Arnold Schwarzenegger
Governor

IDENTIFYING ELECTRIC DISTRIBUTION POLES FOR PRIORITY RETROFITTING TO REDUCE BIRD MORTALITY

PIER FINAL PROJECT REPORT

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The PIER Program conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

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Identifying Electric Distribution Poles for Priority Retrofitting to Reduce Bird Mortality is the final report for the Reduction of Bird Electrocution Deaths project conducted by Southern California Edison, Pacific Gas & Electric, and by BioResource Consultants. The information from this project contributes to PIER's Energy-Related Environmental Research Program.

For more information about the PIER Program, please visit the Energy Commission's website at www.energy.ca.gov/pier or contact the Energy Commission at 916-654-5164.

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Abstract

This report outlines the research findings on reducing bird mortality due to electrocution on electric distribution lines. Field studies were conducted during 2003-07 in two phases. During the study, one-time visits were made to 9,502 distribution poles. Fatality searches were conducted at each and data were collected on numerous variables identifying the environmental and hardware characteristics of each pole. The fatality searches documented 1,079 bird carcasses. Of these, 60 were killed by electrocution. Another 227 were highly-likely to have been electrocuted. This study's data analyses were limited by using systematic sampling approach rather than a randomly-selected sample of poles and by the sample size of fatalities found during this study's searches. The data were analyzed to yield an annual mortality at the poles in the sample studied of 0.06 birds per pole, of which 0.01 were raptors. The most dangerous poles were those supporting lightning arrestors or riser elements. Logistic regression was applied to the data to examine 22 different candidate models that could be selected to predict the electrocution risk associated with poles and thus identify and prioritize poles requiring retrofit. A preferred model was identified and demonstrated with example applications. Applying results of these models can have a direct affect on reducing bird mortality due to electrocutions on power poles. This research benefits California by conserving valuable natural resources, ensuring compliance with environmental laws and regulations, improving the reliability of the electric distribution system, and increasing safety and reducing risk to public safety because bird electrocutions are often the source of wildfires. Monitoring for electrocutions must be expanded into more regions so protective measures can be implemented over a broader geographic area.

Keywords: Avian electrocution, distribution lines, avian electrocution risk model, power pole retrofitting

Executive Summary

Introduction

Electricity improves the quality of life and productivity of millions of Californians. Above-ground distribution systems are found in nearly every environment and support various hardware configurations (e.g., distribution pole frames, cross arms, and conductors), and often represent prevalent landscape features. Birds, such as raptors, use these features for perching and nesting, which can lead to their injury or death from touching energized elements on the pole. The risk of birds being electrocuted can generally be minimized by retrofitting hardware.

Purpose

Previous research has shown that only a small proportion of distribution poles actually electrocute birds suggesting that poles prone to electrocuting birds may have identifiable characteristics that increase risk to birds compared to those that do not electrocute birds. The likelihood of a given pole causing an electrocution might be due to any number (or combination) of environmental factors (e.g., location in foraging habitat or attractiveness as a perch) and hardware configurations. Information on the likelihood of poles electrocuting birds would aid in developing a strategic and cost-effective plan for retrofitting poles that have high-risk factors and configurations. These scientifically based strategic plans reduce bird electrocutions, power outages, and risk to human health and safety. This research developed an efficient and cost-effective system for identifying distribution poles requiring priority retrofitting to reduce bird mortality.

Outcomes

During this study biologists visited 9,502 distribution poles at least once while searching for bird fatalities. Multiple visits were made to a non-randomly selected subset of poles in the Central Valley to estimate bird mortality. Fatality searches conducted during 2003-07 produced 1,079 bird carcasses. Of these, 60 were killed by electrocution. An additional 227 were highly-likely to have been killed by electrocution and the remaining 792 were killed by events unrelated to electrocutions. The data were analyzed yielding an annual mortality in the pole sample studied of 0.06 birds per pole, of which 0.01 were raptors.

The visits to these poles were time consuming because the team searched for fatalities and extensively mapped and characterized numerous features, including the pole's framing, its equipment and the condition of the equipment, and a range of landscape and habitat attributes. These data have provided an unprecedented amount of new and useful information that can now be applied to tests of many additional hypotheses as long as additional fatality data are obtained at the same pole samples. This data analysis was limited by using a systematic sampling approach rather than a randomly-selected sample of poles and by the sample size of fatalities found during this study's searches. Confidence in the predictive model approach would improve with random sampling and increased sample sizes.

Poles that support lightning arrestors or riser elements electrocuted birds at much higher rates than did poles without them. Dead-end poles and midline relays[1] appear to be more dangerous to birds because these are where lightning arrestors and riser elements are more often installed. Poles with switches and fused cut-outs also appear to be considerably more dangerous than most other poles. Poles with only transformers appear to be safer to birds, (Figures 4-1, 4-2, and 4-3 for hardware illustrations).

To predict the electrocution risk associated with poles and identify poles requiring retrofits, a preferred model was selected after examining and testing 22 model options. This final model provided several insights. First, the model includes important predictors from all three basic categories of theoretical electrocution risk: (1) a pole's attractiveness, (2) the landscape setting around the pole, and (3) the hardware features of the pole. Second, four variables stand out as having an exceptional impact on a pole's risk of electrocuting birds: (1) the number of lightning arrestors or riser elements, (2) the number of raptor pellets observed (an indicator of use), (3) sign of prey abundance, and (4) the number of hardware elements in close proximity to each other (< 1m). The risk calculator developed by this study is recommended to the utilities as an effective tool for categorizing power poles electrocution risk. This model can be used to identify poles requiring retrofits to reduce bird mortality and effectively combines ease of use with the rigorous statistical basis of the logistic regression model. Additionally, similar models can be developed that are specific to a wide range of geographic regions or environmental settings.

Conclusions

Retrofitting the most dangerous poles first will quickly and substantially reduce bird mortality caused from electrocution. Utilities now have several tools available to assist them in making decisions regarding how best to apply limited resources to achieve the greatest impact to reduce bird electrocutions at power poles.

Benefits to California

Using these research results can have a direct impact on reducing bird mortality from electrocutions on power poles. This benefits California by conserving valuable natural resources, ensuring compliance with environmental laws and regulations, improving the reliability of the electric distribution system, and increasing safety and reducing risk to public safety because bird electrocutions are often the source of wildfires.

[1] A relay is a pole with hardware that steps down power to a building (e.g., house) or equipment (e.g., irrigation pump).

1.0 Introduction

The distribution of electricity improves the quality of life and productivity of millions of Californians. Above-ground distribution systems occur in nearly every environment and support various hardware configurations (e.g., distribution pole frames, cross arms, and conductors), often representing prevalent landscape features. Birds, such as raptors, use these features for perching and nesting (Bevanger 1994), which can lead to their injury or death by touching energized elements on the pole (Thelander et al. 1989; APLIC 1996; APLIC 2006; Lehman 2001; Harness and Wilson 2001). These electrocutions conflict with the federal Migratory Bird Treaty Act and other environmental laws (Lehman 2001), and reduce human safety and system reliability. Scientifically based studies are needed that identify electric distribution poles that are at high risk of electrocuting birds so alterations can be made to hardware reducing the frequency of these events.

The risk of birds being electrocuted can generally be minimized by retrofitting hardware to Avian Power Line Interaction Committee (APLIC) standards (APLIC 1996; 2006). California's two largest utilities, Southern California Edison (SCE) and Pacific Gas and Electric Company (PG&E) operate a complex array of electric distribution and transmission facilities throughout California that (combined) includes more than 3.7 million distribution poles and more than 150,000 circuit miles of distribution lines. Because it is not financially feasible to retrofit a large proportion of the 3.7 million poles, a method is needed that identifies for priority retrofit poles that are prone to or at high risk for electrocuting birds.

Previous research has shown that only a small proportion of distribution poles actually electrocute birds (Nelson 1980; O'Neil 1988; Lehman 2001). This suggests that poles prone to electrocuting birds may possess identifiable characteristics that increase risk to birds compared to those that do not electrocute birds. The likelihood of a given pole causing an electrocution might be related to any number (or combination) of environmental factors (e.g., location in foraging habitat, attractiveness as a perch, etc.) and hardware configurations (Thelander et al. 1989).

Information on the likelihood of poles electrocuting birds would help in developing a strategic and cost-effective plan for retrofitting poles with high-risk factors and configurations. Such scientifically based strategic plans may provide a substantial reduction in bird electrocutions, in power outages, and in risk to human health and safety.

1.1. Background

Based on a preliminary review of wildlife-related power outages, bird electrocutions often are spatially clustered with several often occurring in the same general area or even at the same poles. Each pole's likelihood of causing an electrocution is presumably caused by some combination of environmental factors (e.g., situated in foraging habitat, attractiveness as a perch, etc.) and hazards posed by particular hardware designs or configurations (Thelander et al. 1989).

Because different investigators often report different factors underlying avian fatalities on distribution poles (e.g., Benson 1982; Thelander et al. 1989; APLIC 1996; APLIC 2006; Harness 1997; Harness and Wilson 2001; Lehman 2001), this suggests that each retrofit program needs to address local conditions. When faced with great uncertainty about factors that may cause specific events, such as bird electrocutions on distribution poles, it is useful to adopt research strategies from the sub-discipline of systems ecology (e.g., Watt 1966; Watt 1968; Watt 1992).

PG&E and SCE have each initiated programs aimed at identifying power poles that pose a relatively high risk of causing electrocutions. For example, in 2002 a preliminary rating system of electrocutions was developed for SCE based on hypothesized causal factors that relied on the literature. That effort assembled and organized existing knowledge of avian electrocutions, and each hypothesis and conclusion was considered according to the evidence applied to it. Factors were identified that formed the basis for an initial rating system that relied on a weighted scoring process, as well as other factors thought to possibly cause or be otherwise associated with raptor electrocutions. The evidence and the literature citations of each factor used for that effort are summarized in Table 1-1. This information was then used to form the basis for identifying possible factors for which data collection in the present study might be used to develop the desired predictive model. The initial idea was to approach building a model based on a series of univariate tests of association, mainly using chi-square statistics.

1.2. Current Study

At the beginning of this study, an attempt was made to expand and improve the initial rating system approach using a univariate approach that relied mainly on chi-square tests of association. This approach was eventually rejected after further consultation with several statisticians and colleagues familiar with the study and the desired results. They determined that the initially-conceived and attempted univariate approach was fundamentally flawed, in large part because it failed to account for interactions between the measured variables. After deciding to depart from this initial approach, the present study chose to pursue analyses that almost exclusively rely on multivariate statistics, expecting that these alternative approaches would likely yield more useful and reliable results. Only the results of this latter approach are presented in this report.

This study describes, implements, and illustrates a new method for calculating the probability that any given power pole will cause an electrocution over a fixed time interval. The model is empirical in that the data (about 6,300 complete records) determine the relative importance of any given characteristic's contribution towards causing an electrocution. Because the dependent variable is binary (whether or not the pole has electrocuted raptor(s)), the authors use a logistic regression model. But before implementing a single model, they use theory and expert judgment from the published literature to develop a series of working hypotheses, each represented by a single logistic regression model with a unique set of independent variables. To choose among those models, the authors employ the Akaike Information Criterion (AIC), a common information theoretic measure.

Upon selection of a single set of independent variables which minimize information loss, a logistic regression was performed. The independent variables for this final model span three classes: (1) the attractiveness of a given pole to a raptor (e.g. the number of crossarms), (2) the pole design itself (e.g. the number of lightning arrestors), and (3) the landscape attractiveness (e.g. whether the surrounding landscape is likely to be used by raptors). The results lead the authors to conclude that all three classes of variables are important in the ultimate determination of a pole's risk. The study concludes by providing a simple and effective risk calculator that can be easily implemented in the field by practitioners with no statistical experience.

The study's research objectives (Section 2.0) necessitated accumulating landscape and pole attribute data for a large sample size of electric distribution poles. In addition, the researchers needed a large sample size of bird fatalities to achieve reliable results. The field time requirement to characterize poles is significantly greater than the time needed to search the areas below poles for bird carcasses. The study's objective to relate bird fatalities on electric distribution poles to the wide array of possible causal factors required the team to spend considerable time and effort measuring multiple variables at numerous poles. Much of this work was completed during Phase 1. For developing mortality estimates the team also needed to locate a large sample size of fatality events and to make repeat visits to a large sample of these, which was a major focus of Phase 2. The research effort was therefore planned to balance the time demands of these two different research objectives while staying within the project's budget.

Table 1-1. A summary of the sources reviewed for evidence founding the factors used in the development of a model prioritizing the retrofitting of distribution poles.

