------------------------------------------------------------------------|--------------|
| Bedrosian et al. (2020) | WY            | Electrocutions more frequent than expected in top bins of power pole density. Higher density bins included higher proportions of complex poles. | Yes          |
| Benson (1981) | ID, NV, NM, OR, UT, WY | No difference in electrocution rates across various wood 3-phase tangent configurations. Electrocutons reduced when ground wires insulated (functionally reduced complexity). | Yes          |
| Cartron et al. (2005) | Chihuahua Mexico | On concrete pylons with steel arms, average mortality per pole greater for double dead-ends with jumpers than for tangents. Golden eagles only three of 72 electrocutions. | Yes          |
| Dixon et al. (2019) | Sukhbaatar, Mongolia | On concrete pylons with steel arms, electrocution rates reduced by insulating conductors (functionally reducing complexity). | Yes          |
| Dwyer et al. (2020a) | CO, KS, NM, NE, OK, TX | Golden eagles perch more frequently than expected on poles supporting transformers. If electrocution risk is proportional to exposure, then risk is greater on transformer poles. | Yes          |
| Goroshko (2018) | Daurian Steppe, Russia | On lines supported primarily by wooden poles interspersed with concrete pylons, pylons had greater electrocution rates, particularly on complex pylons. | Yes          |
| Harness (2000) | CO, UT        | Raptor remains most frequent at three-phase dead-end, intersection, and transformer poles. Tangent poles were 42% of poles studied but caused only 9% of electrocutions. | Yes          |
| Study                          | Region          | Findings                                                                 | Consistent? |
|-------------------------------|-----------------|--------------------------------------------------------------------------|-------------|
| Harness and Wilson (2001)     | Western United States | Golden eagles frequently electrocuted on poles with transformers and infrequently electrocuted on tangent poles even though transformer poles were rare and tangent poles common in CA, CO, ID, KS, MT, ND, NE, NM, OR, TX, UT, and WY. | Yes         |
| Lehman et al. (2010)          | CO, UT          | Of 13 electrocutions on distribution poles (golden eagles n = 10), 10 were on dead-end, intersection, or transformer poles. Three on tangents. Study design resulted in low proportions of tangents evaluated. | Yes         |
| Schomberg (2003)              | MT              | The most important driver of electrocution risk on distribution poles was jumpers. Also important was the presence of grounds above conductors. | Yes         |

*“Consistent?” is short for “Are the findings of the study consistent with those of Dwyer et al. (2014)?” “Yes” indicates more complex pole configurations were associated with higher rates of electrocutions, as in the model in Dwyer et al. (2014).
Table 2. Original research associating power pole configuration with electrocutions involving species other than golden eagles *Aquila chrysaetos*.

