CONSULTANT REPORT

A Continued Examination of Avian Mortality in the Altamont Pass Wind Resource Area

BioSystems

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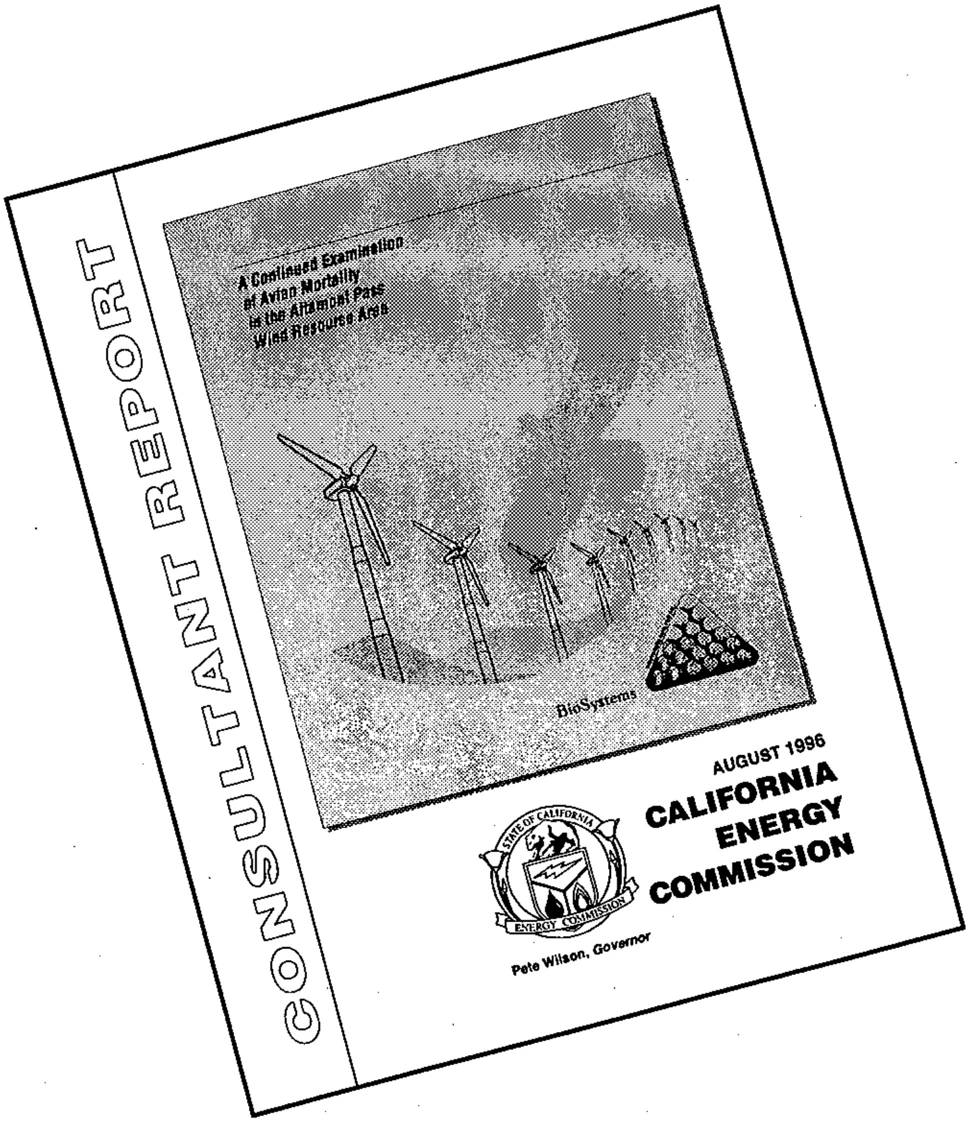
NOTICE



CALIFORNIA ENERGY COMMISSION

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Executive Summary

Further growth of wind power development has elicited growing concern over bird/wind turbine interactions. The California Energy Commission has continued its efforts to investigate, understand, and, when needed, find solutions to this matter. This investigation is a continuation of our 1992 Altamont Pass study, *Wind Turbine Effects on Avian Activity, Habitat Use, and Mortality in Altamont Pass and Solano County Wind Resource Areas* (Orloff and Flannery 1992). Both the 1992 study and the present study were funded by the Energy Commission.

This study had two objectives. The first was to further analyze mortality and observation data collected during our original 1992 study to: a) assess the potential effect of several additional turbine-specific and site-specific variables on the observed death rate, b) conduct a more detailed analysis of end turbine mortality, and c) assess whether data we collected on raptor perching could help explain observed mortality. The second objective was to collect and analyze new mortality data to attempt to corroborate some of our original findings. New mortality data were collected in 1994.

The results of different bivariate analyses suggest that several new variables were associated with mortality; raptor mortality was associated with turbines that had higher tip speeds, larger rotor diameters (i.e., larger rotor-swept area), variable-pitch blades, and that operated more frequently (percent time in operation). For reasons we discuss in text, however, we question the association of rotor diameter and blade pitch with raptor mortality. We believe that all four factors should be the focus of future studies to further test their potential association with mortality.

Our comparative analysis of mortality among the six turbine types studied indicated that mortality was significantly higher at lattice-tower turbines with horizontal cross arms (lattice/horizontal) than at all other turbine types combined, while mortality was significantly lower at guyed-pipe turbines than at all other turbine types combined. Mortality rates at the other turbine types were moderate. The principal features of lattice/horizontal turbines that may have contributed to their high mortality rate include a high percent of time in operation and high tip speed. We believe that the primary reason mortality was significantly lower at guyed-pipe turbines was because these turbines operated far less frequently than any other turbine type.

A multivariate analysis (multiple logistic analysis), that included new variables as well as some of the original variables, indicated that only turbine position in row (end vs. non-end) and turbine proximity to canyon were significantly associated with mortality. These two variables appear to be dominant over all other variables included in the analysis. Our analysis of new, 1994 mortality data corroborated our original finding that both position in row and proximity to canyon were significantly associated with mortality. Other recent studies have reported that mortality appears to be higher at end turbines as well (Hunt 1994, Winkelman 1992a).

There has been speculation recently about the possible role of perching in mortality. Birds may be injured or killed when they attempt to fly through spinning blades looking for a place to perch or when they leave a turbine once the blades have started spinning. In addition, by perching on turbines that are not operating, raptors may become habituated to turbines making them less cautious around spinning blades. Our original observation data suggested that raptors seldom perched on operating turbines. However, a recent observation of a raptor that died attempting to land on an operating turbine, as well as another recent study in Altamont Pass that indicated that some raptors remained perched on operating turbines for extended periods, suggest that this could be a more common cause of mortality than previously suspected. Perching or attempting to perch on operating turbines may be rare events, but so are turbine-related mortalities; they may be rare but highly associated.

Our perching data may partly explain why some species appear to be more susceptible to collision than others. Red-tailed hawks and American kestrels exhibited a high perching frequency and we found in our original study that they were killed more often than would be expected from their abundance in the study area. In contrast, the turkey vulture's low perching frequency may help explain its lower relative mortality rate. However, perching frequency does not explain relative mortality for golden eagles or common ravens. Golden eagles rarely perched on turbines, but their relative mortality was high, while common ravens often perched, but their relative mortality was low.

"Perchability" of turbines may contribute to observed mortality for some turbine types. Perching frequencies were highest at lattice/horizontal (including windwall) turbines, followed closely by lattice-tower turbines with diagonal cross arms, guyed-pipe turbines, and vertical-axis turbines. Perching at tubular-tower turbines was considerably lower. The low perching frequency (low perchability) at tubular-tower turbines may partly explain their relatively low mortality rate, while the high perching frequency (high perchability) at lattice/horizontal turbines may partly account for their significantly higher mortality rate. For the other three turbine types (lattice/diagonal, guyed-pipe, vertical-axis), however, perching does not appear to help explain mortality. The design and operation of these three turbine types may make perching birds less vulnerable to collision mortality.

Perching frequencies were higher at end turbines than at non-end turbines. This may be one reason the mortality rate was higher at end turbines. End turbines may provide better perch sites because they often provide a better view of a canyon where prey densities may be higher. This may also be why turbine proximity to a canyon was significantly associated with mortality.