Rating Factors	Evidence	Citation
Phase spacing	APLIC standard of 152 cm exceeds 137 cm between wrists of golden eagle	APLIC 1996
Extra hardware spacing	APLIC standard of 152 cm exceeds 137 cm between wrists of golden eagle	APLIC 1996
Transformers	Eagles prefer transformer poles, reasoning these poles have larger silhouette	Benson 1982
	Pole-mounted transformers are the most dangerous device, based on questionnaire sent to power companies in Norway	Bevanger 1994
	Transformers kill more raptors	Harness 1997
	47.6% of RIMS fatalities at poles with transformers	Use of SCE RIMS data
	Poles with transformers 2.64 times more likely to kill Harris' hawk, but other equipment (lightning arrestors, fused cut-outs) implicated	Dwyer 2004
Switches	Industry incident reports	APLIC 1996
Jumper wires	Industry incident reports	APLIC 1996
Insulation	Industry incident reports	APLIC 1996
	Partial insulation reduced mortality 93% in S. Spain (cited Negro et al. 1989)	Negro and Ferrer 1995
	Insulating poles near nests reduced Harris' hawk electrocutions 74%	Dwyer 2004
Guy Wires	Guying attachments are more dangerous	APLIC 1996
Crossarm braces	Grounded metal crossarm braces are more dangerous	APLIC 1996
Metal crossarms	Metal crossarms are more dangerous	APLIC 1996
Crossarm orientation	Raptors prefer poles with crossarms crosswise to prevailing winds	Ansell and Smith 1980
	Crossarms parallel or diagonal to wind blow raptors into elements; Hypothesis test not significant, but still regarded as important	Benson 1982

Rating Factors	Evidence	Citation
Effective height of pole	Poles on crests or ridges provide updrafts for takeoff	Boeker and Nickerson 1975
	Utility poles preferred as perches	Marion and Ryder 1974
	Raptors prefer poles with commanding topographic position	Ansell and Smith 1980
	Eagles prefer poles on topographic salient	Benson 1982
	Taller poles kill more raptors	Benson 1982
Line aspect	Dead-end poles improve visibility	O'Neil 1988
	Corner poles improve visibility	O'Neil 1988
	Corner poles (i.e., line & buck) are more deadly due to need for jumper wires	APLIC 1996
	15.3% of RIMS fatalities at corner poles	Authors use of SCE RIMS data
	Eagles prefer corner poles	Benson 1982
	Dead-end poles kill more raptors	Harness 1997
	30% of RIMS fatalities at dead-end poles	Authors use of SCE RIMS data
Number of crossarms	Raptors prefer perching on poles with multiple crossarms	Smallwood et al. 1996
	36% of fatalities reported under poles with two crossarms;	O'Neil 1988
	61.2% of RIMS fatalities at poles with ≥2 crossarms	Authors use of SCE RIMS data
Crossarm position	Eagle electrocutions more frequent on poles with crossarm far below pole top	Benson 1982

Rating Factors	Evidence	Citation
Raptor fatalities	Industry incident reports	APLIC 1996
Raptor use area	Speculation	None
Vegetation structural diversity	Raptors more often use poles in heterogeneous habitats	Pearson 1979, c.f. in APLIC 1996
	Poles perched on randomly in uniform habitats, other factors notwithstanding	Ansell and Smith 1980
Vertical/lateral edge	Prey base, i.e., small mammals, prefer vertical and lateral edge conditions	Smallwood 2002
Prey base	Prey-bearing habitat is preferred	Boeker and Nickerson 1975, Ansell and Smith 1980
Cottontails	Eagles prefer poles in cottontail habitat; Significant correlation	Benson 1982
Ground squirrels	Raptors more often perch near ground squirrels	None
Pocket gophers	Raptors more often perch near gophers or other small mammals	Smallwood 1995, Smallwood et al. 1996
Vegetation stature	Prey species more available in shorter vegetation	None
Land use	Poles killed more raptors in uncultivated lands	Benson 1982
	Poles near alfalfa fields attract raptors	Smallwood et al. 1996
	Poles near pastures attract raptors	Smallwood et al. 1996
	Poles near fallow fields attract raptors	Smallwood et al. 1996
	Grassland preferred over agriculture	O'Neil 1988
Perch options	Fewer perch options increase the attractiveness of a pole for perching	Boeker and Nickerson 1975, Bevanger 1994

Rating Factors	Evidence	Citation
Proximity to nest trees	Harris' hawks susceptible to electrocution ≤2 weeks after fledging	Dawson and Mannan 1995,
	Harris' hawks susceptible to electrocution when nests ≤300 m from pole	Dwyer 2004
Other Factors		
Cold weather	Eagles still-hunt from poles more often; 81% of eagle electrocutions occurred during winter; inferred ultimate cause	Benson 1982
Wet weather	Wet feathers more conductive; 81% of eagle electrocutions occurred during winter; inferred ultimate cause	Benson 1982
Winter	More eagles electrocuted in winter	Harness 1997
	White-tailed kites used utility poles more often during winter and summer	Erichsen et al. 1996
Mating season	Buteos perform courtship on poles; 46% of *Buteo* electrocutions during spring and summer; inferred ultimate cause	Benson 1982
Summer/fall	Mortality greatest during this period	Harness 1997
Tangent pole	Upward-facing phase conductors kill more raptors	Harness 1997
Breeding areas	Poles in breeding areas attract hunting raptors	Bevanger 1994

Source: Citations provided in Table

2.0 Research Goal and Objectives

This research developed an efficient and cost-effective prioritization system for identifying distribution poles requiring priority retrofitting to reduce bird mortality.

The project was conducted in two phases. Phase 1 was conducted during 2003-2004 with the objectives being:

> (1) Identify and collect field data on possible causal factors of bird electrocutions at power poles in the SCE and PG&E service territories. This involved searching a large sample of selected poles once not only for fatalities but also for collecting environmental and pole hardware data needed for later analyses and predictive model development.

Phase 2 was conducted during 2005-2007. By revisiting selected power poles visited once during Phase 1 with the objectives being to:

> (1) Identify and collect additional field data on possible causal factors of bird electrocutions at power poles,
>
> (2) Apply various statistical approaches leading to the evaluation and selection of one or more predictive models for identifying poles for priority retrofitting, and
>
> (3) Estimate bird mortality due to electrocution at power poles by conducting multiple visits over a 12-month period.

3.0 Study Areas

In 2000 and 2001 respectively, SCE and PG&E identified and mapped what they termed 'raptor concentration areas' (RCAs) in SCE's service area (Figure 3-1) and 'raptor concentration zones' (RCZs) in PG&E's service area (Figure 3-2). Maps showing the boundaries of these areas were provided to the study team.

Phase 1 of this study was conducted during 2003-2004 within these broad areas of highest expected use by raptors. During Phase 1, 9,502 poles were visited. In 2005-2007, Phase 2 of the research focused on the Central Valley, which is primarily PG&E's service territory. Some 6,375 poles were searched more than once (see Section 4.0) during Phase 2. During Phase 2 the authors decided to not search poles for electrocution events in the SCE service area because the Phase 1 results demonstrated that the frequency of electrocutions was low there. The Central Valley region had the highest frequency of electrocution events poles surveyed in Phase 1. The team concluded that by focusing the searches during Phase 2 in this region of California the searchers would likely record the largest number of fatalities within the study's budget limitations for this task.

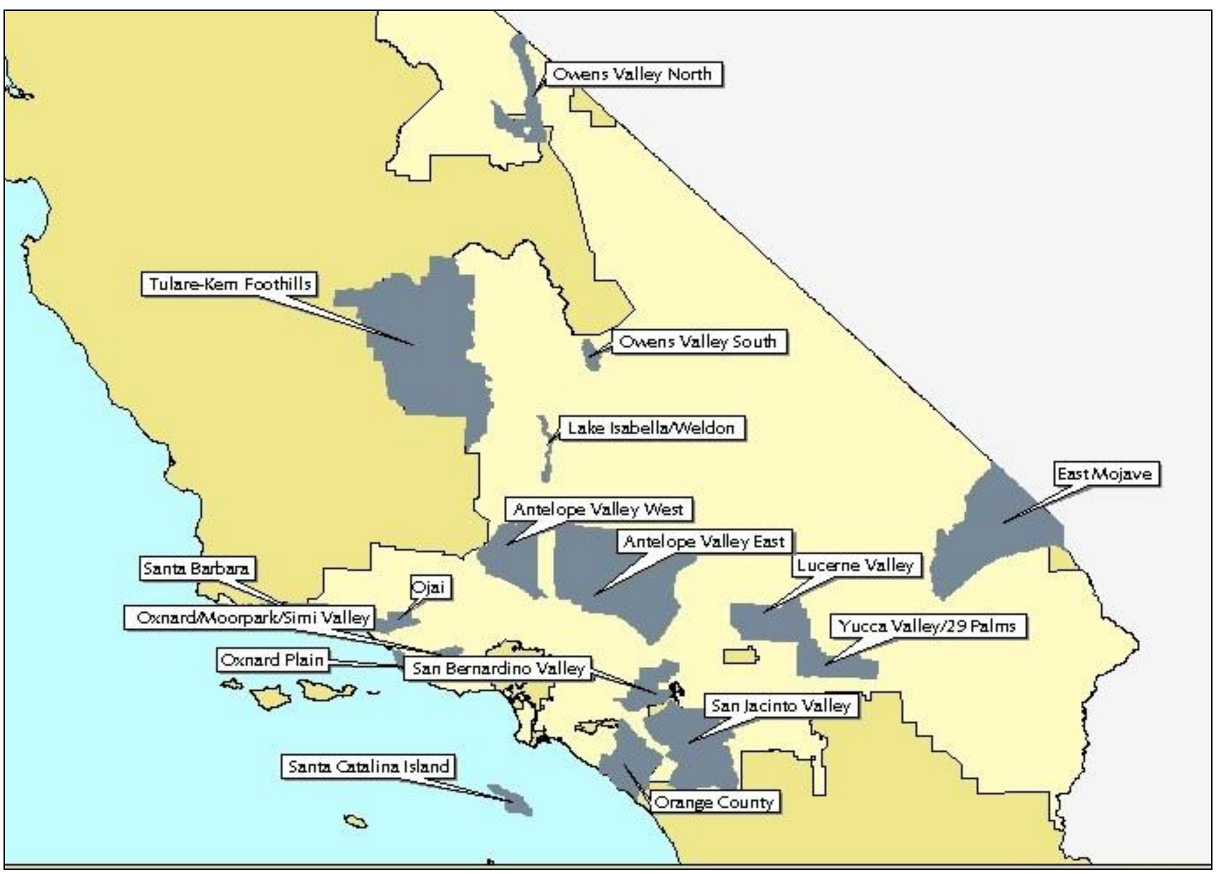


Figure 3-1. Raptor concentration areas in SCE's service territory.
Source: Southern California Edison

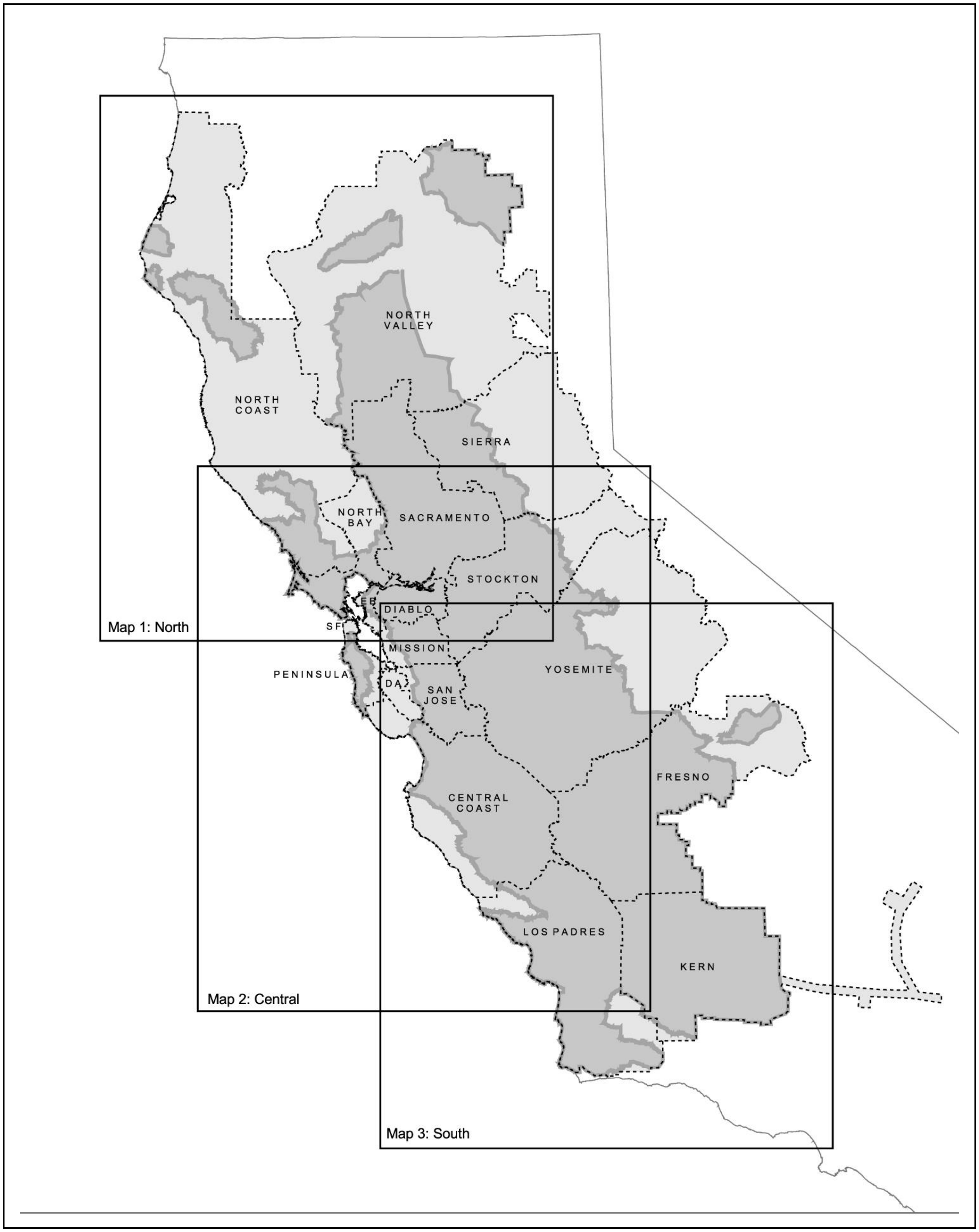


Figure 3-2. Raptor concentration zones (darker shade) in PG&E's service territory (dotted line).
Source: Southern California Edison

4.0 Methods

4.1. Sampling Approach

To achieve one of the study's main objectives, i.e., developing a model to predict priority retrofits, the team focused its field efforts on two fundamental data requirements: (1) finding a large sample of electrocution fatalities and (2) characterizing the hardware configurations and environmental features at a large sample of power poles. To accomplish this, the researchers employed a systematic sampling approach rather than random sampling.