| Publication                  | Location                              | Finding regarding pole design and avian electrocutions                                                                 | Consistent?* |
|------------------------------|---------------------------------------|----------------------------------------------------------------------------------------------------------------------|--------------|
| Benson (1981)                | ID, NV, NM, OR, UT, WY                | Assessed tangent poles only. 6-ft crossarms more dangerous than 8-foot crossarms.                                         | N/A          |
| BRC (2008)                   | Central and southern CA               | Electrocution risk increased on corner poles, and with number of conductors, presence of equipment, and the presence of metal arms. | Yes          |
| Cartron et al. (2005)        | Chihuahua, Mexico                     | On concrete pylons with steel arms, average mortality per pole was higher for double dead-ends with jumpers than for tangent. | Yes          |
| Demeter et al. (2018)        | Hungary (nationwide)                  | Pylons with terminal connections (more complex than tangent poles) were most dangerous, accounting for 8% of pylons and 24% of electrocutions. | Yes          |
| Dixon et al. (2019)          | Sukhbaatar, Mongolia                  | On concrete pylons with metal crossarms, electrocution rates reduced by insulating conductors (functionally reducing complexity). | Yes          |
| Dwyer and Mannan (2007)      | Tucson, AZ                            | Poles supporting transformers were more likely to electrocute a bird, particularly near nests.                          | Yes          |
| Ferrer et al. (1991)         | Doñana NP, Spain                      | Pylons including a jumper connecting conductors on double dead-end structures had higher electrocution rates.            | Yes          |
| Ferrer (2012)                | Throughout Spain                      | Pylons with jumpers or circuit breakers increased electrocution risk.                                                 | Yes          |
| Authors            | Location          | Findings                                                                 | Summary |
|--------------------|-------------------|--------------------------------------------------------------------------|---------|
| Gális et al. (2019)| Southern Slovakia | Corner pylons with exposed jumpers routed over insulators and metal crossarms were most dangerous. | Yes     |
| Galmes et al. (2017)| Central Argentina | Electrocutions most frequent on concrete pylons with jumpers above the cross-arm. | Yes     |
| Goroshko (2011)    | Trans-Baikal, Russia | When all pylons considered are concrete with grounded steel arms, complex structures are more dangerous. | Yes     |
| Guil et al. (2011) | Southeastern Spain | Dead-end and equipment steel lattice distribution structures had higher rates of electrocution than tangent structures. | Yes     |
| Harness and Wilson (2001) | Western United States | Electrocutions frequent on poles with transformers and infrequent on tangent poles in CA, CO, ID, KS, MT, ND, NE, NM, OR, TX, UT, and WY. | Yes     |
| Harness et al. (2013) | Rajasthan, India | On concrete pylons with metal crossarms insulator height and jumper count were important variables in modeling electrocution risk. | Yes     |
| Hernández-Lambraño (2018) | Northwest Spain | Greater numbers of conductive elements on the pole-tops increase electrocutions | Yes     |
| Hernandez-Matías et al. (2020) | Iberian Peninsula | Used Tintó et al. (2010) to guide retrofitting to complex pylons. Showed significant reduction in electrocution numbers. | Yes     |
| Authors          | Location | Findings                                                                                                                                                  | Consistent? |
|------------------|----------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|-------------|
| Janss and Ferrer (2001) | Southwest Spain | Electrocutions more frequent on steel lattice distribution pylons with pin insulators, than without pin insulators. More grounding = more risk. Jumper routing more important than jumper count. | Yes         |
| Kemper et al. (2013) | Alberta, Canada | Carcasses frequently found beneath 3-phase transformer poles; rarely beneath 3-phase tangents.                                                              | Yes         |
| Kemper et al. (2020) | Alberta, Canada | 24 electrocutions, all on poles with equipment, particularly bypass switches and riser poles. Consistent = N/A because numbers of simple poles were not reported. | N/A         |
| Matsyna et al. (2011) | Kalmykia, Russia | On tangent concrete pylons with steel arms, metal perch deterrents intended to reduce risk correlated with higher electrocution rates.               | Yes         |
| Mañosa (2001) | Catalonia, Spain | Configurations with conductors or jumpers near grounded components were more dangerous.                                                                   | Yes         |
| Sarasola et al. (2020) | Argentina | 55% of electrocutions occurred on steel-reinforced concrete pylons with jumpers above crossarms. Risk associated with grounding above conductors. | Yes         |
| Tintó et al. (2010) | Catalonia, Spain | Electrocutions associated with metal pylons, presence of jumpers, and conductors in dominant places.                                                       | Yes         |

* “Consistent?” is short for “Are the findings of the study consistent with those of Dwyer et al. (2014)” “Yes” indicates more complex pole configurations associated with higher rates of electrocutions, as in Dwyer et al. (2014).
Table 3. Risk Index scores (Dwyer et al. 2014) for incident poles that electrocuted golden eagles *Aquila chrysaetos* from 2011 to 2019 in Arizona, Colorado, New Mexico, Oklahoma, Texas, and Utah in the United States, and Chihuahua, Mexico and for adjacent poles not known to have electrocuted a bird.