Our data suggest that mortality at different turbine types may be caused by many interrelated factors. It is probably a combination and interplay of factors that determines observed mortality. We consider the analyses and results discussed in this report to be exploratory. The analysis was limited by an inherent lack of variability in some of the variables. We hope that this report will assist others by narrowing the scope of possible contributing factors and by providing a basis for future research and resolution of this issue.

1.0 Introduction

1.1 Background

Recent years has brought growing interest and controversy concerning the interactions of birds with wind power developments. Beginning with the 1989 Energy Commission review of existing data (California Energy Commission 1989) that first documented the occurrence of wind turbine-related bird injuries and deaths, biologists, windfarm companies, and other stakeholders have become aware of this issue and the potential for adverse effects on birds. This unexpected effect has since resulted in the generation of many reports, from both private industry and government agencies. The Energy Commission has funded two field studies in recent years to investigate the issue of avian mortality at windfarms: 1) a two-year study at the Altamont Pass Wind Resource Area (WRA), the findings of which were published in Orloff and Flannery 1992, and 2) a baseline study at the Tehachapi WRA, published in Orloff 1992. Throughout this present report, we refer to the Altamont Pass study as our original report.

This present investigation, also funded by the Energy Commission, is a continuation of the 1992 Altamont Pass study. Since the use of wind turbines to generate electricity continues to increase in California and elsewhere, the Energy Commission has continued its efforts to investigate, understand, and resolve this bird/wind turbine issue.

1.2 Goals and Objectives

This study had two primary objectives: 1) to further analyze our original mortality data and some of our original observation data (section 1.2.1 below), and 2) to analyze new mortality data we collected during the winter of 1994 (section 1.2.2 below). We consider both our original study and this current effort exploratory. Our goal was to identify possible contributing factors and to provide a basis for future research.

1.2.1 Analysis of Existing Mortality and Observation Data

Three tasks were associated with the first objective. The first task was to assess the potential effect of several additional (in addition to those examined in our original report) variables on mortality using our original mortality data. The additional variables include various turbine- and site-specific characteristics such as the percent of time turbines operate, blade tip speed, turbine height, rotor diameter, rotor-swept area, rotor direction relative to wind (upwind or downwind), and others. The variables we considered in our original report did not entirely explain raptor mortality in the Altamont Pass. For example, we felt that the percent of time turbines operated was a potentially important factor in bird collision mortality. We did not have this information for inclusion in our original analysis. It is possible that observed mortality may have been significantly higher at certain turbine types in our original analysis simply because they operated more often than other turbine types. We feel that the additional variables we consider in this report are important contributions to a more comprehensive evaluation of factors contributing to mortality. Many of these variables were suggested to us by wind industry personnel.

The second task was to conduct a more-detailed analysis of end-turbine mortality. This included evaluating whether end-turbine mortality was different among turbine types and whether the specific location of carcasses found around the base of end turbines might shed some light on the circumstances under which birds were killed.

The third task was to use our original observation data to further analyze the possible effects of perching on mortality. There has been a lot of speculation recently about the role of perching as a factor contributing to mortality. Birds may be injured or killed when they attempt to fly through spinning blades either looking for a place to perch or leaving a turbine once the blades have started spinning. We tried to answer the following questions:

- Do some species perch on turbines more than others?
- Are there seasonal differences in perching?
- Are some turbine types used for perching more frequently than others?
- Are end turbines used for perching more frequently than non-end turbines?
- Do raptors perch on operating turbines?

1.2.2 New Mortality Data — Collection and Analysis

Our second objective was to analyze new mortality data we collected during a one-time walk-through of our original mortality sample sites. The collection of new mortality data was an attempt to corroborate some of our earlier findings about mortality at end turbines and turbines close to canyons. In our original analysis, we found raptor mortality to be significantly higher at end turbines and turbines close to canyons (within 500 feet), but other researchers have found no such relationships (Howell and Noone 1992).

We believe that verifying whether these variables are associated with mortality is important and should be completed before any turbine alteration studies are initiated. For example, if raptor mortality were indeed higher at end turbines, then using them as sample turbines in experimental studies of turbine alterations would increase a researcher's ability to detect differences in mortality rates between experimental groups.

1.3 Summary of Past and Ongoing Studies

We summarize below many of the pertinent past and ongoing studies, both in this country and abroad, that address the issue of avian mortality at wind-power generating sites. An annotated bibliography of wind energy-related studies and publications, encompassing all impacts and issues of wind energy from the United States and abroad, has recently been completed and is now available (California Energy Commission 1996).

1.3.1 Altamont Pass WRA 1992 Study Results

For the reader to better understand the current study, the following is a review of the findings of our original study. We conducted observation and mortality surveys for six seasons between 1989 and 1991. Of the 182 dead birds we found within our sample sites during mortality surveys, 119 (65%) were raptors. Most carcasses were old and decomposed when found; only 19 were fresh. Most of the dead raptors were red-tailed hawks (*Buteo jamaicensis*), followed by American kestrels (*Falco sparverius*) and golden eagles (*Aquila chrysaetos*). We also discovered a few dead turkey vultures (*Cathartes aura*), owls, and common ravens (*Corvus corax*).

We attributed 55 percent of all raptor deaths to collisions with turbines, 8 percent to electrocutions, 11 percent to collisions with wires, and 26 percent to unknown causes. Our data indicated that mortality was significantly higher at: 1) end turbines (turbines at the end of a row) than at non-end turbines (turbines within a row), 2) turbines close to canyons (within 500 feet) than at those farther from canyons, 3) higher elevations, and 4) sites having lower structure density (a measure of structure congestion). Mortality differed among turbine types and was significantly higher at lattice-tower turbines than at any other turbine type. Other turbine types studied included windwall, guyed-pipe, vertical-axis, and tubular-tower.

From our observations, raptors appeared to be accustomed to the presence of turbines, showing no signs of increased vigilance or being aware of potential danger. Many of the birds we observed commonly flew close to turbines, foraged around operating turbines, and perched on not-operating turbines. We suggested that habituation may be an important factor contributing to mortality.

Our original study showed that relative mortality of the five most common species was not directly related to the relative abundance of each. Golden eagles, red-tailed hawks, and American kestrels were killed more frequently than we would have predicted from their abundance in the study area, whereas turkey vultures and common ravens were killed less often than we would have expected. We discussed how differences in foraging behavior could broadly explain differences in relative mortality for these five species. We hypothesized that raptors that stoop on prey (such as eagles, hawks, and falcons) may be less aware of or misjudge the distance to rotating turbine blades during a high-speed, focused stoop, thereby increasing their potential for collision, whereas birds that fly more slowly and primarily scavenge, such as vultures and ravens, might be more aware of turbine blades.

From sample data, we extrapolated annual site-wide (Altamont Pass WRA) estimates of raptor mortality for each of the two years of the study. Estimates ranged from 164 to 403 raptor deaths. We conservatively estimated that 39 golden eagles were killed during a one-year period. The raptor mortality rate varied from 0.02 to 0.05 deaths per turbine per year. We acknowledged that these estimates had a large potential for error because of the low number of fresh carcasses found, the number of variables involved, and the potential variability in mortality in different areas within the WRA. It is also important to remember that these estimates are for an area that comprised more than 7,500 turbines in the WRA.

When our original report was first distributed it became the object of much controversy and criticism. It was the first detailed study on the subject of impacts of wind turbines on birds of prey in this country and it represented the first time windfarms had been associated with any potentially serious environmental impacts. Understandably, windfarm companies and their shareholders may have been fearful of the consequences of the report and of the myriad interpretations that were published in magazines and newspapers. Original criticisms largely concerned our statistical methods and analyses, and our perceived failure to adhere to the underlying assumptions of statistical procedures. Pursuant to that early controversy, we addressed criticisms in a letter we made available to all interested parties, and had our report reviewed by independent statisticians who found our original analysis to be statistically sound according to current accepted practices. Many early criticisms, it turns out, were based on outdated or incomplete knowledge of statistics. Several years have passed now and many of the results we published in that original report have become more accepted or have been corroborated by other researchers.