Under ideal conditions the study's sample of electric distribution poles would have been randomly selected to allow for interpreting the results in terms of a broader geographic context. But the cost of achieving a random selection of over 9,500 poles among some 3.7 million poles was prohibitive because searchers would have had to travel great distances between poles over large geographic areas, and repeat this sampling several times over 12 months. As a result of this approach, interpreting many of this study's results was limited to the specific poles visited. Those results cannot, in the strictest sense, be inferred beyond the specific poles that were sampled.

This study was mensurative, meaning the study units (i.e., individual poles) were not manipulated (Hurlbert 1984). Passive observations were related to measured variables of environmental and physical attributes of the poles. The study units could not be placed randomly within the study area because they were already in place long before the study began. The "replicates" and the degrees of interspersion of "treatments," both of which are critical aspects of any experimental design, were already established. What was left to do was to select poles (i.e., non-randomly) from the population of poles in a manner that, in the team's professional judgment, best represented local conditions.

To represent different parts of the Central Valley, while trying to maximize search efficiency and reduce costs, the team non-randomly selected poles in numerous groups of about 300 contiguous poles along individual distribution lines. The searchers arbitrarily chose the starting point of each contiguous group within three regions of the Central Valley. These non-randomly selected regions were generally northwest of Sacramento, around Tracy, and around Fresno. Additionally, poles were added (non-randomly) to the fatality searches if they occurred along a bird monitoring transect that Smallwood used during the 1990s in a previous study (Smallwood et al. 2006 and unpublished data) that recorded hundreds of observations of raptors perching on these electric distribution poles. The searchers non-randomly selected poles within 400 m of Smallwood's 125.4 miles of road survey transect in the Sacramento Valley to be searched for electrocutions. The combined total of these non-randomly selected poles where electrocution searches were conducted in Phase 2 was 6,375 individual poles.

While some key statistical assumptions pertaining to Type I and II error[2] likely do not strictly hold using the chosen sampling approach, they all are likely to hold approximately, at least

[2] Type I error refers to the mistake of rejecting the null hypothesis when it is true. Type II error refers to the mistake of failing to reject the null hypothesis when it is false.

within the geographic region covered by the data and on average across greater than 6,375 poles.

4.2. Conducting Carcass Searches

The researchers chose electric distribution poles as their sampling units. A team of searchers, all qualified biologists, conducted foot-based surveys in a 15-m radius area around each non-randomly selected pole, and along a 30-m wide length between intervening poles. Narrower transects were used in taller vegetation, and in all cases an equal area of ground was thoroughly searched.

Each pole was rated for the portion of the search area in which a carcass was able to be detected, where 0 was none of the 15-m search area, 1 was <10%, 2 was 10-20%, 3 was 21-30%, 4 was 31-40%, and 5 was 41-100%. Initial searches in the Sacramento and Tracy areas were performed during August 2003 through mid-February 2004, as well as during July 2004.

The initial searches in the Fresno area were performed during November and December 2003. The initial (and final) searches in the SCE service area were performed mid-February through mid-June 2004, but the electrocution data that were obtained there were not used in this report for mortality estimates because the searchers did not conduct follow-up surveys in the SCE service area for reasons described elsewhere in this report.

During Phase 2, carcass searches at poles in the Central Valley were performed four more times, once per season during Winter 2005-06, Spring 2006, Summer 2006, and during Fall/Winter 2006-07.

All bird carcasses found during Phase 1 (2003-04) were mapped using a Trimble Pathfinder Pro-XRS. During 2005-07 searchers recorded distance and bearing to the poles. Each carcass was photographed with an engineers' survey card of 10.1 x 6.1 cm for scale.

During Phase 1 (2003-04), carcass condition was classified as consisting of old remains, bones only, bones and feathers, dried flesh, harboring maggots, recent and odiferous, or no decay or smell. This classification expressed a gradient of conditions typical of how long a carcass has been in the environment. During Phase 2 (2005-07), searchers recorded whether the carcass consisted of old remains, bones only, feathers were present, the flesh was dried, maggots were present, an odor of decay was noticeable, did not smell because its deposition was recent, included enamel on the culmen, or included enamel on the talons. The feathers of each carcass were classified for color, including original, intermediate, and bleached. The skeleton was rated for the degree to which it was intact, where 5 = fully articulated, 4 = mostly articulated, 3 = partly articulated, 2 = mostly disarticulated, and 1 = disarticulated. Biologists also noted whether carcasses were bloody, eyes were bright or cloudy, rigor mortis had set in, and whether other insect larvae had established a presence.

In Phase 1 (2003-04), found body parts were classified as whole carcass, wings only, talons only, head only, torso, feathers or other. In Phase 2 (2005-07), found body parts were described in terms of their condition and measurements of flesh-free bones were recorded.

Intact carcasses were examined for evidence of burning, singed feathers and the types of wounds typically caused by electrocution (see Dwyer 2004, EDM 2004). Bone measurements were compared to trends identified in EDM (2004) to identify old remains of raptors to species.

Evidence used to attribute cause of death as a 'certain' electrocution included singed feathers, scorched, curled talons, and any other features that unequivocally indicated to the biologist that the bird had been electrocuted. Electrocutions lacking such obvious features were more difficult to identify. Evidence used to attribute cause of death as 'highly-likely' electrocution included the appearance of what may have been singed feathers or scorching, possible contorted positioning of the carcass immediately below the pole, and professional judgment about the possibility, based on local and specific circumstances, of non-electrocution causes of death through a process of elimination.

The designation of a carcass as a 'highly likely' electrocution was generally done by consensus among the searchers present at the time of discovery and subsequent discussions and/or evaluations with and by Smallwood during data entry and analysis. While the 'highly likely' category is based largely on subjective criteria and non-repeatable professional judgment, the authors believe that the reduction of 1,079 total carcasses found to just the designation of 227 'highly likely' electrocutions results in a frequency that can be reasonably relied upon to calculate the upper limits of an estimate of mortality due to electrocutions at the sample of poles that were searched. Conversely, using only the carcasses designated 'certain' (n = 60) would likely under-estimate mortality due to electrocution in this study's sample of poles because it is almost certain that electrocutions were involved in the deaths of birds that were discovered even though clear and direct evidence may not have been absolutely discernable in the field at the time of the discovery.

The disposition of the carcass was classified as on the ground, hanging from the pole, or both on the pole and on the ground. The estimated age of the bird at the time of death was classified as adult, subadult, juvenile, or unknown, and the gender was classified as male, female, or unknown.

4.3. Measuring Environmental Variables

Numerous environmental variables were measured at each pole. Biologists recorded the number of road verges, dirt roads, canals/ditches, streams and fences within 200 m of the pole. They also recorded the presence of rabbits (i.e., desert cottontails and black-tailed jackrabbits), ground squirrels, pocket gophers, and California voles according to whether no evidence of each was found, or habitat was present, burrows or animals were seen, or evidence of each was abundant.

At each pole, the primary and secondary vegetation cover types near the pole were classified as annual field crops, rice, fallow, pasture, alfalfa, vineyard, orchard, grassland, wetland, riparian, woodland, chaparral, scrub, residential, commercial or industrial. The number of stand heights of vegetation within 150 m of the pole was recorded as 1, 2, or 3, so rice alone would be recorded as 1 whereas the occurrence of rice, a riparian forest and a peach orchard would be recorded as 3. Primary and secondary land uses around the pole were classified as cropland, rangeland, game refuge, natural reserve, public use or restricted government land. Also, the number of tall perch options within 200 m – not including other electric distribution poles – was recorded, where the number of other tall perches was recorded as 0, 1 to 4, 5 to 9, or 10 or more.

Poles were characterized according to their framing, starting with any crossarms or equipment at the top of the pole and working down to the lowest crossarm or equipment on the pole. Only a few poles supported more than 5 framing elements. Figures 4-1 through 4-3 depict some of the poles and types of framing and equipment that were recorded into the searcher's GPS data dictionaries for later hypothesis-testing. Each frame was sketched and assigned a number code. Sketches were kept in folders organized by general types, and frames encountered again were assigned the same code in the GPS data dictionary. All newly encountered frames were sketched, coded and both added to the folders.

Biologists recorded each pole's aspect of the distribution line, whether it was midline, on a corner, forming an angle, and any related characterizations identifying the type and hardware supports present. Midline poles typically support phase conductors or switches. Various other devices provide support for equipment-bearing poles, such as bracing against winds, or for poles with long distances between them. Midline relays typically support transformers that step down power to a home or business, and pump relays are typically at the ends of taps feeding irrigation pumps in agricultural fields. Some poles can be characterized as more than one of these types, but each was attributed a type characterization based on the most prominent and prevailing circumstances where the pole was installed.

The orientation of the upper crossarm relative to the prevailing wind direction was recorded in degrees of angle, where 90˚ indicated the crossarm was oriented perpendicular to the prevailing wind direction. The biologists recorded whether a lower crossarm was oriented perpendicular to the upper crossarm. The number of safe perch sites on the pole was recorded as none, 1, 2, more than 2, and whether a safe alternative perch site on the same pole was provided.

The pole's array of phase conductors was classified as horizontal, triangular or vertical. The phase aspect was classified as tangent (upward oriented), lateral (extended from pole in direction of the line), dead-end, suspended, vertical or mixed. The number of phase conductors on the pole was recorded, as was the number of distances between phase conductors that were <0.5 m, <1 m, and <1.53 m. The number of distances between hardware elements that were < 0.5 m, <1 m, and <1.53 m were also recorded, where the term 'hardware' meant the same thing as 'equipment' other than phase conductors.

Each status of jumpers was classified as to whether it had jumper wires or not, insulated jumpers versus uninsulated jumpers and how many of each, had gaps in insulation, were located under the carriage (crossarm), or whether the investigator was uncertain about the jumper being insulated. The biologists recorded whether the electric elements at each frame level were insulated or covered, and whether lightning arrestors were floated. The crossarm material was also recorded, whether it was wood, metal or ceramic, and the biologists recorded whether the crossarm brace was wood or metal. Guy wires were recorded as close to electric elements and not insulated or distant or insulated.

Perch guards on poles were classified as not present, 1 delta-type perch guard, 2 or more delta-types, spike strips, flight diverters, other types, or a combination of perch guards. Poles were classified according to whether they included mitigation against mid-span collisions, including whether they supported kingpin extenders, line spacers or flight diverters.

Poles were classified according to any extra equipment they carried, such as transmission lines, secondary lines, telephone lines, telecommunication equipment, street lights, and combinations of extra equipment or some other type. Poles were noted for nests or old nest material. Finally, the height of the pole was compared to the heights of neighboring poles, and classified according to whether it was the same height, <1 m taller, >1 m taller or >3 m taller.

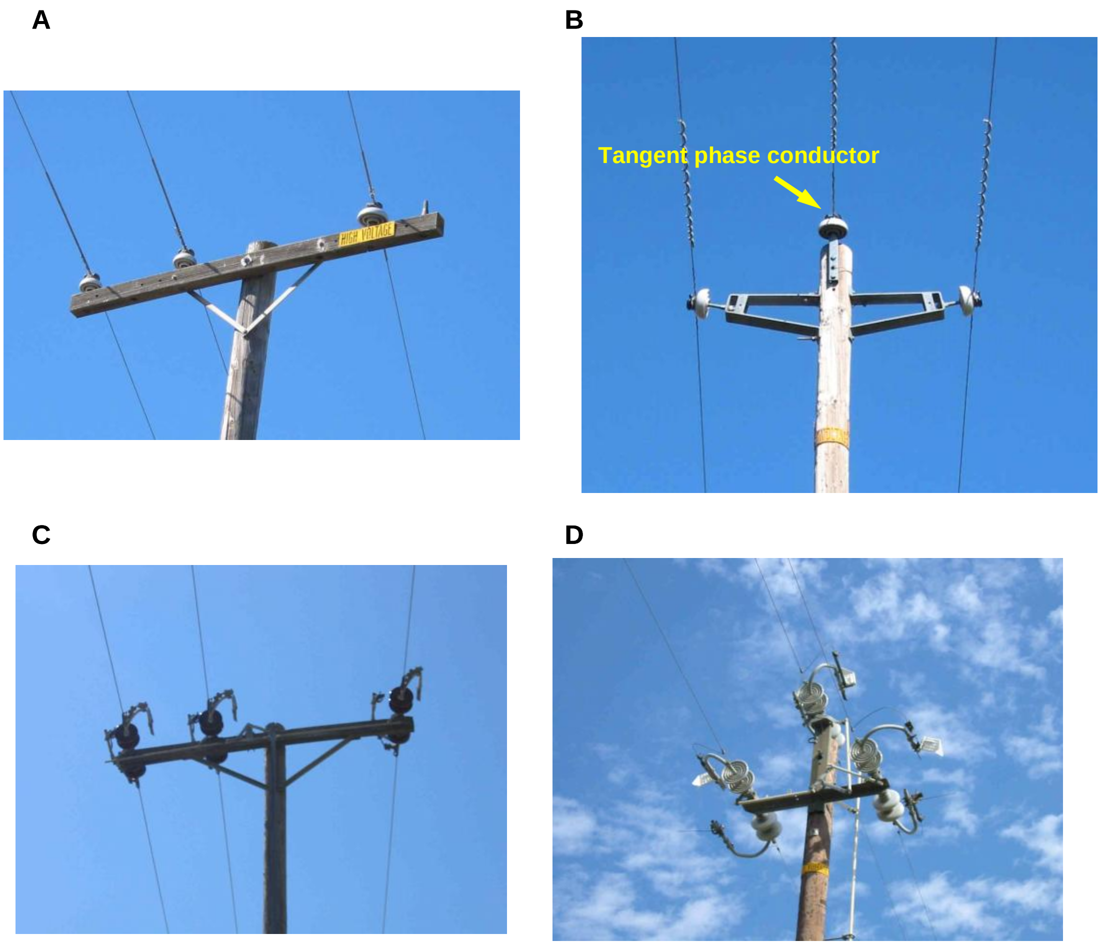


Figure 4-1. Photo A depicts a midline pole with tangent phase conductors in a horizontal array. Photo B shows a midline pole with triangular phase array on short, metal crossarms. Photos C shows switches mounted above a wood crossarm at top of pole, and D shows manual switches in a triangular array, with lower two mounted on metal arm (D).