| ID  | Pole Type | Incident pole | Four adjacent poles | High ground | Incident pole correct? | Scoring error / Description of high ground |
|-----|-----------|---------------|---------------------|-------------|------------------------|------------------------------------------|
| 01  | 3 / Tangent | 0.378 (0)     | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0), **0.512 (6)** | N           | N/A                    | No pole data provided / neutral down.            |
| 02  | 3 / Tangent | 0.509 (0)     | 0.509 (0), 0.509 (0), 0.509 (0), 0.509 (0) | Y           | N/A                    | No pole data provided / concrete pole.           |
| 03  | Unidentified | N/A          | N/A                 | N/A         | N/A                    | GPS point midspan, score N/A / cannot see ground. |
| 04  | 1 / Tangent | 0.437 (0)     | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | Y           | Y                      | No error / pole top ground.                     |
| 05  | 3 / Tangent | 0.378 (0)     | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N           | Y                      | No error / neutral down.                        |
| 06  | 1 / Equipment | **0.353 (2)** | 0.313 (0), 0.313 (0), 0.313 (0), 0.313 (0) | N           | Y                      | No error / neutral down.                        |
| 07a | 1 / Equipment | **0.353 (2)** | 0.313 (0), 0.313 (0), 0.313 (0), 0.313 (0) | AB          | Y                      | No error / cannot see grounding.                |
| 07b | 1 / Equipment | **0.482 (2)** | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | PR          | Y                      | No error / cannot see grounding.                |
| 08  | Transmission | N/A          | N/A                 | N/A         | N/A                    | Not appropriate for Dwyer et al. (2014) model / N/A. |
| 09a | 1 / Equipment | **0.353 (2)** | 0.313 (0), 0.313 (0), 0.313 (0), 0.313 (0) | AB          | N/A                    | No pole data provided / cannot see grounding.   |
| 09b | 1 / Equipment | **0.482 (2)** | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | PR          | N/A                    | No pole data provided / cannot see grounding.   |
| 10a | 1 / Equipment | **0.353 (2)** | 0.313 (0), 0.313 (0), 0.313 (0), 0.313 (0) | AB          | N/A                    | No pole data provided / cannot see grounding.   |
| 10b | 1 / Equipment | **0.482 (2)** | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | PR          | N/A                    | No pole data provided / cannot see grounding.   |
| 11  | 3 / Intersection | **0.579 (9)** | 0.378 (0), **0.444 (3)**, **0.444 (3)**, 0.378 (0) | AB          | Y                      | No error / cannot see grounding.                |
| 11b | 3 / Intersection | **0.701 (9)** | 0.509 (0), **0.576 (3)**, **0.576 (3)**, 0.509 (0) | PR          | Y                      | No error / cannot see grounding.                |
| 12  | 1 / Equipment | **0.504 (3)** | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | Y           | Y                      | USFWS reported 3 transformers / neutral on crossarm. |
| 13a | 3 / Tangent | 0.378 (0)     | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | AB          | Y                      | No error / cannot see grounding.                |
| 13b | 3 / Equipment | **0.701 (9)** | 0.509 (0), 0.509 (0), 0.509 (0), 0.509 (0) | PR          | Y                      | No error / cannot see grounding.                |
| 14a | 3 / Tangent | 0.378 (0)     | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | AB          | N/A                    | No pole data provided / cannot see grounding.   |
| 14b | 3 / Tangent | 0.509 (0)     | 0.509 (0), 0.509 (0), 0.509 (0), 0.509 (0) | PR          | N/A                    | No pole data provided / cannot see grounding.   |


a and b correlate to the high ground column indicating poles where grounding was not definitive were modeled with and without high grounding present. b Number = number of conductors. c Risk index scores assume high-quality habitat. d Bold font indicates non-tangent poles. Scores are followed by the number jumpers. e Bold font indicates grounding could be identified; AB = Unknown, assume grounding absent; PR = Unknown, assume grounding present. f Indicates the incident pole was correctly identified in Google Earth (Y = Yes, N/A = indicates no data on incident pole provided). g Scoring errors indicate pole features important to the 2014 model were not visible in Google Earth resulting in an incorrect risk assessment score for the electrocution pole.
Table 4. Risk Index scores (Dwyer et al. 2014) for incident poles that electrocuted golden eagles *Aquila chrysaetos* in Wyoming, United States (Bedrosian et al. 2020), and for adjacent poles not known to have electrocuted a bird.