1.3.2 Other Past Studies in the United States

Before the 1989 Energy Commission review, the few studies that attempted to investigate bird mortality at windfarm structures involved only one or a few turbines, or focused on nocturnal migrants (waterfowl or passerines). In-depth studies of raptor mortality at large windfarms primarily began in the 1990s. Kenetech Windpower, Inc. (formerly U.S. Windpower, Inc.) has funded three main studies of avian use patterns and mortality at their lattice-tower turbines in both the Altamont Pass and Solano County WRAs. The first was a single-year study of avian use patterns and mortality at 359 lattice-tower turbines in the Altamont Pass WRA which revealed 17 raptor mortalities for a rate of 0.05 deaths per turbine per year (Howell and DiDonato 1991). The second was a multiyear, pre- and post-construction study of 237 lattice-tower turbines at the Solano County WRA during which three raptor mortalities were found the first year and 11 the second year, for a rate of 0.02 to 0.05 deaths per turbine for the two years, respectively (Howell and Noone 1992). The third study tested whether increasing the contrast of turbine blades by painting them would reduce turbine mortality (Howell et al. 1991b). For a general review of these past studies see Colson and Associates 1995.

1.3.3 Ongoing Studies in the United States

In 1992, Kenetech Windpower, Inc. (Kenetech), established an Avian Research Task Force composed of nationally known research biologists to develop and oversee a multiphase research program focusing on the interaction of birds and turbines at Kenetech turbines in the Altamont Pass WRA. The research program encompasses several study efforts including: 1) examining the sensory capacities of raptors common to the Altamont Pass to determine what visual stimuli are most effective in improving their recognition of a wind turbine as an obstacle to be avoided, 2) monitoring and evaluating controlled flights of trained birds using a 3-D video tracking system to study their evasive actions around turbines, 3) initiating a telemetry study to ascertain the dynamics of the golden eagle population in the Altamont Pass WRA and vicinity, 4) developing anti-perching devices to deter avian use of turbines as hunting and roosting sites, and 5) operating one remote video camera monitoring system to record mortalities, located where multiple bird collisions have occurred.

In addition to the activities of the Task Force, several pre-construction studies at proposed windfarms have recently been completed and an ongoing monitoring study initiated. These include an examination of avian use in the Montezuma Hills for the Sacramento Municipal Utility District (Howell and Noone 1994), an EIS in Carbon County, Wyoming (Mariah Associates 1995), a study of a proposed 450-turbine windfarm in Klickitat County in the state of Washington (Jones and Stokes 1995), and an ongoing monitoring study of avian use and mortality at Buffalo Ridge Windplant in Minnesota (Higgins et al. 1995).

1.3.4 Foreign Studies

European scientists have completed considerably more studies on the effects of wind power plants on bird life than American scientists. We annotated more than 35 such studies in our bibliography (California Energy Commission 1996), and there are many more without English translations or summaries that we were not able to annotate. Unlike U.S. windfarms, European windfarms typically occur in coastal areas and contain far fewer turbines, usually less than 25 turbines per site, and many sites have only one turbine. With the exception of one site in Spain, all European turbines have tubular towers. Below we provide a brief summary of European studies to date. Reviews of European research can be found in Benner et al. (1993) and Crockford (1992).

From the European point of view, in most circumstances, disturbance and habitat loss are thought to be much more important impacts than bird mortality (Peterson and Nohr 1989; Crockford 1992; Benner et al. 1993). The disturbance effect varies with species, time of day, and season, and with whether the birds are migrating through, breeding, or feeding and resting (non-breeding). The primary disturbance has been to feeding, resting, and migrating birds (Crockford 1992; Benner et al. 1993). The disturbance effect on breeding birds appears to be negligible; only one study showed that breeding birds were affected by disturbance (Pedersen and Poulsen 1991).

Studies have shown disturbance to birds as far as 250 m to 800 m from the wind turbines (Peterson and Nohr 1989; Pedersen and Poulsen 1991; Vauk 1990; Winkelman 1989; Winkelman 1990b; Winkelman 1992d). Winkelman (1994) reported a 95 percent reduction in bird numbers in disturbance zones. Migrating birds show disturbance effects by changing their course or by avoiding the windfarm entirely (Peterson and Nohr 1989; Vauk 1990; Winkelman 1992d). Results of several studies suggested habituation of local birds to wind turbines (Peterson and Nohr 1989; Winkelman 1985; Winkelman 1992c).

The number of mortalities from windfarms in Europe was considered to be negligible. Musters et al. (1991) and Winkelman (1994) showed that mortality rates varied between 0.01 and 0.09 birds per turbine per day (3.7 to 32.9 per turbine per year), depending on site and season. In a summary of avian impacts at wind turbines by Benner et. al (1993), bird deaths per turbine per year were as high as 309 in Germany and 895 in Sweden. Although these estimates represent considerably higher mortality rates than we have found in this country, European scientists consider these rates acceptable for several reasons: 1) the number of deaths is small relative to the total number of birds using or passing through the area, 2) the number of victims is small compared to the number of victims of other unnatural causes of deaths, 3) species included are passerines and waterbirds, not raptors, and 4) European windfarms typically contain few turbines (Crockford 1992; Benner et al. 1993; Winkelman 1994).

European studies have shown that some species seem more susceptible to collision than others; small passerines and some species of waterbirds appear to be particularly susceptible (Pedersen and Poulsen 1991; Winkelman 1990a,c). Winkelman (1989) found seasonal differences in mortality rates: the number of collisions was two to three times higher in the fall than in the spring and winter, probably due to the passage of migrating birds. She also implicated weather in collision mortality and found that more birds collided with turbines at night and twilight than during the day (Winkelman 1990c).

In one major study, Winkelman (1992a,b) found that fewer birds collided with the middle row of wind turbines. Because of this, she suggested that a dense cluster formation may cause fewer impacts than a line formation. This same study showed that deaths were caused when birds were swept down by the wake behind the rotor (Winkelman 1994).

2.0 Methods

2.1 Analysis of Existing Mortality and Observation Data

In this report we further analyze mortality and observation data we collected between 1989 and 1991; the study design and methods for those data were published in our original report (Orloff and Flannery 1992). We use those original data to test the effect of several additional variables on mortality and to further evaluate the potential contribution of both end turbines and perching to the observed death rate. As in our original study, this study focuses on diurnal raptors and we only mention other species or groups when differences between them are potentially important. In the following sections, we describe the additional variables analyzed and tests applied to the data.

2.1.1 Turbine Characteristics and Operation

We analyzed the effects of several additional variables on mortality rates, including the percent of time turbines were in operation (hereafter referred to as "percent time in operation"), rotor diameter, rotor-swept area, tip speed, rotor solidity, turbine height, turbine spacing, blade pitch, turbine yaw, rotor direction relative to the wind (upwind or downwind), and raptor use. In this analysis, we categorized turbine types slightly differently than in our original report (see Turbine Types below). For each variable, all sample turbines were classified according to their individual characteristics. Although turbines within a particular sample site were of the same basic type and manufacture, they did not necessarily have identical turbine characteristics. For example, turbine height varied with individual turbines within some sample sites. Often, however, all turbines within a particular sample site or turbine type had identical turbine characteristics.

Variables

Percent Time in Operation. Percent time in operation is the percentage of time that turbines operate. It is a function of wind speed and operation capabilities, i.e., cut-in speeds and downtime. Because the actual percent of time turbines were operating was not available from windfarm companies, we derived estimates from wind speed data. Windfarm meteorologists confirmed that wind speed should be highly correlated to actual operating time (Ron Nierenburg pers. comm.). We then corrected this estimate for downtime, which is the percent of turbines not available to operate because of repair, testing, malfunction, or shutting down during the off season; each windfarm company had estimates for "on-line availability." We discuss this further in the following paragraphs.

We estimated percent time in operation for each of the 18 sample sites by determining the proportion of hourly average wind speeds *during daylight hours* that were within the operational window for a particular turbine model or type. We used only daylight hours because all but one of the dead raptors we found were diurnal species. We used site-specific, hourly wind data from all our original 18 sample sites for the time periods during which we were conducting our first-year mortality surveys (spring, fall, and winter of 1989, and summer of 1990). Wind speed data were taken from local meteorological towers that best represented our site locations and turbine heights. From these hourly averages, we derived monthly, seasonal, and yearly averages of percent time in operation. Only two months of data were used to represent each season: March and April for spring, July and August for summer, September and October for fall, and January and February for winter. We assumed that wind speed data for these sample months represented an average for our survey areas over that time period.