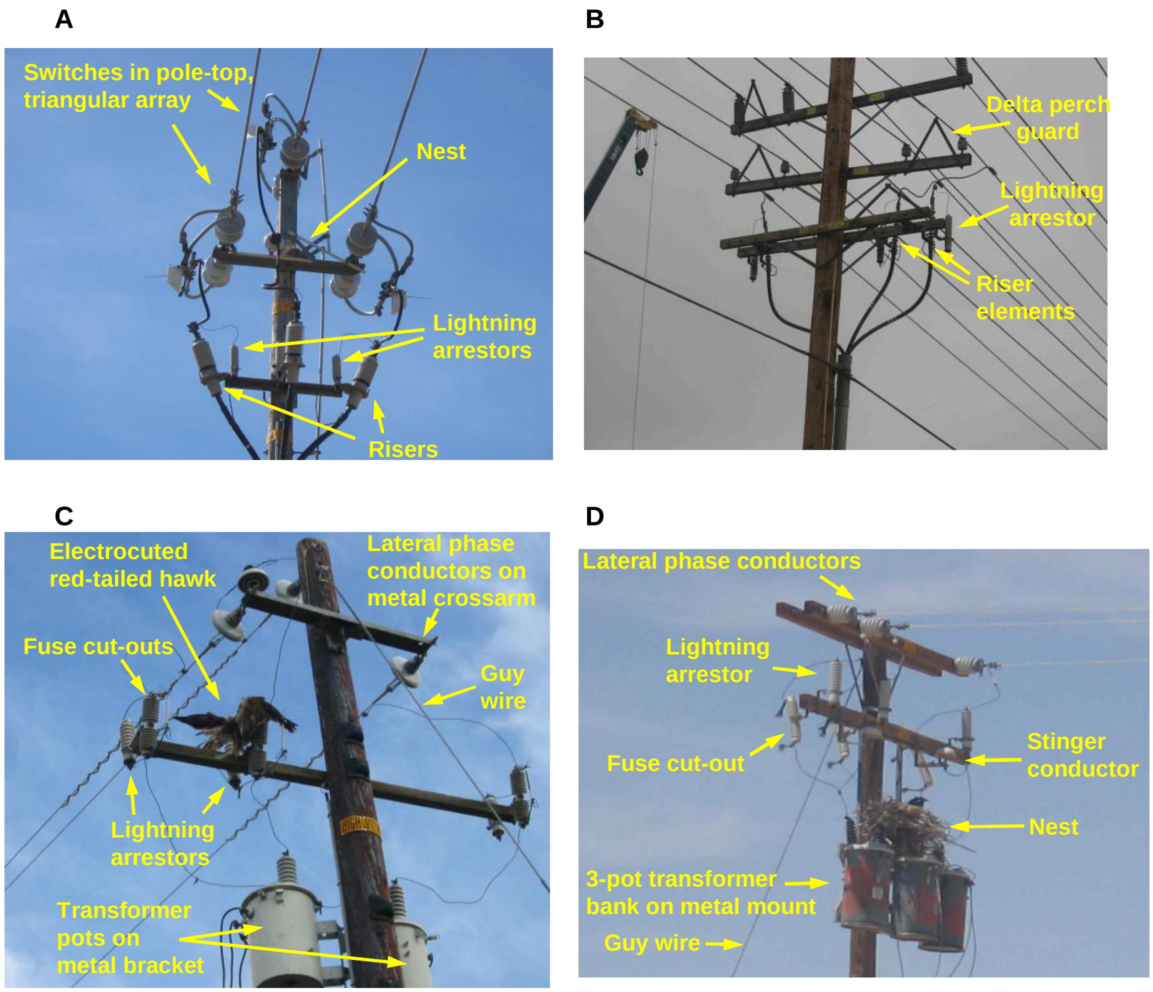
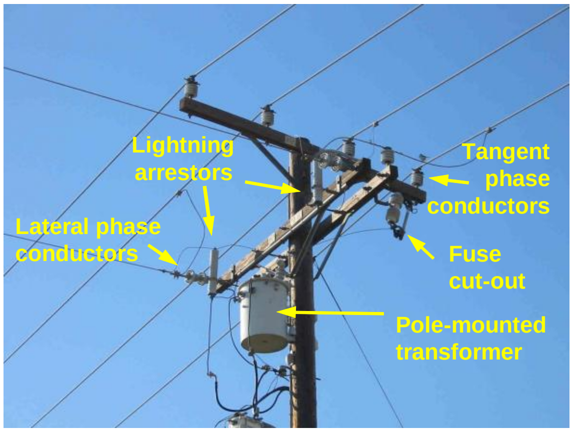


Figure 4-2. Photo A depicts a dead-end pole with lateral phase conductors feeding into a triangular switch array, as well as riser elements composing the second framing element. Photo B depicts riser elements on the lowest frame and perch guards above the risers. Photo C depicts a relay pole with lateral phase conductors on frame 1, fused cut-outs and lightning arrestors on frame 2, and a 2-pot transformer bank mounted on a metal bracket composing frame 3. Photo D shows a relay pole servicing an irrigation pump and supporting a nest on the transformer bank.

A



B

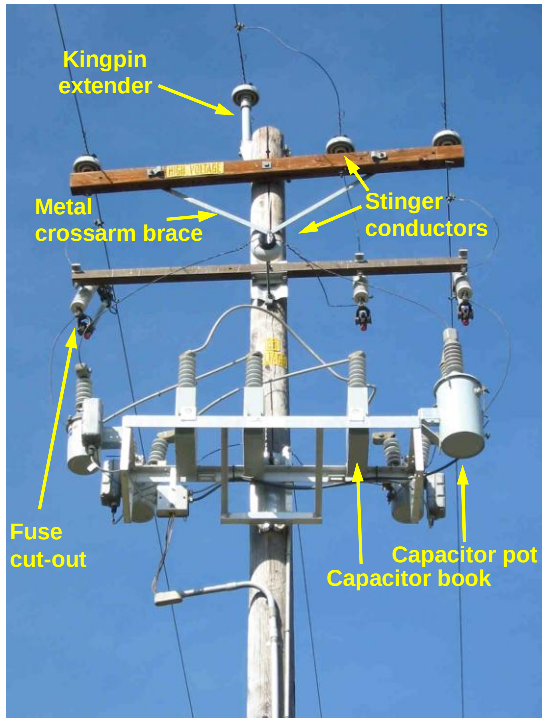


Figure 4-3. Photo A shows a midline relay and line and buck, where power is stepped down by transformer and a line sent off in another direction from the main line. Photo B depicts three frame elements: Frame 1 (top) consists of a wood crossarm supporting three tangent phase conductors and a stinger conductor (1 phase conductor is on a kingpin); Frame 2 supports fused cut-outs and a stinger conductor; and, Frame 3 supports a capacitor bank.

4.4. Estimating Bird Mortality

Unadjusted mortality (Mu; $0 \leq M_U \leq 100$) was the number of fatalities per 100 poles per year for fatality searches completed in Phase 2 from late 2005 to early 2007. Four searches were made at each pole during this time period, and the period of monitoring represented a 12-month period. The average time periods intervening searches were longer than 90 days during that period. Also, because the first search yielded carcasses, we concluded that 90 days was a reasonable period when carcasses may have initially become findable prior to the first search.

For older remains, it is likely our estimates of time since deaths are inaccurate. Including them would tend to increase the mortality estimates and the extent of this bias cannot be determined. Therefore, we elected to conservatively analyze the results by including only those carcasses that were regarded by the field crew to have been electrocuted less than 90 days before discovery.

We computed unbiased estimates of mortality, expressed as a percentage, ($0 \leq M_A \leq 100$) by adjusting the number of fatalities per 100 poles using two sources of error, 1) probability of detecting carcasses, and 2) proportion of carcasses remaining after scavenger removals. We computed our unbiased estimatator of mortality M_A as:

$$M_A = \frac{M_U}{p \times R}, \qquad \text{(Eq. 1)}$$

where M_U is the biased mortality expressed as number of fatalities per 100 poles, $p \leq 1$ is a measure of searcher efficiency, defined as the probability of detecting a bird carcass that was available for detection, $R \leq 1$ is the proportion of carcasses remaining after scavenger removal since the previous fatality search. The standard error ($SE[M_A]$) was calculated using the delta method (Goodman 1960):

$$SE[M_A] = \sqrt{\left(\frac{1}{p \times R} \times SE[M_U]\right)^2} \times \left(\frac{M_U}{p} \times \frac{-1}{R^2} \times SE[R]\right)^2 \times \left(\frac{M_U}{R} \times \frac{-1}{p^2} \times SE[p]\right)^2. \qquad \text{(Eq. 2)}$$

The searcher efficiency and the scavenger removal terms are normally estimated from field trials of searcher detection and scavenger removal, respectively, but this study did not implement such trials for cost reasons. In place of trials, this study made use of average search detection rates from reports of trials performed across the US, and estimated detection rate values from empirical models of scavenger removal trials (Smallwood 2007).

Based on searcher detection trials conducted in grasslands across the United States (Smallwood 2007), the search detection rates chosen as fairly representative for this study used the following average detection rates:

Species Group	Mean +/- SE (%)
Small non-raptor birds	51 +/- 2.1
Medium and large non-raptors (incl. rock doves)	78 +/- 5.4
Small Raptors	75 +/- 9.1
Large Raptors	100 +/- 0

Equation 1 requires that p be expressed as a probability, so we divide the estimates above by 100 to obtain p for use in Equation 1.

To estimate R, we first predict the percentage of carcasses remaining after each successive day following a fatality search, Ri. We adopt the following logarithmic model developed from least squares regression of published scavenger removal rates (Smallwood 2007) :

$$Ri = a + b\ln(i + 1) \qquad \text{(Eq. 3)}$$

Where $R_i \leq 100$ is the percent of carcasses remaining on the *i* th day into the scavenger removal trial, and a and b are fitted parameters derived from fitting the logarithmic model to data gathered from reports of scavenger removal trials performed 1989-2006 throughout the United States. That study considered small-bodied non-raptor birds (SE = 0.158), medium and large-bodied non-raptor birds (SE = 0.129), small-bodied raptors (SE = 0.040), and large-bodied raptors (SE = 0.089) (Smallwood 2007: Table 4). Typical parameter estimates from that study are a=100 and b=-30. Equation 1 requires that R be expressed as a proportion, so we must divide Ri by 100. Further, we must account for fatalities that occurred any time between fatality searches. For example, suppose the interval between searches is 90 days. Fatalities that occurred on day 1 are less likely to still be present (on day 90) than are fatalities that occurred on day 89 (this result is a consequence of the negative sign on the parameter b in Equation 3). To account for this difference, we assume that fatalities are evenly distributed throughout inter-search period (in this example, 90 days), and then we simply need to sum up over all intervening periods.

The cumulative proportion of carcasses remaining is just:

$$Rc = \frac{\sum_{i=1}^{I} Ri/100}{I} \qquad \text{(Eq. 4)}$$[3]

where I is the search interval (average number of days between fatality searches). As indicated earlier, however, the time periods between fatality searches tended to be longer than 90 days. The empirical models of scavenger removal rate developed by Smallwood (2007) predicted the number of carcasses remaining out to 90 days since deposition, because 90 days was the longest time period used during any scavenger removal trials (Smallwood did not want to extend the model predictions beyond the range of data used to develop the models). Therefore, the mortality estimates herein relied on the model predictions of accumulated carcasses remaining at 90 days since the previous search. This approach left gaps in time between the previous search date and the date corresponding with 90 days prior to the next search, but in most cases these gaps were only about 10 to 30 days. We do not believe this caused significant shifts in the estimates of mortality because we limited the analyses to include only birds believed to be electrocuted within 90 days of discovery.

No adjustment was made for birds discovered that died of other 'natural causes', which might be substantial along electric distribution lines because the poles offer perch sites for birds and

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[3] Equation 4 is presented here as it originally appeared in Smallwood (2007). An error in the equation required the author to publish an erratum. For more details refer to Smallwood, K.S. 2008. Erratum. Journal of Wildlife Management. 72:853.

the poles tend to occur along road verges where wildlife often travel and congregate, and where autos kill many animals. Undoubtedly, some of the fatalities attributed to electrocution based on location, i.e., distance from the pole, were actually killed by such things as autos, West Nile Virus, predation, or firearms activity.

In addition, our mortality estimates do not account for crippling bias or search radius bias. Crippling bias refers to the number of birds mortally injured by the electrocution but that die undetected somewhere else outside the search area. Search radius bias refers to number of birds killed by electric distribution poles but whose carcasses end up beyond the search radius and are not found.

Another potential bias was how well the search radius could be searched. Many poles were located next to irrigation canals that when full cannot be searched. Many poles also occur along road verges or in field crops, where tilling is routine. Tillage would have turned bird carcasses under the soil. These types of activities and situations were atypical of the grassland settings where search detection trials were performed for estimating search detection error (Smallwood 2007). These were activities and situations that predisposed search detection failures because the deposited carcasses were essentially unavailable to be detected. This type of error was handled by first omitting all searches and discovered fatalities from poles given an average search rating of 0 to 0.75, and having the lowest range of the search rating applied to each search area during each search. Mortality estimates were then computed for groups of poles associated with the three ranges of average search rating.