| ID  | Pole Type | Incident pole | Four adjacent poles | High ground | Incdent pole correct? | Scoring error* / Description of high ground |
|-----|-----------|--------------|--------------------|------------|----------------------|------------------------------------------|
| 01  | 3 / Tangent | 0.378 (0)   | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 02  | 3 / Intersection | 0.444 (3)  | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 03a | 1 / Tangent  | 0.313 (0)   | 0.313 (0), 0.313 (0), 0.313 (0), 0.313 (0) | AB         | Y                    | No error / could not see grounding.     |
| 03b | 1 / Tangent  | 0.437 (0)   | 0.437 (0), 0.437 (0), 0.437 (0), 0.437 (0) | PR         | Y                    | No error / could not see grounding.     |
| 04  | 3 / Equipment | 0.512 (6)  | 0.579 (9), 0.378 (0), 0.378 (0), 0.378 (0) | N          | N                    | Did not see arresters. 1st score = 0.444 (3) / neutral down. |
| 05  | 3 / Equipment | 0.579 (9)  | 0.378 (0), 0.444 (3), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 06  | 3 / Intersection | 0.512 (3)  | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 07  | 3 / Equipment | 0.579 (9)  | 0.378 (0), 0.378 (0), 0.444 (3), 0.478 (0) | N          | Y                    | No error / neutral down.                 |
| 08  | 3 / Tangent  | 0.378 (0)   | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 09  | 3 / Equipment | 0.641 (6)  | 0.576 (0), 0.509 (0), 0.509 (0), 0.509 (0) | Y          | N                    | Did not see arresters. 1st score = 0.576 (3) / neutral down. |
| 10  | 3 / Equipment | 0.444 (3)  | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | N                    | Did not see arresters. 1st score = 0.378 (0) / neutral down. |
| 11  | 3 / Tangent  | 0.378 (0)   | 0.444 (3), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 12a | 3 / Equipment | 0.579 (9)  | 0.378 (0), 0.512 (3), 0.378 (0), 0.378 (0) | AB         | Y                    | No error / could not see grounding.     |
| 12b | 3 / Equipment | 0.701 (9)  | 0.509 (0), 0.641 (3), 0.509 (0), 0.509 (0) | PR         | Y                    | No error / could not see grounding.     |
| 13  | 3 / Equipment | 0.579 (9)  | 0.378 (0), 0.378 (0), 0.378 (0), 0.378 (0) | N          | Y                    | No error / neutral down.                 |
| 14a | 1 / Equipment | 0.374 (3)  | 0.313 (0), 0.333 (1), 0.313 (0), 0.313 (0) | AB         | Y                    | No error / could not see grounding.     |
| 14b | 1 / Equipment | 0.504 (3)  | 0.437 (0), 0.459 (1), 0.437 (0), 0.437 (0) | PR         | Y                    | No error / could not see grounding.     |

*a and b correlate to the high ground column indicating poles where grounding was not definitive were modeled with and without high grounding present. *bNumber = number of conductors. *cRisk index scores assume high-quality habitat. *dBold font indicates non-tangent poles. Scores are followed by the number jumpers. *eBold font indicates grounding could be identified; AB = Unknown,
assume grounding absent; PR = Unknown, assume grounding present. †Indicates the incident pole was correctly identified in Google Earth (Y = Yes, N = No). ‡Scoring errors indicate pole features important to the 2014 model were not visible in Google Earth resulting in an incorrect risk assessment score for the electrocution pole.
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