We calculated both a conservative and a liberal estimate of percent time in operation. The conservative (low) estimate used only cut-in speeds (speeds at which the turbine blades start to reliably turn at a specified RPM that produces electricity) and high-end cut-out speeds (high speeds at which the turbine blades would shut down to avoid damage). For example, if 12 mph was the cut-in speed and 44 mph was the high-end cut-out speed, we determined the number of hours in a day that the average hourly wind speed was between 12 and 44 mph. If average wind speed equalled or exceeded the cut-in speed for a particular turbine type in 6 of 12 daylight hours, but never exceeded the cut-out speed, the estimated time in operation for that day was 50 percent. Daily percentages were then averaged for each season and for the entire sampling period.

The liberal (high) estimate also included low-end cut-out speeds. For some turbine types, once the blades have started rotating for a period of time they will continue to rotate and produce electricity even if the wind speed falls slightly below the cut-in speed. This extended the percent of time turbines were presumed operating and yielded the liberal estimate.

For most tubular-tower turbines we needed to determine the conservative and liberal estimates of percent time in operation somewhat differently. Most of these turbines have two different cut-in speeds because each turbine has two generators, one that kicks in at lower wind speeds and one that takes over at higher wind speeds. Each produces different maximum revolutions per minute. In this case, the lower cut-in speed was used to calculate the liberal estimate of percent time in operation (because it resulted in more time in operation), while the higher cut-in speed was used to calculate the conservative estimate.

Percent time in operation was then adjusted for downtime. We obtained an estimate from each windfarm company of the percent of turbines within our sample sites that were not operational during the time frame of our study. To correct percent time in operation for downtime, we multiplied the percent of turbines that were operating (the inverse of downtime) by the wind speed-derived estimate of percent time in operation.

One yearly figure of downtime was considered suitable by some companies to represent the entire study period. Other companies considered it more appropriate to separate downtime estimates by season. Companies that shut down in the off-season had large differences in downtime between seasons. Because our mortality data were not separated into seasons (most carcasses were too old to determine precise time of death), seasonal estimates for downtime and percent time in operation for each sample site were averaged over all seasons.

Rotor Diameter. Rotor diameter is typically the distance from the center of rotation to the tip of the blade multiplied by two. For vertical-axis turbines (the "egg-beater" types), rotor diameter is the widest distance between the blades, representing the maximum distance in the horizontal plane. Rotor diameter varied both between and within turbine types and sometimes within sample sites as well. Rotor diameter ranged from 36 to 71 feet.

Rotor-swept Area. Rotor-swept area is a variable that has received some attention recently as a factor possibly contributing to mortality. It is the area of the circle that is swept by the rotating blades and is calculated by the following formula:

$$\text{Rotor-swept Area (RSA)} = \frac{\pi D^2}{4}$$

where: $\pi = 3.1416$
D = Rotor diameter

Since RSA is derived by multiplying and dividing rotor diameter by a constant, RSA and rotor diameter are highly correlated: one is a function of the other.

Tip Speed. Tip speed is the speed in miles per hour (mph) that the tip of the blade travels when the turbine is producing electricity. We used two estimates of tip speed, average and maximum, because some turbines have a range of tip speeds. For example, turbines at four out of five of our tubular-tower turbine sample sites had two generators that engaged at different wind speeds, each operating at a different tip speed. All other turbines had constant-speed blades. Tip speed varied both between and within turbine types and sometimes within sample sites as well. Maximum tip speeds varied from 89 to 154 mph. Average tip speeds varied from 77 to 152 mph. For vertical-axis turbines we used the speed of the blades at the widest diameter.

Rotor Solidity. Rotor solidity, as we defined it, is a measure of the 3-dimensional obstacle that rotating blades present. It is a function of number of blades, blade velocity, and blade area (depth, width, and length). Rotor solidity was used by Rogers et al. (1976) and McCrary et al. (1983, 1984) to calculate the probability of a bird colliding with a rotating turbine blade. These authors suggested that the probability of a bird striking one of the rotor blades is proportional to the area swept by the blade during the time it takes the bird to pass through the depth of the blade, assuming the bird makes no attempt to avoid the blades. Therefore, the low rotor solidity of some turbine designs may actually allow birds to fly through rotating blades without being struck. Our calculation of rotor solidity is different from that of Rogers et al. (1976) and McCrary et al. (1983, 1984), who did not include blade length in their calculation. We felt this was an important dimension to incorporate.

In our study, rotor solidity varied both between and within turbine types and sometimes within sample sites. We calculated rotor solidity as follows:

Rotor Solidity = NWLDV

where:
N = Number of blades
W = Average blade width
L = Blade Length
D = Average blade depth
V = Maximum blade velocity in rpm

This formula does not account for the fact that some turbines have variable-pitch blades (blades change pitch, or tilt, according to the wind; see Blade Pitch below). Rotor solidity of turbines with variable-pitch blades would vary with the amount of blade surface area facing the wind, which could change the probability of collision.

Turbine Height. We measured turbine height from the bottom of the turbine tower to the top of the hub (rotor assembly). Within some turbine types, height varied from turbine to turbine. For example, guyed-pipe turbine heights are 40 feet, 60 feet, and 80 feet, arranged alternately within rows. In other turbine types, height was the same for all turbines. For all sample turbines, individual heights ranged from 40 to 140 feet. For windwall sites, which had both 60-ft and 140-ft turbines placed side by side, each pair of tall and short turbines was considered one turbine and was classified as a 140-ft turbine.

Turbine Spacing. Turbine spacing is the distance between two adjacent turbines situated in the same row, as measured from the center of each turbine. As with the other variables above, spacing varied between and within turbine types and sometimes within sample sites. Spacing ranged from 68 to 180 feet.

Blade Pitch. There are two blade pitch classifications: fixed and variable. Fixed-pitch machines have blades positioned at a stationary angle to the wind. Variable-pitch machines have a mechanism that adjusts the angle of the blades relative to the wind to maximize and control performance. The proportion of the energy in the wind being used to generate electricity is controlled by the angle of the blades to the wind. A higher angle creates more resistance to the wind, allowing the turbine to operate at a lower wind speed. A lower angle makes it possible for turbines to operate at higher wind speeds. Thus, a variable-pitch blade allows turbines to operate over a wider range of wind speeds.

Approximately half of our sample turbines had variable-pitch blades, including four of the lattice-tower sample sites, one tubular-tower sample site, and two windwall sites. Fixed-pitch blades were found on all guyed-pipe turbines, two other lattice-tower sites, and the other four tubular-tower sites. Since blade pitch does not apply to vertical-axis turbines, they were placed in a third category for the chi-square analysis.

Turbine Yaw. Yaw is the rotation of the rotor assembly on the tower. There are two types of yaw: free yaw or driven yaw. Free-yaw machines freely rotate on the rotor assembly of the tower to track the changing direction of the wind. Driven-yaw machines use a motor to actively position the rotor assembly relative to the wind. Free yaw occurs on most machines in the study area, including all six lattice-tower sites, two windwall sites, all three guyed-pipe sites, and one tubular-tower site. Driven-yaw machines occur on four tubular-tower sample sites. Because this variable does not apply to vertical-axis turbines, they were placed into a separate category for the chi-square analysis.

Rotor Direction Relative to Wind. All turbines were classified as either upwind or downwind. Upwind turbines face into the wind with the blades rotating in front of the tower. Downwind turbines face away from the wind with the blades rotating in back of the tower. Among our sample sites, turbines at all lattice-tower sites except one, both windwall sites, and all three guyed-pipe sites were downwind. Turbines at all five tubular-tower sites were upwind. As with pitch and yaw, this variable does not apply to vertical-axis turbines, so they were placed into a separate category for the chi-square analysis.