4.5. Identifying Critical Pole Attributes and Selecting a Predictive Model

One of the fundamental questions posed by this research is, "What attributes of a pole or its locale will significantly influence whether that pole is likely to cause a raptor electrocution?" One approach for answering this question would be to proceed with an exhaustive set of univariate tests that are capable of detecting a correlation between any given feature (e.g. whether the pole has lightning arrestors) and electrocutions. This approach is insufficient, and likely misleading, because univariate approaches ignore possible joint effects, often ignore mitigating impacts, and fail to control for spurious correlation, a phenomenon whereby the impact of one factor may be mistakenly attributed to a different factor which, for whatever reason, is correlated with the former.

Instead, using theoretical guidance and the published literature on raptor electrocutions, we generated a set of working hypotheses about the combination of factors that influences the probability that a given pole poses a risk of electrocution. Each of these working hypotheses gives rise to a unique logistic regression model. These models and their origin and justification are described below. The union of all variables represented in at least one of these models is presented in the following table.

Table 4-1. Summary list of the variables used for development of the various models tested.

Variable No.	Variable Name	Description
1	Mortality	Raptor Mortality occurred 2003-2007 (1/0)
2	hard0.5	Number of distances < .5m between hardware elements
3	hard1sum	Number of distances <1m between hardware elements
4	hard1.5s	Number of distances <1.53 m between hardware elements
5	stransfo	Number of transformer pots on pole
6	sfusecut	Number of fuse cut-outs on pole
7	slightar	Number of lightning arrestors/risers on pole
8	sswitch	Number of switches on pole
9	sjumper	Number of jumpers on pole
10	Guy_insul	Guy wires "distant or insulated"
11	Guy_uninsul	Guy wires "close & insulated"
12	Phase_tangent	Phase conductor aspect is "tangent (upward)"
13	Metal_armbrace	Whether the pole has a metal armbrace (1/0)
14	Metal_arm	Whether pole has a metal crossarm (1/0)
15	armorien	Orientation (degrees) relative to direction of prevailing wind
16	effheigh	Effective height of pole relative to adjacent poles (in meters 'taller')
17	Aspect_dead	Pole's aspect is "deadend"
18	Aspect_corner	Pole's aspect is "corner"
19	arms	Number of cross-arms on pole
20	pellets	Number of raptor pellets counted among all searches at pole
21	vegstruc	Number of vegetation canopy heights within 200 m of pole
22	rabbit_1	Number of times rabbit sign was recorded near pole
23	gs_1	Number of times ground squirrel sign was recorded near pole
24	pg_1	Number of times pocket gopher sign was recorded near pole
25	prey_1	Total number of times prey sign was recorded near pole
26	Veg_gr_wet	Primary vegetation is "grassland" or "wetland"
27	use_govt	Primary land use "restricted govt land"
28	use_rangeland	Primary land use "rangeland"
29	use_public	Primary land use "public use"
30	use_reserve	Primary land use "natural reserve area"
31	use_game	Primary land use "game"
32	use_cropland	Primary land use "cropland"
33	Perchopt	Number of tall perch options near pole (other than other poles)

Following Burnham and Anderson (2002; 2004), employing an information theoretic criterion for model selection requires that a set of working hypotheses is generated *a priori*, and that each hypothesis is represented by a separate model. The generation of models is where a balance between scientific judgment and theory enter the process. The authors defined a total of 22 models, each using the binary Mortality variable as the dependent variable, and a unique subset of the remaining variables listed in Table 4-1.

These 22 models and their variables are listed below (Table 4-2). For example, Model 4 uses Variable 1 ("Mortality") as the dependent variable, and Variables 5 and 33 ("stransfo" and

"Perchopt") as independent variables. The justification for each model is also provided in Table 4-2.

Table 4-2. Summary of 22 models tested with 'mortality' as the dependent variable and their corresponding unique subset of remaining variables.

Model	Dependent Variable	Independent Variable	Justification
1	1	15,16, 21	Ansell and Smith (1980)
2	1	2, 3, 4, 8, 9, 10, 11, 13, 14, 18	APLIC (1996)
3	1	5, 15, 16, 18, 22, 29	Benson (1982)
4	1	5, 33	Bevanger (1994)
5	1	16, 33	Boeker and Nickerson (1975)
6	1	5, 6, 7, 9	Dwyer (2004)
7	1	16	Marion and Ryder (1974)
8	1	20, 23, 26	None
9	1	17, 18, 19, 26	O'Neil (1988)
10	1	5, 12, 17	None
11	1	5, 17, 19	Based on SCE RIMS data
12	1	21	Pearson (1979) c.f. in APLIC 1996
13	1	24	Smallwood (1995)
14	1	19, 24, 29	Smallwood et al (1996)
15	1	2-12	Hardware
16	1	13-19	Pole Attractiveness
17	1	20-24, 26, 29, 33	Landscape, abridged use
18	1	2-19, 20-24, 26, 29, 33	All, abridged use
19	1	3, 5-11, 12-19, 20, 21, 25, 26, 29, 33	All, abridged use/prey/hardware
20	1	3, 5-11, 12-19, 20, 21, 25, 26, 33	All, abridged hardware/prey, no use
21	1	3, 5-11, 12, 20, 21, 25	All, no attractiveness, abridged hardware/prey
22	1	3, 5-11, 12, 20, 21, 25, 26, 33	All, vegwetland, abridged hardware/prey, no use

Source: As cited in Table

Models 1-14 are direct interpretations of the variables suggested as being important in the published literature (one model implied by each cited source). Models 15-21 are extended models that use various combinations of variables in the three main categories of interest (e.g., pole attractiveness, pole hardware, site attractiveness). For example, Model 15 contains Variables 2-12, which are all of the variables that may influence a pole's electrocution potential, quite aside from its attractiveness. Inasmuch, Model 15 can be thought of as a "Hardware Only" model.

With these 22 models defined, the procedure is to estimate each model (see Section 5.4, below), compare the information criteria, and ultimately select a single model for more comprehensive analysis and interpretation. While additional extensions to "multi-model inference" are possible, they are beyond the scope of this report.

The process of selecting a preferred model began by ensuring that the study's dataset was complete and comparable across models. This entailed dropping observations with missing entries, leaving a total of 6,286 poles in the statistical analysis. Of the 6,286 poles, 119 recorded one or more mortalities. Importantly, it is not just the 119 electrocutions that provide information, the non-mortalities are equally important in estimation. The authors followed Burnham and Anderson (2004) to ensure that the requirements were met for theoretically defensible comparison of AIC among models.

For each of the 22 models, the authors estimated the respective logistic regression model and saved the maximized log likelihood value lnL(i), the number of observations n(i), and the number of estimable parameters, K(i). They followed Burnham and Anderson to calculate the AIC, corrected for small sample, giving an AICc(i) of:

$$AICc(i) = -2\log L(i) + 2K(i) + 2K(i)(K(i)+1)/(n(i)-K(i)-1),$$

which is almost identical to AIC(i) because n(i)/K(i) is large (thus the latter term approaches zero). The absolute values of AICc(i) do not provide much information for model selection (Burnham and Anderson, 2004). Instead, it is the difference between a given model's AICc(i) and the smallest AICc(i) among all tested models (see following equation). The authors were, therefore, primarily interested in this difference:

$$\Delta(i) = AICc(i) - \min_j\{AICc(j)\}$$

For this study, Model 19 has minimum AICc, so $\Delta(20)=0$ and $\Delta(i)=AICc(i)-AICc(20)$. Table 4-3 lists the 22 models and their D(i) in increasing order.

Table 4-3. A list of the 22 models examined and their D(i) values in increasing order.

Model	Δ(i)
19	0.0
18	3.2
22	3.3
20	3.5
21	13.9
17	22.3
5	50.1
1	51.1
4	51.3
12	58.1
14	58.7
13	59.2
3	69.9
15	72.6
6	73.5
17	77.1
9	78.3
8	82.0
2	83.1
10	85.8
7	87.1
11	87.4

The larger is Δ(i), the less plausible the model is at being the best approximating model of the given set. Burnham and Anderson (2004) cite the convention that values of Δ(i) <3 have substantial support, those 4< Δ(i) <7 have considerably less support, and those Δ(i) >10 have essentially no support. In addition to Model 19, Models 18, 22, and 20 have some support, and the remaining models have essentially no support relative to the superior Model 19. Based on this analysis, the authors decided to adopt Model 19 as the model within the study's *a priori* set that is the best approximation. In what follows, we thoroughly examine the results of Model 19 and use those results to derive a "risk calculator" for application in the field.

5.0 Results

5.1. Carcass Searches and Fatalities

Fatality searches conducted during 2003-07 produced 1,079 bird carcasses (Table 5-1). Of these, the authors concluded that 60 were certainly killed by electrocution. They similarly concluded that an additional 227 were highly-likely to have been killed by electrocution. They also concluded that the rest (n = 792) were killed by events unrelated to electrocutions.

Table 5-1. The frequency of bird carcasses found during fatality searches completed in 2003-07. Size categories are: S-NR = small non-raptor; M-NR = medium non-raptor; L-NR = large non-raptor; S-R = small raptor; M-R = medium raptor; L-R = large raptor.

Species/Group	Size Category	All Carcasses	Electrocution-caused Fatalities	
			Highly Likely	Certain
Common loon	L-NR	1	0	0
American white pelican	L-NR	15	0	0
American bittern	L-NR	6	0	1
Least bittern	L-NR	1	1	0
Great blue heron	L-NR	79	16	1
Great egret	L-NR	24	0	1
Snowy egret	L-NR	7	2	0
Cattle egret	L-NR	1	0	0
Green heron	L-NR	3	0	0
Black-crowned night heron	L-NR	22	3	0
White-faced ibis	L-NR	3	0	0
Tundra swan	L-NR	2	0	0
Greater white-fronted goose	L-NR	1	0	0
Snow goose	L-NR	5	0	0
Canada goose	L-NR	1	0	0
Mallard	L-NR	18	2	0
Cinnamon teal	L-NR	1	0	0
Northern shoveler	L-NR	4	0	0
American widgeon	L-NR	1	0	0
large raptor	L-R	1	1	0
Turkey vulture	L-R	18	6	1
Cooper's hawk	M-R	5	1	2
Red-tailed hawk or Swainson's hawk	L-R	2	2	0
Red-shouldered hawk	L-R	2	0	1
Swainson's hawk	L-R	19	15	2
Red-tailed hawk	L-R	98	53	31
Ferruginous hawk	L-R	1	0	1
California gull	L-NR	1	0	0
Golden eagle	L-R	2	2	0
American kestrel	S-R	12	4	0

Species/Group	Size Category	All Carcasses	Electrocution-caused Fatalities	
			Highly Likely	Certain
Prairie falcon	M-R	1	1	0
Ring-necked pheasant	L-NR	90	12	2
Wild turkey	L-NR	2	0	0
Virginia rail	M-NR	2	0	0
Sora	M-NR	2	1	0
Common moorhen	M-NR	30	1	0
American coot	M-NR	119	3	0
Sandhill crane	L-NR	4	0	0
Killdeer	S-NR	9	1	0
Black-necked stilt	M-NR	1	0	0
American avocet	M-NR	1	0	0
Greater yellowlegs	N-NR	1	1	0
Rock pigeon	M-NR	9	0	0
Mourning dove	M-NR	7	0	0
Barn owl	L-R	104	25	3
Common peafowl	L-NR	3	2	1
Great horned owl	L-R	18	9	1
Burrowing owl	S-R	6	2	0
Short-eared owl	M-R	3	1	1
Acorn woodpecker	S-NR	1	0	0
Northern flicker	S-NR	2	0	0
Cliff swallow	S-NR	3	0	0
Scrub jay	S-NR	3	0	0
Yellow-billed magpie	S-NR	6	3	1
American crow	L-NR	30	17	4
Common raven	L-NR	11	6	1
Western bluebird	S-NR	1	0	0
Swainson's thrush	S-NR	1	0	0
American robin	S-NR	2	0	0
Northern mockingbird	S-NR	3	0	0
Loggerhead shrike	S-NR	2	0	0
European starling	S-NR	11	1	0
Orange-crowned warbler	S-NR	1	0	0
Black-throated gray warbler	S-NR	1	0	0
Rufous-crowned sparrow	S-NR	2	0	0
Savanna sparrow	S-NR	1	0	0
Grasshopper sparrow	S-NR	1	0	0
Song sparrow	S-NR	1	0	0
Golden-crowned sparrow	S-NR	1	0	0
Red-winged blackbird	S-NR	4	0	0
Tricolored blackbird	S-NR	2	0	0

Species/Group	Size Category	All Carcasses	Electrocution-caused Fatalities	
			Highly Likely	Certain
Western meadowlark	S-NR	27	1	0
Brewer's blackbird	S-NR	12	3	0
Brown-headed cowbird	S-NR	1	0	0
House finch	S-NR	1	0	0
House sparrow	S-NR	5	0	0
Emu	L-NR	1	0	0
Chicken	L-NR	1	0	0
Budgerigar	S-NR	1	0	0
Unknown	-	12	8	3
Small bird (songbird)	S-NR	33	7	1
Small nonraptor	S-NR	3	1	0
Medium bird	-	38	7	1
Medium nonraptor	M-NR	11	4	0
Large bird	-	13	0	0
Large non-raptor	L-NR	2	0	0
Large wading bird	L-NR	1	0	0
Heron	L-NR	1	1	0
Egret	L-NR	4	0	0
Duck	L-NR	47	1	0
Gull	L-NR	1	0	0
Sparrow	S-NR	1	0	0
Blackbird	S-NR	5	0	0
Totals		**1,079**	**227**	**60**

The number of fatalities found at poles associated significantly with the average search rating applied to the search area surrounding the pole (Table 5-2). Fatalities were found in increasingly disproportionate numbers as the search rating increased. Search ratings were lower where road verges were disked regularly for weed control, where canals composed much of the area within the 15-m search radius, or where flooding around the pole was common. There was no reason to believe search ratings would have interacted significantly with measured pole attributes, but search ratings may have interacted with land use, vegetation cover in the area, and related variables.

The main effect of the search ratings is on mortality estimates, as fewer carcasses deposited by poles would have been found where search ratings were low. Additionally, it is possible that more carcasses may have been available for detection where search ratings were high because those carcasses were afforded cover by tall vegetation that may have reduced their exposure to scavengers (regardless of the detection probabilities being lower). Thus, availability for detection and search rationings may be confounded.

Table 5-2. Results of chi-square test for association between fatalities of all bird species highly likely plus certainly killed by electrocution (n = 287) and average search rating at the poles. Search rating values correspond to the following: 0 = Carcass detection unlikely; 1 = Carcass likely detectable on <10%; 2 = Carcass likely detectable on 10-20%; 3 = carcass likely detectable on 21-30%; 4 = Carcass likely detectable on 31-40%; 5 = Carcass likely detectable on 41-100%.

Mean Search Rating in 15-m area	Searches	Observed	Expected	Obs ÷ Exp	χ^2
0.00 - 0.75	429	1	3.93	0.25	
0.76 -1.50	13765	74	126.23	0.59	
1.51 -2.50	13872	159	127.21	1.25	
2.51 -3.50	2088	41	19.15	2.14	
3.51 - 5.00	161	3	1.48	2.03	58.25**

** = P < 0.005

5.2. Estimates of Bird Mortality at Selected Electric Distribution Poles in the Central Valley of California

Estimates of electrocution mortality at electric distribution poles throughout California have yet to be made. Even in relatively small survey areas, mortality estimates require repeat searches at large numbers of poles over a defined time period, which was the objective of the searches performed during Phase 2 (2005-2007). These estimates also require adjustments for known sources of error, such as searcher detection error and scavenger removal of carcasses between searches. The results of repeat searches are presented in terms of mortality estimates, and adjustments are made for the established, quantified sources of error.

Based on a conservative application of the data (i.e., consisting of fatalities estimated to have been killed within 90 days of discovery) annual mortality among the poles searched was estimated as 0.06 birds per pole, of which 0.01 were raptors.

The most dangerous poles that were searched in Phase 2 – those supporting lightning arrestors or riser elements – electrocuted 2.3 birds per pole of which 0.3 were raptors.

Electrocution-caused mortality generally increased with average search rating (Tables 5-3 and 5-4). Table 5-3 shows the adjustments made to the estimates for searcher detection error and scavenger removal rates, and the degrees to which these adjustments increased mortality estimates for each group of bird species. Table 5-4 summarizes the adjusted mortality estimates for all birds, all raptors, and all large-bodied non-raptor species.

Due to small sample size of poles averaging a search rating in the range of 2.5 to 5.0, and because mortality did not always increase between groups of poles averaging a search rating in the range of 1.51 to 2.5 and in the range of 2.5-5.0, the remainder of the mortality estimates were based only on poles averaging search ratings of 1.5 to 5.0. Additionally, the previously used top two categories of search ratings were aggregated. Thus, the rest of the mortality estimates in this report were based on fatalities found at 3,259 poles where the average search rating was middling to good.

Medium-sized non-raptors appeared to be electrocuted more often than any other group of birds (Table 5-5), followed in frequency by small-bodied non-raptor species, and then large-bodied non-raptors.

Among individual species examined, mortality was highest for American crow, followed by red-tailed hawks, great-blue herons, ring-necked pheasants, Swainson's hawks, great horned owls, turkey vultures, and barn owls (Table 5-6).

Poles supporting lightening arrestors or riser elements electrocuted birds at much higher rates than did poles without these hardware elements (Table 5-7).

Table 5-3. Unadjusted and adjusted mortality estimates for six groups of bird species electrocuted on non-randomly selected distribution poles in California's Central Valley during 2005-2007. These estimates are based on fatalities concluded to have died within 90 days of discovery and regarded to have been highly-likely or certainly electrocuted.

Search Rating	Unadjusted Mortality (Events/100 poles)		Adjustment Factors		Adjusted Mortality (Events/100 poles)	
	$\bar{x}$	SE	R	p	$\bar{x}$	SE
Small-bodied non-raptors						
0.76 - 1.50	0.107	0.062	0.12	0.51	1.755	2.526
1.51 - 2.50	0.036	0.036	0.12	0.51	0.586	0.970
2.51 - 5.00	0.212	0.212	0.12	0.51	3.469	5.740
0.76 - 5.00	0.083	0.037	0.12	0.51	1.350	1.879
Medium-sized non-raptors						
0.76 - 1.50	0.072	0.051	0.12	0.78	0.765	0.987
1.51 - 2.50	0.359	0.124	0.12	0.78	3.832	4.345
2.51 - 5.00	0.000	0.000	0.12	0.78	0.000	0.000
0.76 - 5.00	0.198	0.062	0.12	0.78	2.118	2.381
Large-bodied non-raptors						
0.76 - 1.50	0.143	0.072	0.40	0.80	0.448	0.267
1.51 - 2.50	0.323	0.107	0.40	0.80	1.009	0.469
2.51 - 5.00	0.000	0.000	0.40	0.80	0.000	0.000
0.76 - 5.00	0.215	0.060	0.40	0.80	0.671	0.286
Small-bodied raptors						

Search Rating	Unadjusted Mortality (Events/100 poles)		Adjustment Factors		Adjusted Mortality (Events/100 poles)	
0.76 - 1.50	0.036	0.036	0.11	0.75	0.434	0.465
1.51 - 2.50	0.000	0.000	0.11	0.75	0.000	0.000
2.51 - 5.00	0.000	0.000	0.11	0.75	0.000	0.000
0.76 - 5.00	0.017	0.017	0.11	0.75	0.200	0.215
Medium-sized raptors						
0.76 - 1.50	0.036	0.036	0.88	0.79	0.052	0.052
1.51 - 2.50	0.036	0.036	0.88	0.79	0.052	0.052
2.51 - 5.00	0.000	0.000	0.88	0.79	0.000	0.000
0.76 - 5.00	0.033	0.023	0.88	0.79	0.048	0.034
Large Raptors						
0.76 - 1.50	0.251	0.095	0.88	1.00	0.285	0.111
1.51 - 2.50	0.681	0.172	0.88	1.00	0.774	0.210
2.51 - 5.00	1.699	0.668	0.88	1.00	1.930	0.783
0.76 - 5.00	0.562	0.104	0.88	1.00	0.638	0.135

Table 5-4. Summary of adjusted mortality estimates for birds found at non-randomly selected distribution poles in California's Central Valley during 2005-07. These estimates are based on fatalities (n=287) concluded to have died within 90 days of discovery and to have been highly-likely or certainly electrocuted.

Search Rating	Adjusted Mortality Events/100 poles	Lower Bound of 95% CI Events/100 poles	Upper Bound of 95% CI Events/100 poles
Birds killed ≤90 days			
0.76 - 1.50	3.739	-4.901	12.379
1.51 - 2.50	6.253	-5.596	18.102
2.51 - 5.00	5.399	-7.388	18.186
0.76 - 5.00	5.025	-4.640	14.690
Raptors killed ≤90 days			
0.76 - 1.50	0.771	-0.461	2.003
1.51 - 2.50	0.826	0.312	1.340
2.51 - 5.00	1.930	0.393	3.467
0.76 - 5.00	0.886	0.132	1.640

Search Rating	Adjusted Mortality Events/100 poles	Lower Bound of 95% CI Events/100 poles	Upper Bound of 95% CI Events/100 poles
Large non-raptors killed ≤90 days			
0.76 -1.50	0.448	-0.073	0.969
1.51 - 2.50	1.009	0.090	1.928
2.51 - 5.00	0.000	0.000	0.000
0.76 - 5.00	0.671	0.110	1.232

Table 5-5. Summary of adjusted mortality estimates of eight groupings of birds found at non-randomly selected distribution poles in California's Central Valley during 2005-07. These estimates are based on a subset of fatalities concluded to have been highly-likely or certainly electrocuted within 90 days of discovery and discovered among the 3,259 poles that averaged search ratings of 1.51 through 5.00.

Species Groups	Adjusted Mortality, Events/100 poles	Lower bound of 95% CI Events/100 poles	Upper bound of 95% CI Events/100 poles
Small-sized non-raptors	1.003	-1.937	3.943
Medium non-raptors	3.278	-4.009	10.565
Large non-raptors	0.863	0.077	1.649
Small raptors	0.000	0.000	0.000
Medium raptors	0.044	-0.043	0.131
Large raptors	0.941	0.507	1.375
All raptors	0.986	0.466	1.506
All birds	6.130	-5.402	17.662

Table 5-6. Summary of adjusted mortality estimates of particular bird species found at non-randomly selected distribution poles in California's Central Valley during 2005-07. These estimates are based on a subset of fatalities concluded to have been highly-likely or certainly electrocuted within 90 days of discovery and discovered among the 3,259 poles that averaged search ratings of 1.51 through 5.00.

Species	Adjusted Mortality, Events/100 poles	Lower Bound of 95% CI Events/100 poles	Upper Bound of 95% CI Events/100 poles
Great blue heron	0.384	-0.064	0.832
Turkey vulture	0.070	-0.028	0.168
Red-tailed hawk	0.593	0.260	0.926
Swainson's hawk	0.174	0.17	0.331
Barn owl	0.044	-0.043	0.131
Great horned owl	0.105	-0.014	0.224
Ring-necked pheasant	0.288	-0.085	0.661
American crow	2.623	-3.286	8.532

Table 5-7. Summary of adjusted mortality estimates of groups of birds found at selected distribution poles in California's Central Valley during 2005-07. These estimates are based on a subset of fatalities concluded to have been highly-likely or certainly electrocuted within 90 days of their discovery on 3,146 non-randomly selected electric distribution poles without lightning arrestors or riser elements (top rows) plus 113 poles supporting lightning arrestors or risers (bottom rows). These poles also averaged search ratings of 1.51 through 5.00.

Species Groups	Adjusted Mortality, Events/100 poles	Lower Bound of 95% CI Events/100 poles	Upper bound of 95% CI Events/100 poles
Poles without risers or lightning arrestors			
Small-sized non-raptors	0.519	-1.166	2.204
Medium non-raptors	1.358	-1.810	4.526
Large non-raptors	0.894	0.079	1.709
Small raptors	0.000	0.000	0.000
Medium raptors	0.000	0.000	0.000
Large raptors	0.867	0.456	1.278
All raptors	0.867	0.598	1.278
All birds	3.639	-2.438	9.716
Pole with risers or lightning arrestors			
Small-sized non-raptors	14.460	-32.435	61.355
Medium non-raptors	56.728	-73.945	187.401
Large non-raptors	0.000	0.000	0.000
Small raptors	0.000	0.000	0.000
Medium raptors	1.273	-1.239	3.785
Large raptors	3.017	-1.415	7.449
All raptors	4.290	-2.654	11.234
All birds	75.478	-109.034	259.990

The precision of this study's mortality estimates is generally low, with the lower bound of the 95% confidence interval sometimes less than zero. Probably the principal reason for low precision was insufficient search effort. The low precision may also be due to how the mortality estimates were computed. For example, the average number of days between searches was used to compute cumulative number of carcasses remaining, which was used to compute mortality estimates. This average contained error that could not be accounted for in the equation used to estimate mortality. Also, the equation of cumulative number of carcasses remaining relied on the average detection rates previously reported from other studies but their associated variances could not be incorporated into this study's estimations.

Another reason for the low precision was the large standard errors derived from the synthesis of reported estimates of search detection and scavenger removal rates (Smallwood 2007). The standard errors from searcher detection and scavenger removal trials have been large. Directed research towards these sources of error could reduce the standard errors considerably. Species-specific estimates of search detection and scavenger removal rates are needed, along with sufficient sample sizes of volitionally placed carcasses, and minimization of biases associated with scavenger swamping, reducing the attractiveness of carcasses to scavengers, and alerting searchers to the searcher detection trial (Smallwood 2007).

Despite the search effort in this study probably having been greater than any study of electrocutions yet conducted, it was still insufficient for generating estimates with high enough precision for the purpose of comparisons to detect treatment effects or trends through time. The standard error of the mean was large because the majority of the search results were 0-values, and some poles produced many birds, even up to 14 electrocution events per pole.

The influence of insufficient search effort on precision of the estimates could be reduced by searching poles more frequently, i.e., with shorter periods between searches, by searching the poles over longer periods of time, or by detecting more of the fatalities, or perhaps through the use of remote sensing technologies. Another way to reduce the influence of insufficient search effort would be to direct the searches to poles more likely to electrocute birds, such as to poles supporting risers and lightning arrestors, or poles in areas with few tall perches available nearby.

Conversely, the mortality estimates reported here possibly were inflated by inadvertent inclusion of fatalities caused by line collisions, predation, disease, auto collisions, and hunting/poaching. However, considerable effort was directed toward identifying fatalities likely caused by these other factors. The cause of death for most (73%) of the carcasses the searchers found was attributed to something other than electrocution. Even so, it is possible some fatalities considered to be electrocutions were caused by other factors; though it is also possible some of the 73% of the excluded fatalities were actually caused by electrocution on distribution poles.

The mortality estimates also did not account for crippling bias, which may be considerable. Another factor that tended to lead to conservative mortality estimates was this study’s lumping of poles and fatalities across average search ratings from 1.51 to 5.00. Even though it was already established that the number of fatalities found generally increased with average search rating, the mortality estimates were made from all poles with average search ratings of 1.51 to 5.00. This inclusion of low-rated poles undoubtedly reduced the mortality estimates from what would have been obtained using only the poles with the highest search ratings. However, the more conservative approach was taken because the data are admittedly preliminary in nature.