Raptor Use. We included raptor use as a measure of bird activity in our sample sites. We hypothesized in our original report that there may be a relationship between raptor use and mortality in a given area. Although our original data did not support this hypothesis, we only examined the relationship between site-wide raptor abundance and mortality and did not examine any site-specific relationships in our original report. In this study, we calculated raptor use for each of our 18 sample sites using our original data. We compared site-specific raptor use to site-specific mortality data. Raptor use was defined as mean number of raptors observed per 10-min scan period for all sampling seasons combined. We included only those raptors seen within the boundaries of the sample site. We included repeat observations, i.e., birds that were observed in more than one 10-min scan period, because we believe this gives a better indication of raptor use of the site.

Turbine Types. In our original analysis of mortality by turbine type, we divided all sample turbines into five categories: lattice-tower, guyed-pipe, tubular-tower, vertical-axis, and windwall. We lumped all lattice-tower turbines except windwalls into one category. Although windwalls are lattice-tower turbines, we felt they deserved to be categorized separately because they occur in an unusual arrangement, i.e., 60-ft and 140-ft turbines are placed side by side. For this present analysis, we have further divided lattice-tower turbines into those with horizontal cross arms, hereafter called lattice/horizontal, and those with diagonal cross arms, hereafter called lattice/diagonal (See Figure 2-1). We did this to correspond with the perching analysis (which we describe in section 2.1.3 below) because the two lattice-tower types provide different opportunities for perching. We now have six turbine-type categories.

Data Analysis

The association of variables with mortality was statistically evaluated using either bivariate tests (chi-square, t-test, one-way ANOVA), or multivariate techniques (multiple logistic or discriminant analysis), or both. We used chi-square tests when data were categorical (e.g., yes/no, upwind/downwind), while t-tests and ANOVAs were used with continuous data. Where appropriate, the Fisher exact test was used instead of the chi-square to correct for the small number of mortalities (Dowdy and Wearden 1983). For the multivariate analysis, we used variables that were either statistically significant or had what we considered to be potential biological relevance; these included some of the variables discussed above as well as several variables from our original study. The "original" variables from our previous study are defined as follows:

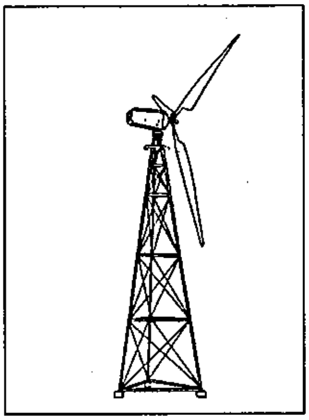
- Elevation — elevation above sea level at the turbine base;
- Number of slopes — the number of steep-sided (> 20°) slopes within 500 feet of a turbine;
- End turbine — whether a turbine is at the end of a row or within a row (this variable is now called position in row);
- Proximity to canyon — whether a turbine is closer to or farther than 500 feet from a canyon;
- Position on slope — top, middle, or bottom; and
- Structure density — the number of structure (turbine or powerline) rows occurring within 500 feet of a turbine, a measure of structure "congestion."

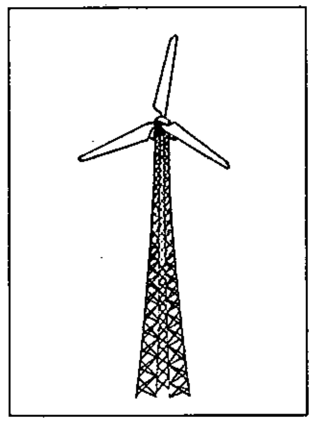
For the multivariate analysis, the dependent variable was presence or absence of raptor mortality at each sample turbine. The independent variables were certain selected new variables as well as the original variables identified above. The multiple logistic model ranks the variables by their relative contribution to the dependent variable, mortality.

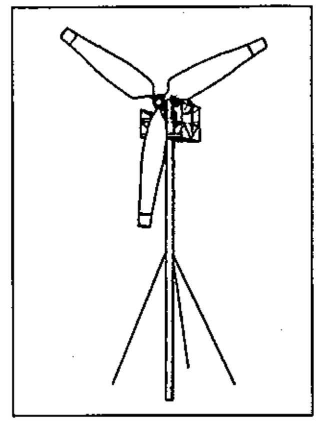
Our criterion for significance of statistical tests was a P value ≤ 0.05. In this exploratory analysis (and in our original report as well) we interpret P values as indications of relationships rather than as strict probability statements. We have used P values as objective measures to prioritize variables that may be affecting mortality, to decide which variables to include in the multivariate analysis, and to suggest which factors we believe deserve further study.

Our analysis of mortality followed the same basic methods used in the original analysis, i.e., we compared characteristics of turbines at which we found dead raptors to characteristics of turbines at which we did not. Our mortality sampling effort was equal among all turbines, whether they killed raptors or not, and we assume (based on scavenging and observer error tests) that other biases were also equal among sample sites.

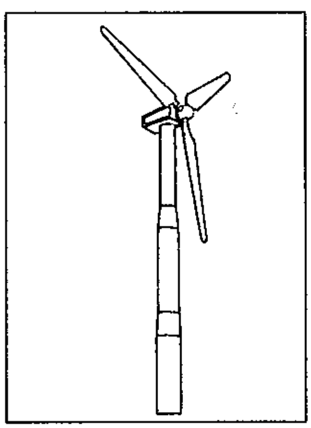
As in our original analysis, our mortality data consisted of only those raptor deaths we were confident were turbine-related. We used only dead birds found within our sample sites and did not include birds found at extra sample end turbines.

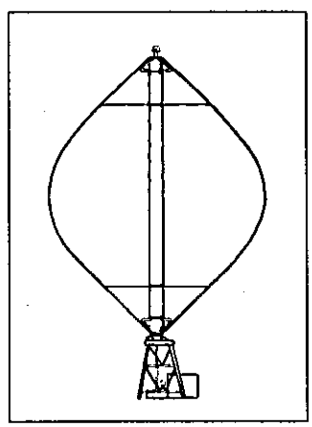


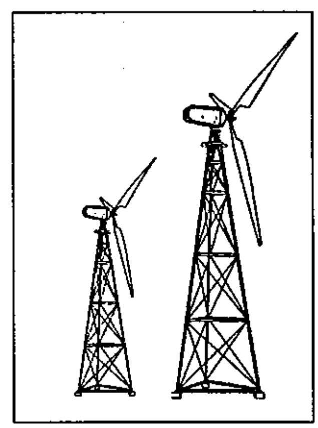




Turbine type:	Lattice/horizontal	Lattice/diagonal	Guyed pipe
Tower height:	60 feet	40-60-80 feet	40-60-80 feet
Rotor diameter:	59 feet	44-56 feet	36 feet
Maximum tip speed:	152 mph	90-104 mph	154 mph
Blade pitch	Variable	Fixed	Fixed
Description:	Downwind, free yaw	Upwind and downwind, free yaw	Downwind, free yaw
Operator:	Kenetech Windpower	SeaWest Energy Group, Zond Systems	Arcadian Renewable Power







Turbine type:	Tubular	Vertical axis	Windwall
Tower height:	60-80 feet	100 feet	60-140 feet
Rotor diameter:	50-71 feet	58 feet	59 feet
Maximum tip speed:	89-137 mph	120 mph	152 mph
Blade pitch	Variable and fixed	NA	Variable
Description:	Upwind, free and driven yaw	NA	Downwind, free yaw
Operator:	Windmaster, LFC Power Systems, Altamont Energy Corp., FloWind	FloWind	Kenetech Windpower

Prepared by BioSystems Analysis, Inc.

Figure 2-1. Six turbine types refered to in text.

2.1.2 End Turbines

Location of Carcasses

We postulated that the location of a dead raptor on the ground at end turbines might help explain why we found mortality to be significantly higher at end turbines in our original analysis. We divided a circular area (radius 100 feet) around the base of each end turbine into four quadrants and identified the quadrant in which each raptor carcass was found (Figure 2-2). Quadrant A was the outside quadrant that faced no other turbines. Quadrants B and C were sides. Quadrant D was inside and faced an adjacent turbine in the same row. We determined the number of carcasses found in each quadrant and applied a chi-square test to those data. Carcasses that were more than 100 feet away or were not distinctly in one quadrant or another were eliminated. We included carcass data from both our original study and the 1994 field survey. We describe the more-recent 1994 field survey in section 2.2 below.