5.3. Correlations Between Environmental Factors, Hardware Configurations and Fatalities

Poles supporting lightning arrestors or riser elements electrocuted birds at much higher rates than did poles without these pieces of hardware (Table 5-7, above).

Dead-end poles and midline relays appear to be more dangerous to birds because these are the aspects of the distribution line where lightning arrestors and riser elements are more often installed. Midline relays often have transformers installed, also, which confounds being able to separate in effect of each element. Poles with switches and fused cut-outs also appeared to be considerably more dangerous than most other poles. Poles with transformers appear to be somewhat safer to birds, unless they also supported other equipment such as risers or lightning arrestors.

This study's results appear to support hypotheses that poles are more likely to electrocute birds when crossarms are parallel to the wind (Benson 1982), the pole is a dead-end pole (O'Neil 1988; Harness 1997), poles already have a history of electrocutions (APLIC 1996; APLIC 2006), poles are located in prey-bearing areas (Boeker and Nickerson 1975; Ansell and Smith 1980), non-cultivated areas (Benson 1982) and grassland (O'Neil 1988), and where alternative perches are scarce on the landscape (Boeker and Nickerson 1975; Bevanger 1994). These generalized correlations were identified using chi-square (univariate) tests of association; therefore, the causal relationships cannot be defined with certainty because of the possible interaction of numerous other factors.

5.4. Using Logistic Regression to Select a Priority Retrofit Model

Section 5.4 presents the results, interpretation, and resulting power pole scoring method that derive from Model 20 (refer to Section 4.5, Methods, for how Model 20 was selected).

5.4.1. Model Estimation

The logistic regression approach allows for identifying the effect of each individual characteristic while controlling for all others. Logistic regression also provides a natural method for ranking each pole by its propensity to electrocute birds. Logistic regression results in a probability between 0 and 1, where 0 suggests that there is no chance of electrocution over a fixed time interval and 1 suggests a 100% chance. A natural interpretation is that high ranked poles are those that should be retrofitted first, assuming a constant cost of retrofit. Even if costs are not constant, the results of the regression approach could serve as the foundation for prioritizing retrofit based on a cost benefit analysis.

5.4.2. Statistical Methods

The logistic regression model assumes that poles are randomly selected, that there is no error in the detection of a raptor electrocution, and that there is no measurement error in the calculation of independent variables. While none of these assumptions likely holds strictly, they all are likely to hold approximately, at least within the geographic region covered by the data and on average across the 6,286 poles in our dataset. Logistic regression models were all performed in Matlab.

5.4.3. Results

The 23 independent variables (including a constant term) that remained in the final regression are shown in Table 5-8, along with their minimum (column 2), maximum (column 3), and mean (column 4) values. The estimated coefficient from the logistic regression model is reported in column 5. Of the 23 estimated parameters, 13 had a positive sign and 10 had a negative sign. A positive coefficient for a variable indicates that a larger value of the variable increases the probability of an electrocution. For example the variable "Pellets" has a positive estimated coefficient: the more pellets that are found near the pole, the greater is the risk of electrocution from that pole. A negative sign indicates that a larger value of the variable decreases the probability of an electrocution. For example, the variable "perchopt" has an estimate coefficient that is negative. The more (non-power pole) perch options that are available to the raptor, the lower is a pole's risk.

An issue quite aside from the sign of a variable's effect on the probability of electrocutions is whether the variable is statistically significant. To test the null hypothesis that a coefficient is zero the authors performed a t-test (and associated p-value) on each of these coefficients. Burnham and Anderson (2004) note that it is inconsistent to mix standard hypothesis testing with information theoretic measures of model selection, so the authors avoided culling variables from the model (e.g. by stepwise elimination of statistically insignificant variables), and instead, simply provide the test statistics to provide a measure of how likely it is that they would observe the estimated coefficient even under the null that the underlying coefficient was 0. The t-statistic and p-values are reported in Columns 7 and 8 of Table 5-9.

Table 5-8. Variables included in the final retrofit priority model.

Variable No.	Variable Name	Description
3	hard1sum	Number of distances <1m between hardware elements
5	stransfo	Number of transformer pots on pole
6	sfusecut	Number of fuse cut-outs on pole
7	slighter	Number of lightning arrestors on pole
8	sswitch	Number of switches on pole
9	sjumper	Number of jumpers on pole
10	Guy_insul	Guy wires "distant or insulated"
11	Guy_uninsul	Guy wires "close & insulated"
12	Phase_tangent	Phase conductor aspect is "tangent (upward)"
13	Metal_armbrace	Whether the pole has a metal armbrace (1/0)
14	Metal_arm	Whether pole has a metal crossarm (1/0)
15	armorien	Orientation (degrees) relative to direction of prevailing wind
16	effheigh	Effective height of pole relative to adjacent poles (in meters taller)
17	Aspect_dead	Pole's aspect is "deadend"
18	Aspect_corner	Pole's aspect is "corner"
19	arms	Number of cross-arms on pole
20	pellets	Number of raptor pellets counted among all searches at pole
21	vegstruc	Number of vegetation canopy heights within 200 m of pole
25	prey_1	Total number of .times prey sign was recorded near pole
26	Veg_gr_wet	Primary vegetation is "grassland" or "wetland"
29	use_public	Primary land use "public use"
33	Perchopt	Number of tall perch options near pole (other than other poles)

Table 5-9. Results for the final logistic regression model.

Variable	min	max	mean	Logit Coefficient, b	exp(b)	t-statistic	p-value	max effect on probability (%)
slightar	0	9	0.1290	0.41	1.50	3.47	0.00	28
pellets	0	58	0.2673	0.05	1.05	2.05	0.04	15
prey_1	0	11	2.8431	0.27	1.30	5.05	0.00	8
hard1sum	0	24	0.4978	0.09	1.09	1.27	0.20	7
Veg_gr_wet	0	1	0.0332	0.81	2.25	2.01	0.04	1
perchopt	0	10	6.1942	-0.10	0.91	-2.88	0.00	1
Guy_uninsul	0	1	0.0051	-5.34	0.00	-0.20	0.84	1
Aspect_corner	0	1	0.0151	0.70	2.01	1.06	0.29	1
sfusecut	0	8	0.5622	0.09	1.09	0.76	0.45	1
effheigh	0	3	0.1459	-0.68	0.51	-1.93	0.05	1
use_public	0	1	0.0498	-1.78	0.17	-1.74	0.08	1
vegstruc	1	4	2.5159	-0.27	0.76	-1.60	0.11	1
sswitch	0	4	0.0908	-0.34	0.71	-1.26	0.21	1
Aspect_dead	0	1	0.0375	0.56	1.74	1.26	0.21	1
Guy_insul	0	1	0.2047	0.56	1.75	2.12	0.03	1
stransfo	0	5	0.2496	-0.19	0.83	-0.92	0.36	1
armorien	0	135	43.8363	0.00	1.00	-1.90	0.06	1
arms	0	5	1.4747	-0.06	0.94	-0.40	0.69	0
Metal_arm	0	1	0.4271	0.27	1.31	1.20	0.23	0
Phase_tangent	0	1	0.7676	0.23	1.26	0.76	0.45	0
sjumper	0	9	0.3382	-0.03	0.97	-0.21	0.83	0
Metal_armbrace	0	1	0.7323	0.14	1.15	0.58	0.56	0
Constant	1	1	1	-4.13	0.02	-6.99	0.00	0

While interpreting the sign of a coefficient in a logistic regression model is relatively straightforward (see above), interpreting the magnitude of that effect is less straightforward. How important are each of the pole's characteristics? Intuitively, what is needed is an assessment of the relative importance of each pole characteristic for producing an electrocution. A standard calculation along these lines is, $\exp(\beta_j)$, for variable j. Because a logit is naturally interpreted in terms of odds, $\exp(\beta_j)$ is interpreted as the odds arising from a one unit increase in variable xj divided by the odds from no change in the variable. For example if $\exp(\beta_j)=1.5$, for variable j, then a 1 unit increase in xj increases the odds by 50%. This calculation is provided for all variables in column 6 of Table 5-9. For example, $\exp(\beta_{prey\_1})=1.30$; finding one more sign of prey increases the odds (importantly, not probability) of electrocution by about 30%.

In this application the authors were directly interested in the probability of an electrocution, and how changes in measured characteristics affected that probability. Unlike a linear regression model in which a unit increase of a variable has a known and constant impact on the dependent variable regardless of other impacts, the coefficients in a logistic regression are not "marginal effects"; the effect of an increase or decrease in a variable on the probability of electrocution will vary depending on the level of all other variables.

The calculation of exp(β_j) provides some guidance, but since it only informs odds, not probabilities directly, the authors performed the following calculation: first, they calculated the average, maximum, and minimum value for each variable (see table above). Holding all variables at their mean value, they calculated the change in probability from moving a variable i from its minimum to its maximum observed value. They did so for all variables i. This statistic therefore represents the maximal impact that any given variable will have (within the variable's range represented in the dataset) on the overall probability of causing a raptor electrocution. These calculations are reported in the final column of Table 5-9 (above, and also note that the variables themselves are reported in descending order of this statistic). For example consider the variable "hard1sum". The maximum effect on probability for that variable is 7%, interpreted as follows: Consider a pole that is "average" in every respect, except that it has 0 hardware elements less than 1m apart. By how much would the probability of electrocution increase if the same pole had, instead, 24 hardware elements <1m apart? (Note: the benchmarks of 0 and 24 are the minimum and maximum observed values for this variable in the dataset).

The answer is 7%. This statistic, therefore, offers a way to determine which characteristics are most "important" in terms of their ability to influence the probability of electrocution. This result is also significant for allocating resources and training towards recognition and accurate recording of pole characteristics; an error in counting perch options may have very little impact, but an error in counting lightning arrestors could significantly bias the estimate of a pole's risk. This statistic is graphically represented below (Figure 5-1).

Using this measure, four variables stand out as being exceptionally relevant: (1) the number of lightning arrestors or riser elements, (2) the number of raptor pellets observed, (3) sign of prey abundance, and (4) the number of hardware elements in close proximity (< 1m). While other features are important (and some are statistically significant), any given one of these components is less capable of dramatically influencing the estimate of a pole's risk.

5.4.4. A Model for Priority Retrofit

Finally, what do the results of the logistic regression model suggest about the ranking of poles? Can the method be applied in the field? Or does the analysis need to be simplified to assess a pole's risk? The answer is that the model provided above is easily applied. This model should be used to assign a risk to all poles included in the initial survey.

One simply has to measure the pole characteristics defined above (Table 5-8), apply the logistic equation, and thus estimate the probability that the pole will cause one or more electrocutions. Because the data do not come from a truly random sample, this model is most appropriately applied to within-sample poles. The model can be applied with less confidence out of sample; however, to the extent that the sample can be considered random (see discussion above), the model can be defensibly applied out-of-sample.

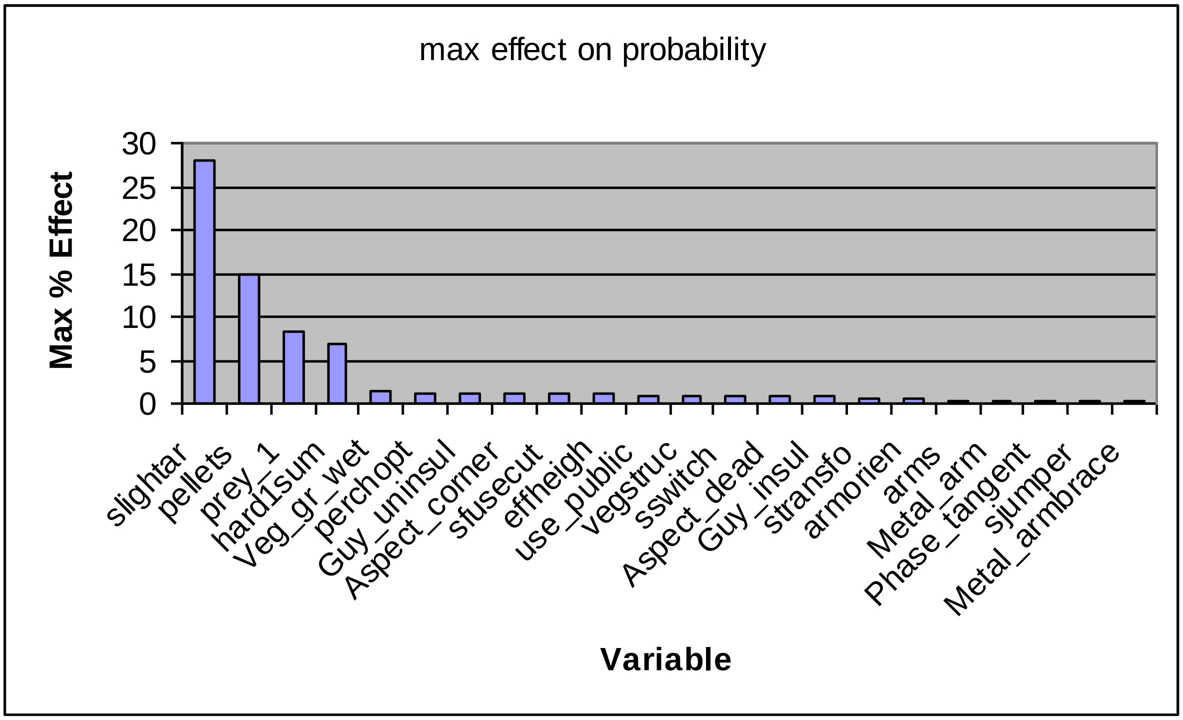

Figure 5-1. Potential difference in probability resulting from a maximum change of a given characteristic. See Table 5-8 for descriptions of variables.