End-turbine Mortality at Different Turbine Types

In our original analysis, which showed that raptor mortality was highly associated with end turbines, we tested end-turbine mortality at all turbine types combined. To determine whether this association was also significant for each turbine type, we analyzed mortality, position in row (end vs. non-end), and turbine type (all of which are categorical variables) using a Mantel-Haenszel chi-square test.

2.1.3 Perching

To evaluate whether perching could affect mortality, we analyzed our perching data in several ways. We determined the frequency of perching at turbines by species, by season, and by turbine type. We also compared the frequency of raptors perched at end turbines with the frequency perched at non-end turbines. This end-turbine analysis included comparisons among the different turbine types. In addition, we compared the number of raptors observed perched at operating turbines with the number observed perched at not-operating turbines.

We used two methods for determining perching frequency. For the first method, we divided the number of observations of birds perched on turbines by the total number of bird observations within a sample site, e.g., the number of American kestrels observed perched on turbines was divided by the total number of American kestrels observed. This method was used for deriving perching frequencies for species, seasons, and turbine types.

We did not incorporate (divide by) number of turbines into the calculation of perching frequency for turbine types. We do not believe that turbines were limiting for perching within our sample sites or that one sample site supported more perching birds simply because it had more turbines. All sample sites consisted of 12 plots that were all of equal size. Therefore, we assume that the number of turbines available did not affect the degree to which raptors perched. If turbines were a limiting factor in the study area, sample sites with more turbines might be expected to support more perching birds. Perching frequency at vertical-axis sites, then, would be expected to be twice that at some of the other sites, given an equal number of perching birds, because they contained half as many turbines per site. Rather, we believe that birds were perching at one site more than another for other reasons, such as turbine "perchability," foraging opportunities, local abundance, or other factors.

The second method of calculation was used for end turbines. The frequency of perching at end turbines was derived by dividing the number of observations in which a raptor was perched at an end turbine with the number of available end turbines within each turbine type; we did the same for non-end turbines. We calculated perching frequencies at end and non-end turbines by turbine type and for all turbine types combined. Perching frequencies at end turbines were then compared with perching frequencies at non-end turbines.

Observation data used in our analysis included only birds observed within our sample sites. In every sample site but one, all turbines were visible from the observation point; we eliminated the one site on which all turbines were not visible from the observation point. We used individual records of birds rather than mean number of birds per 10-min scan. A bird was recorded as being perched if it perched anywhere on the turbine at any time during a 10-min sample scan. Only data on raptors were included in the perching analyses except that we included ravens in the analysis of perching by species. Groups of ravens perched together were considered one bird because ravens often were seen perched in groups and behaved similarly, whereas other raptors were usually observed perched singly. Our analysis was conducted both with and without repeat sightings (individual birds seen in more than one 10-min scan period). Inclusion of repeat sightings gives a better idea of overall bird use of an area, whereas exclusion of repeat sightings provides a better representation of actual numbers of birds in an area. We were also able to derive some measure of relative duration of perching by comparing the two.

For the analysis of perching by turbine type we classified turbines according to structural characteristics that we believed would influence perching frequency. Five turbine classifications were chosen: lattice/horizontal turbines, lattice/diagonal turbines, tubular-tower, vertical-axis, and guyed-pipe turbines. As mentioned above, we separated lattice/horizontal turbines (including windwalls) from lattice/diagonal turbines because we perceived their "perchability" to be different. Lattice/horizontal turbines have horizontal cross arms and may be easier to perch on or more comfortable for perching birds. Lattice/diagonal turbines have diagonal ($\sim 45°$) cross arms and may be harder to perch on or less comfortable for perching birds.

This is a slightly different turbine-type breakdown from the one we used in our mortality analysis, where windwall turbines were placed in a separate category due to their unique arrangement where one row of "regular" 60-ft turbines is placed immediately adjacent to a row of taller 140-ft turbines. For the perching analysis, windwalls were combined with other lattice/horizontal turbines because they are basically of the same design and therefore provide similar perchability. Moreover, we did not record whether perched birds were using the tall or the regular turbines in windwall sample sites, so it was not possible to derive a separate perching frequency for windwall turbines.

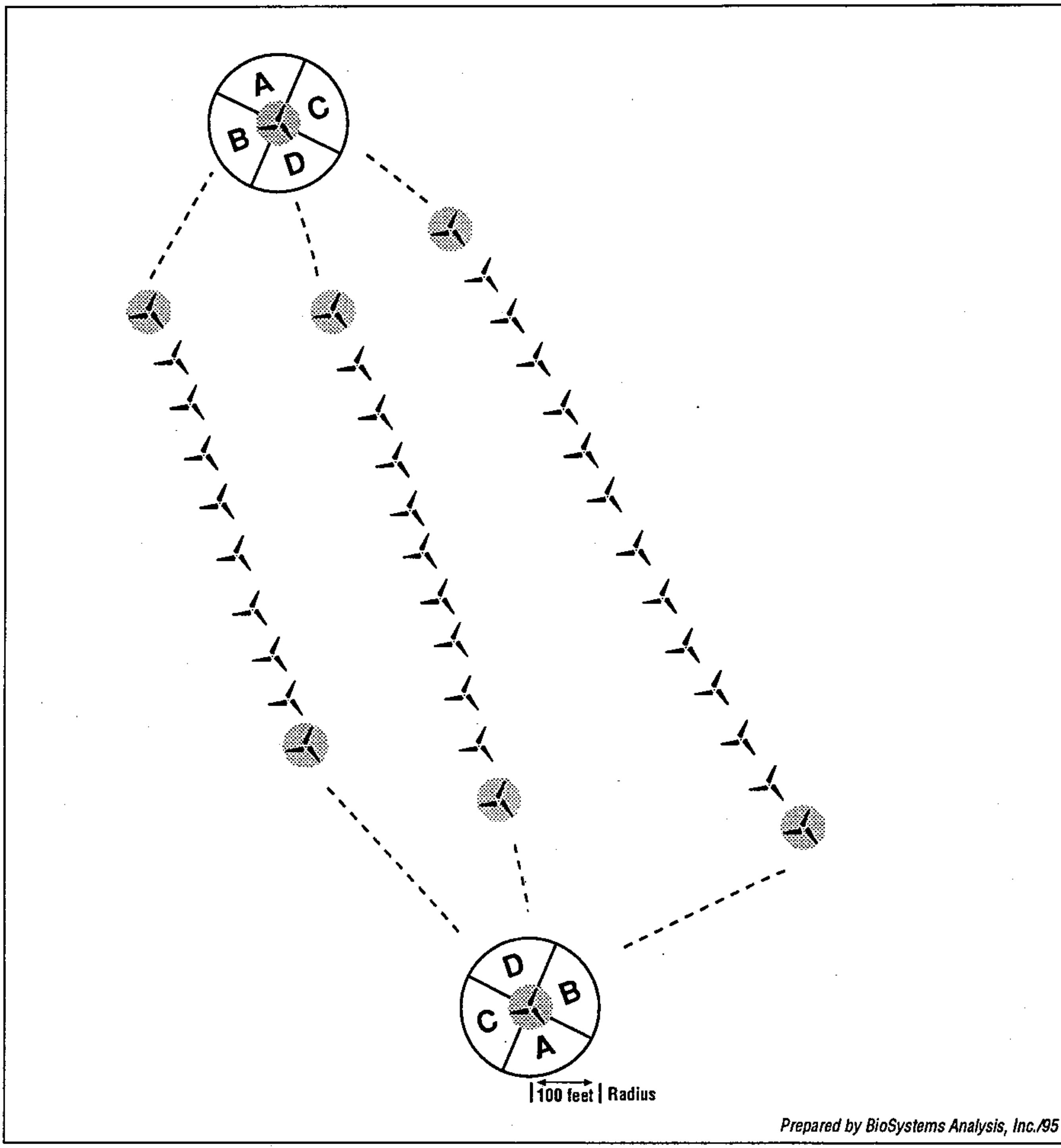
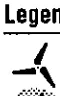


Figure 2-2. Diagram of the four quadrants around the base of end turbines.

Legend



Turbine

End Turbine

A Outside Quadrant

B, C Side Quadrants

D Inside Quadrant

The perching data we used for these analyses differed from the perching data used in our original analysis in two ways. First, for the present analysis we used records of raptors perched at any time within a 10-min scan period. In our original analysis we called a bird perched only if it was perched when first observed. Second, in the present analysis data were limited to on-site observations where all turbines were clearly visible. We consider these changes to provide a more precise representation of perching in our sample sites. We did not apply any statistical tests to perching data because our observations did not meet the test assumptions of independence and exclusivity. Instead, we summarize and tabulate the data for presentation in this report.

2.2 New Mortality Data — Collection and Analysis

We conducted a one-time field survey of our old sample sites in January of 1994 to search for new raptor carcasses. Three years had elapsed since our previous mortality surveys. Our original study showed that the scavenging rate for medium and large raptors was low, so we expected to find carcasses of many birds killed within the last three years. We also gathered data collected by windfarm companies on collision-related mortalities they have documented in the last three years within our sample sites. These new data were collected to test some of our original findings, i.e., the indication that mortality was higher at end turbines and turbines closer to canyons.

Following the same survey methods used in our original study, we searched the ground around our sample turbines. The search area included only a 100-ft radius around each turbine, compared to a 200-ft radius searched during our original study. Our previous data showed that 77 percent of carcasses were found within a 100-ft radius. When a carcass was discovered, we recorded all relevant information using the same data sheets we used in our original study. The U.S. Fish and Wildlife Service performed necropsies on all carcasses in a single blind fashion (no other data except assigned carcass numbers were given to them). We used the necropsy data along with other pertinent factors to attempt to determine cause of death. Only those deaths we were confident were turbine-related were included in this analysis. Some of the turbines included in our original field survey had been subsequently removed, so we eliminated those records from our data set.

We applied statistical tests to the position in row and proximity to canyon variables to determine whether these factors may contribute to mortality. As in our original analysis, we analyzed these variables by comparing turbines at which we found dead raptors to turbines at which we did not. We used mortality data only on those carcasses found within our sample sites and did not include data on carcasses found at the extra sample end turbines.

3.0 Results

3.1 Analysis of Existing Data

3.1.1 Turbine Characteristics and Operation

We began by applying bivariate statistical tests to each of the new variables to determine which were most closely associated with mortality. We then applied a multiple logistic test to variables that were shown to be statistically associated with mortality or those we thought might have some biological relevance whether they were statistically significant or not; these included some of the new variables and several variables from our original, 1992 study. In the multiple logistic analysis, these variables were compared with each other to determine which ones had the strongest competitive multivariate association with mortality (see section called Comparison of Variables - Multivariate Analysis below). Table 3.1 provides a summary of the results.

Table 3.1 Summary of results of bivariate and multivariate statistical tests.

	Bivariate		Multiple logistic[1]
Variable	Test Type	P Value	P Value
Position in Row [2,3]	χ^2	<0.001	<0.001
Proximity to Canyon [2,3]	χ^2	0.002	0.002
Elevation [2,3]	t-test	0.006	0.057
Number of Slopes [2,3]	χ^2	0.003	0.207
Position on Slope [2,3]	χ^2	0.116	0.053
Structure Density [2,3]	t-test	0.005	0.376
Percent Time in Operation			
Conservative	t-test	0.002	0.965
Liberal	t-test	0.024	—
Rotor Diameter	t-test	0.002	—
Rotor-swept Area	t-test	0.002	0.079
Tip Speed			
Maximum	t-test	0.283	0.264
Average	t-test	0.302	—
Rotor Solidity	t-test	0.188	—
Turbine Height	t-test	0.489	—
Turbine Spacing	t-test	0.742	—
Blade Pitch	χ^2	0.009	0.156
Turbine Yaw	χ^2	0.754	—
Rotor Direction Relative to Wind	χ^2	0.919	—
Raptor Use	t-test	0.089	0.361

Table 3.1 Summary of results of bivariate and multivariate statistical tests (cont.).

Variable	Bivariate Test Type	Bivariate P-Value	Multiple logistic P-Value
Turbine Type			
Lattice/horizontal	χ^2	0.001	0.110
Lattice/diagonal	χ^2	0.595	—
Windwall	Fisher exact	0.556	—
Guyed-pipe	χ^2	0.015	—
Tubular-tower	χ^2	0.646	—
Vertical-axis	χ^2	0.689	—

[1] Multiple logistic was used for the multivariate analysis to obtain P values (See Methods section 2.1.1)
[2] Bivariate test results for these variables were taken from our original study (Orloff and Flannery 1992). Only those original variables that were either statistically significant or that we thought might have some biological significance were included.
[3] Definitions:
Position in row — whether a turbine is at the end of a row or within a row;
Proximity to canyon — whether a turbine is closer to or farther than 500 feet from a canyon;
First turbine row in area — whether a row has other turbine rows within ½ mile or not;
Elevation — elevation at the base of turbines;
Number of slopes — the number of steep-sided (> 20 degree) slopes within 500 feet of a turbine;
Position on slope — top, middle, or bottom;
Structure distance — minimum distance to next closest turbine row; and
Structure density — the number of structure (turbine or powerline) rows occurring within 500 feet of a turbine, a measure of structure "congestion."

Bivariate Analyses

Percent Time in Operation. Percent time in operation is an estimate of the amount of time turbines were operating in a given period. The estimate was based on wind speeds and operation capabilities of the turbines (cut-in speeds and downtime). T-tests indicated that both conservative and liberal estimates of percent time in operation were significantly associated with mortality (conservative $P<0.01$; liberal $P=0.02$). Turbines that killed raptors were located at sites that had a higher average percent of time in operation than turbines that did not kill raptors. The conservative mean percent time in operation for turbines that killed raptors was 39.7 (SD=11.2, n=53); for turbines that did not kill raptors, it was 34.5 (SD=12, n=971). The liberal mean percent time in operation for turbines that killed raptors was 43.9 (SD=11.8, n=53); for those that did not kill raptors, it was 39.8 (SD=12.8, n=971).

When we used a two-way ANOVA to compare percent time in operation and mortality by turbine type, the association was no longer statistically significant using either liberal or conservative estimates. That is, when we separated turbine types, percent time in operation was not significantly different between turbines that killed raptors and turbines that did not. Table 3.2 shows the mean values of the conservative estimates of percent time in operation by turbine type. We show the conservative means because they are more strongly associated with mortality.

Table 3.2 Results of two-way ANOVA comparing the conservative estimate of the percent of time turbines were operating and turbine type.

Turbine Type	Mean Percent TIO** Turbines That Did Not Kill Raptors	Mean Percent TIO Turbines That Killed Raptors
Lattice/horizontal Turbines	41.0 (*n*=304)	42.1 (*n*=28)
Lattice/diagonal Turbines	36.9 (*n*=135)	46.9 (*n*=6)
Tubular-tower Turbines	34.1 (*n*=209)	35.7 (*n*=10)
Guyed-pipe Turbines	20.3 (*n*=209)	19.6 (*n*=4)
Windwall Turbines	45.2 (*n*=45)	45.2 (*n*=2)
Vertical-axis Turbines	38.9 (*n*=69)	38.9 (*n*=3)
	F=1.259	P=0.262

** TIO=Time in Operation

When we ranked turbine types by the percent of time they operated using the conservative estimates, windwall turbines operated the most, followed by lattice/horizontal, vertical-axis, lattice/diagonal, tubular, and guyed-pipe turbines. When we ranked turbine types using the liberal estimates, tubular turbines operated the most, followed by lattice/diagonal, windwall, lattice/horizontal, vertical-axis, and guyed-pipe turbines. Both tubular and lattice/diagonal turbines operated much more frequently according to the liberal estimate: tubular turbines go from fifth to first place, and lattice/diagonal turbines go from fourth to second position. Percent time in operation increased greatly for those turbine types that have a large difference between the low-end cut-out speed used to calculate the liberal estimate and the cut-in speed used to calculate the conservative estimate (see Variables in section 2.1.1).