With the logistic regression equation determined, determining the risk of a pole in the field is simple. Doing so requires completing the following four steps:

- **Step 1:** Measure the level of each of the 22 variables described above.
- **Step 2:** Combine the variables according to the following weighted formula:

X = -4.13 + .41(slighter) + 0.05(pellets) +0.27(prey_1) + 0.09(hard1sum) + 0.81(Veg_gr_wet) - 0.1(perchopt) -5.34(Guy_uninsul) +0.7(Aspect_corner) +0.09(sfusecut) -0.68(effheigh) -1.78(use_public) -0.27(vegstruc) -0.34(sswitch) +0.56(Aspect_dead) +0.56(Guy_insul) -0.19(stranso) - 0.004(armorien) - 0.06(arms) + 0.27(Metal_arm) + 0.23(Phase_tangent) -0.03(sjumper) + 0.14(Metal_armbrace)

- **Step 3:** Perform the following calculation:

Probability {Electrocution} = 1/(1+exp(-X))

Steps 1-3 determine any pole's probability of causing an electrocution over a fixed time interval, and provide an assessment of its suitability for retrofit. Suppose that a field crew performs Steps 1-3 and determines that a pole's estimated probability of electrocution is 4%. Is this a large number or a small number? To answer this question, the authors calculated below an empirical cumulative density of the predicted probability of all 6,286 poles in this study's sample. Most of the poles have predicted probabilities of < 2%, but a few have predicted probabilities of 10% or more.

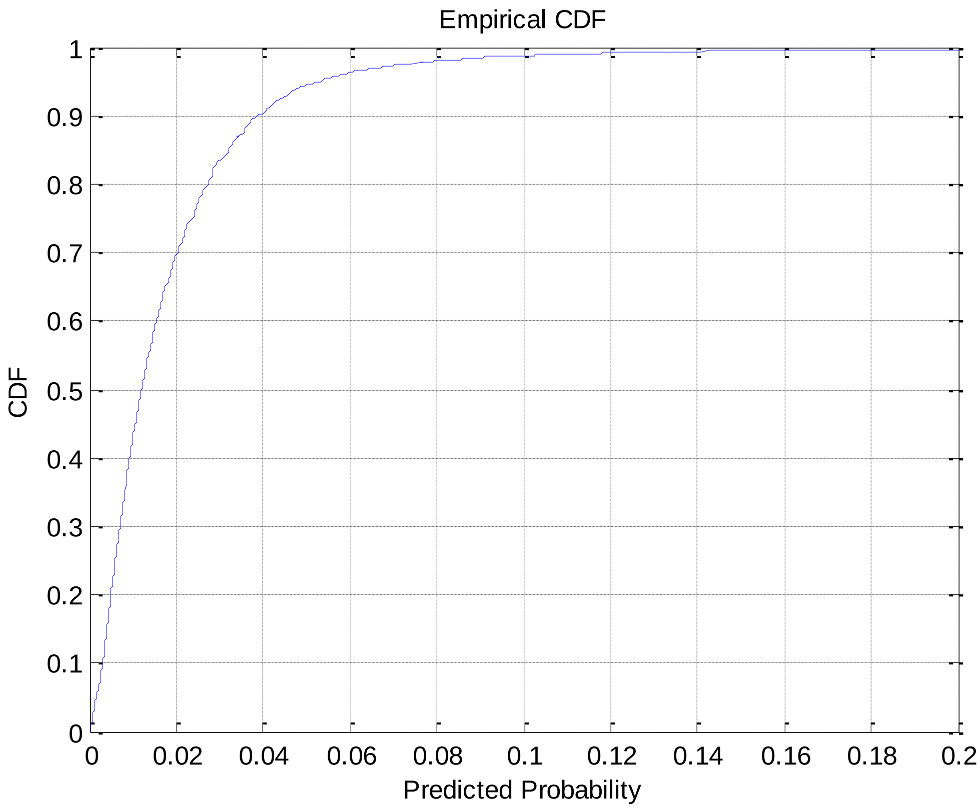

Figure 5-2. Cumulative Density Function for power poles probability of causing electrocution.

So the crew who performed Steps 1-3 on this particular hypothetical pole (and arrived at an estimate of 4%) can look up 0.04 on the horizontal axis of this graph and determine that the pole in question is in the 90th percentile (vertical axis is 0.9). This pole is more dangerous than 90% of all poles represented in this study's sample. The higher the percentile the greater the potential is for the pole to cause an electrocution. Based on this logic the authors propose the following qualitative categorization of risk:

- **Step 4:** Determine the pole's risk.

Predicted Probability	Risk category	Percentile from c.d.f.
P < 1%	Low	50th percentile
1% < P < 3%	Medium	80th percentile
3% < P < 6%	High	95th percentile
P > 6%	Extreme	95th + percentile

5.4.5. Implementing the Recommended Model In Practice: An Example

The model presented here is a practical method for scoring any single pole, or group of poles. This calculation, though it initially appears cumbersome, can be easily calculated using a pre-formatted Excel spreadsheet. Table 5-10 is a depiction of an active Excel spreadsheet that would be used to automatically calculate probabilities, and from those, determine the assigned 'risk'. In practice, Steps 2, 3, and 4 need not even be done manually. A practitioner enters the results of Step 1 into a spreadsheet and the calculation is performed automatically.

Imagine a hypothetical pole with the following characteristics:

Variable	Hypothetical Pole Measurement
slightar	1
pellets	4
prey_1	4
hard1sum	0
Veg_gr_wet	1
perchopt	8
Guy_uninsul	0
Aspect_corner	0
sfusecut	2
effheigh	1
use_public	0
vegstruc	3
sswitch	0
Aspect_dead	0
Guy_insul	1
stransfo	0
armorien	90
arms	2
Metal_arm	0
Phase_tangent	1
sjumper	3
Metal_armbrace	1

The probability can be calculated either by performing Steps 2-3 or by inputting these values into a pre-formatted Excel calculator. Excel then automatically calculates both a probability and a risk classification for the pole. Using the formula above, this gives a value of X = -3.37. Applying Step 3 gives a final probability of Pr{Electrocution}=0.033; this hypothetical pole has an estimated probability of causing an electrocution of about 3%. The cdf plot reveals that this pole would be in about the 85th percentile of all within-sample poles, and our risk categorization shows that this pole would be "High" risk (though not extreme).

In summary, the risk calculator provided here could be recommended to the utilities as an effective tool for categorizing power poles electrocution risk. It effectively combines ease of use with the rigorous statistical basis of the logistic regression model. As better data become available, updated logistic regression models could be run, and the weights (coefficient estimates) could be updated.

Although all of the resultant probabilities will appear to be low, it is important to put these into context. This value does not represent the probability that a pole will *ever* electrocute a raptor. Instead, it represents the probability that it will do so *in a given time interval*.

Table 5-10. Depiction of calculator using Excel that can be used to determine a pole's probability and risk classification based on the selected logistic regression model.

Variable	Coefficient	Measurement	Variable Effect
slightar	0.41	1	0.406056
pellets	0.05	4	0.196168
prey_1	0.27	4	1.060848
hard1sum	0.09	0	0
Veg_gr_wet	0.81	1	0.81256
perchopt	-0.10	8	-0.760024
Guy_uninsul	-5.34	0	0
Aspect_corner	0.70	0	0
sfusecut	0.09	2	0.177792
effheigh	-0.68	1	-0.675014
use_public	-1.78	0	0
vegstruc	-0.27	3	-0.81465
sswitch	-0.34	0	0
Aspect_dead	0.56	0	0
Guy_insul	0.56	1	0.559503
stransfo	-0.19	0	0
armorien	0.00	90	-0.37359
arms	-0.06	2	-0.126846
Metal_arm	0.27	0	0
Phase_tangent	0.23	1	0.233979
sjumper	-0.03	3	-0.078309
Metal_armbrace	0.14	1	0.142276
Constant	-4.13	1	-4.127319
Log Odds	-3.36657		
Probability	**0.033357**		
Risk Category	**High**		

6.0 Conclusions and Recommendations

Retrofitting the most dangerous poles first using the best available hardware alternatives will most quickly and substantially reduce bird mortality caused by electrocutions. Utilities now have several tools to assist them in making decisions regarding how best to apply limited resources to achieve the greatest effect with respect to reducing electrocutions at power poles. This study produced and evaluated several ranking procedures, several of which are reasonably reliable at identifying high risk poles.

The biological significance of the region-specific mortality estimates reported herein is unknown. Whatever the true mortality is, it has likely been experienced for decades. Over many decades, the number of power poles in the Central Valley has increased while the number of suitable natural perches has declined due to the expansion of agriculture and other intensive land uses that significantly alter the landscape. It is therefore likely that mortality due to electrocution has fluctuated since the numbers of birds (especially raptors) that use the Central Valley has probably changed with inter-annual weather changes and their perching behaviors have changed along with the availability of naturally occurring tall perches such as trees.

6.1. Correlations Between Fatalities, Environmental Factors, and Hardware

Riser elements appear to be the most dangerous electric elements installed on distribution poles. They are implicated in an inordinate percentage of bird electrocutions. Lightning arrestors also appear to be very dangerous to birds. Preferably, riser elements should be covered by insulating material whenever possible. Also, installing when possible a benign crossarm might mitigate the situation if installed as an alternative perch site. Lightning arrestors should be removed from metal crossarms, floated, and separated from potential perch sites by insulating material.

6.2. Applying a Predictive Model for Priority Retrofits

To move beyond simple univariate correlations and estimate a more comprehensive model of the factors responsible for raptor electrocutions, the authors developed and implemented a novel logistic regression approach. A set of hypotheses was generated and a single logistic model with 22 independent variables was selected based on a common information-theoretic measure (AIC). That final model yielded several insights. First, the model contained important predictors from all three basic categories of theoretical risk: (1) a pole's inherent attractiveness, (2) the landscape setting in which the pole resided, and (3) the hardware features of the pole. Second, four variables stand out as having an exceptional impact on a pole's risk: (1) the number of lightning arrestors or riser elements, (2) the number of raptor pellets observed (an indicator of use), (3) sign of prey abundance, and (4) the number of hardware elements in close proximity (< 1m). Finally, the authors found that the final logistic regression model provides a natural method for assessing any given pole's risk; this risk calculation is easily performed in the field to assist in priority retrofit.

6.3. Future Research

Monitoring for electrocutions needs to be expanded into regions other than where this study conducted its searches. It would be helpful to perform similar research in areas more likely to be used by golden eagle than is the case where this study focused its efforts. And it would be helpful to discover the extent that bird electrocution varies throughout California, and especially where raptors are known to become seasonally abundant.

How long do bird carcasses remain detectable by fatality search crews along electric distribution lines, and how does variation in environmental conditions relate to the longevity of carcass detection? This information is vital to increasing the precision of mortality estimates, which are vital to assessing the relative impact of the electric distribution system on birds.

Future research should be performed using a random sampling design to estimate the annual number of birds electrocuted per pole in various regions and suites of conditions. Lastly, a better understanding of electrocutions would result if the utilities expanding their efforts to assess the effectiveness of their on-going pole retrofit programs.

6.4. Benefits to California

Applying the results of this research can have a direct affect on reducing bird mortality due to electrocutions on power poles. This benefits California by conserving valuable natural resources, ensuring compliance with environmental laws and regulations, improving the reliability of the electric distribution system, and increasing safety and reducing risk to public safety because bird electrocutions are often the source of wildfires.

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8.0 Glossary

Corner pole – a distribution pole where the line makes a turn. Stresses occur at corner poles so spans to adjacent poles are often shorter and guys are usually installed.

Crossarm – a piece of wood cut to specified dimensions and bolted to a wood pole; used to support electrical conductors for the purpose of distributing electrical energy.

Dead-end pole – the distribution pole at the end of a sequence of poles and usually supported by guy wires. Transformer banks are often installed.

Distribution line – a circuit of low voltage wires energized at voltages from 2.4 kV to 60 kV and used to distribute electricity to residential, industrial, agricultural, and commercial customers.

Fused cut-outs – electrical switches fitted with a fuse, so that the switch will open when the current rating of the fuse is exceeded. Fused cutouts are used to protect electrical equipment and circuits from lightning and occurrences when conductors might be short-circuited by wires, wind, and conductive equipment of all kinds.

Guy – a wire that secures the upright position of a pole and offsets the physical loads imposed by the use of conductors, wind, ice, etc. Guys are normally attached to anchors that are securely placed in the ground to withstand loads within various limits.

Jumper – a conductive wire, normally copper, used to connect various types of electrical equipment. Jumper wires are also used to make electrical conductors on lines continuous when it becomes necessary to change direction of the line, i.e., angle poles, dead-end poles, etc.

Lightening arrestor – an electrical device used to connect lightning charges to ground. Lightening arrestors are normally made of porcelain, which surrounds the necessary electrical connections to achieve the grounding results.

Midline relay – a pole with hardware that steps down power to a pump, a home, etc.

Perch guards – commercially available devices attached to crossarms to discourage birds from perching on them.

Phase – an energized electrical conductor.

Raptor-safe – A power line configuration designed to eliminate raptor electrocution by having 60-inch minimum spacing between phases and phase to ground, and by providing for safe perching areas on the pole.

Retrofitting – the modification of a power line configuration to make it raptor-safe.

Riser – hardware that sends or receives power underground.

Switch – an electrical device used to sectionalize electrical energy sources.

Transformer – a device used to transform voltages to acceptable levels. Transformers have electrical windings placed inside a steel tank and surrounded with clear insulating oil. They are manufactured in various sizes.

Transformer bushing – a lining inserted in the top of a transformer tank to insulate the electrical leads of the transformer winding from the tank. Bushings are usually made of porcelain, and are used on many types of electrical equipment.