Guyed-pipe turbines operated roughly half as often as any other turbine type. Consequently, the low mortality rate at guyed-pipe turbines may be more a function of low operating time than of any other turbine-specific characteristic. Combining data from guyed-pipe turbines with data from all other turbine types may have produced an unwarranted effect on the association of other variables with mortality: it may have masked the effect of a variable on mortality or may have shown an effect where there actually was none. For example, if the value of a particular variable were equal at both guyed-pipe turbines and another turbine type, but mortality rates at those turbine types were opposite, statistical tests might fail to show a significant relationship between that variable and mortality. But if the mortality rate at guyed-pipe turbines were low because they seldom operated, a truly causal relationship might be missed.

We attempted to compensate for the possible unjustified effect of guyed-pipe operating time on variables in two ways. First, we adjusted for the effect of turbine type by using a two-way ANOVA whenever that was an appropriate test to apply (see section 4.4 Study Limitations and Qualifications). Second, we applied bivariate tests to all variables excluding guyed-pipe data (see discussion of this under Bivariate Analyses Excluding Guyed-pipe Turbines below). We feel that the elimination of guyed-pipe turbine data from the analysis may equalize the effect of the low operating time and more accurately represent the association of mortality with other variables.

Rotor Diameter and Rotor-swept Area. Results of t-tests showed that rotor diameter and rotor-swept area were both significantly associated with mortality ($P<0.01$). Turbines that killed raptors had a larger average rotor diameter (56.4 ft, SD=7.1, n=53) than those that did not kill raptors (52.2 ft, SD=9.8, n=971). Turbines that killed raptors had a larger rotor-swept area (2,539 ft^2, SD=571, n=53) than those that did not kill raptors (2,211 ft^2, SD=760, n=971). We discuss these variables again under Bivariate Analyses Excluding Guyed-pipe Turbines below.

Tip Speed. Tip speed is the speed in miles per hour that the tip of the blade is traveling when the turbine is producing electricity. We used both average and maximum estimates. In a t-test, neither average nor maximum tip speed was significantly associated with mortality (Table 3.1). There was no significant difference between the mean tip speeds (mph) for turbines that killed raptors (average 132.8 mph, SD=29.1, n=53; maximum 135 mph, SD=24.9, n=53) and those that did not (average 128.3 mph, SD=31.4, n=971; maximum 130.9 mph, SD=27.2, n=971). We discuss this variable again under Bivariate Analyses Excluding Guyed-pipe Turbines below.

Rotor Solidity. Rotor solidity has been used as a measure of the 3-dimensional obstacle presented by rotating blades, and incorporates the volume and speed of the blades. Rotor solidity was not significantly associated with mortality (Table 3.1). No significant difference (t-test) in rotor solidity was shown between turbines that killed raptors (9891.9, SD=3416.3, n=53) and those that did not (9163.6, SD=3939.9, n=971).

Turbine Height. Turbine height was measured from the bottom of the turbine tower to the top of the hub. Turbine height was not associated (t-test) with mortality in our analysis (Table 3.1). The mean height of turbines that killed raptors was not significantly different (69.1 ft, SD=19.8 SD, n=53) from the height of turbines that did not (71.1 ft, SD=20.9, n=971).

Turbine Spacing. We defined turbine spacing as the distance between two turbines in a row. This variable did not significantly differ (t-test) between turbines that killed raptors (96.2 ft, SD=29.9, n=53) and those that did not (97.6 ft, SD=30.7, n=971) (Table 3.1).

Blade Pitch. Turbine blades can either be fixed (at a stationary angle) or variable (angle adjusts to the wind). Because the blade pitch on vertical-axis turbines was neither fixed nor variable, we placed these turbines in a separate category. Table 3.3 shows the results of a chi-square test demonstrating that the difference between these three categories was significant ($P<0.01$). Raptor mortality was highest (7.8%) at turbines with variable-pitch blades and lowest (3.3%) at turbines with fixed-pitch blades. We discuss this variable again under Bivariate Analyses Excluding Guyed-pipe Turbines below.

Table 3.3 Results of chi-square test comparing blade pitch of turbines that killed raptors to blade pitch of turbines that did not.

	Blade Pitch			
Killed Raptor	**Fixed**	**Variable**	**Neither****	**Total**
No	521 (96.7%)	381 (92.3%)	69 (95.8%)	971
Yes	18 (3.3%)	32 (7.8%)	3 (4.2%)	53
Total	539	413	72	1,024
		$\chi^2=9.421$	$P=0.009$	

** Vertical-axis turbines were neither fixed nor variable.

Turbine Yaw. To position the blades relative to the wind, the rotor assembly can have either free yaw (the rotor assembly freely rotates to track the wind) or driven yaw (the rotor assembly is driven by a motor). We placed vertical-axis turbines, which have neither free nor driven yaw, into a separate group. There was no significant difference between the mortality rates by yaw category (Table 3.4).

Table 3.4 Results of chi-square test comparing yaw of turbines that killed raptors to yaw of turbines that did not.

	Yaw			
Killed Raptor	**Free**	**Driven**	**Neither****	**Total**
No	725 (94.5%)	177 (95.7%)	69 (95.8%)	971
Yes	42 (5.5%)	8 (4.3%)	3 (4.2%)	53
Total	767	185	72	1,024
		$\chi^2=0.563$	$P=0.754$	

** Yaw on vertical-axis turbines was neither free nor driven.

Rotor Direction Relative to Wind. Turbines can be upwind (blades face into the wind), downwind (blades face away from the wind), or neither (vertical-axis turbines). There was no significant difference in the mortality rates by rotor direction (Table 3.5).

Table 3.5 Results of chi-square test comparing rotor direction relative to wind of turbines that killed raptors to that of turbines that did not.

	Rotor Direction			
Killed Raptor	**Upwind**	**Downwind**	**Neither****	**Total**
No	276 (94.8%)	626 (94.7%)	69 (95.8%)	971
Yes	15 (5.2%)	35 (5.3%)	3 (4.2%)	53
Total	291	661	72	1,024
		$\chi^2=0.169$	$P=0.919$	

** Vertical-axis turbines were neither upwind nor downwind.

Raptor Use. Raptor use was defined as the mean number of raptors observed per 10-min scan period within each of our 18 sample sites. There was no significant difference in raptor use at turbines that killed raptors (1.15, SD=0.34, n=53) and those that did not (1.09, SD=0.26, n=971). Raptor use was also not significantly associated with mortality when we adjusted for the effect of turbine type in a two-way ANOVA. That is, when we separated turbine types, raptor use was not significantly different between turbines that killed raptors and turbines that did not.

One reason that raptor use may not be associated with mortality is that raptor abundance did not vary much between the different sample sites, as indicated in our original analysis (Orloff and Flannery 1992). Other studies have indicated that raptor abundance is associated with level of mortality (Orloff 1992; Dick Anderson pers. comm.).

Turbine Type. A chi-square test of mortality by turbine type was significant ($P<0.03$; Table 3.6). Detailed comparisons (not shown in Table 3.6) showed that mortality at lattice/horizontal turbines was significantly higher (8.4%) than at all other turbine types combined (3.6%, $P<0.01$) and that mortality at guyed-pipe turbines was significantly lower (1.9%) than at all other turbine types combined (6%, $P=0.01$). Mortality rates at the other four turbine types (lattice/diagonal, windwall, tubular, and vertical-axis) ranged from 4.2 to 4.6 percent. To correct for the small number of mortalities in some cells, we used the Fisher exact test where necessary.

Table 3.6 Results of chi-square test comparing the number of turbines that killed raptors to the number that did not, by turbine type.

Turbine Type	Killed Raptor: Yes	Killed Raptor: No	Number of Turbines
Lattice/horizontal[1]	28 (8.4%)	304 (91.6%)	332
Lattice/diagonal	6 (4.3%)	135 (95.7%)	141
Windwall	2 (4.3%)	45 (95.7%)	47
Guyed-pipe[2]	4 (1.9%)	209 (98.1%)	213
Tubular-tower	10 (4.6%)	209 (95.4%)	219
Vertical-axis	3 (4.2%)	69 (95.8%)	72
Total Number of Turbines			1,024
		$\chi^2=12.54$	$P=0.028$

[1] Detailed comparisons showed that mortality was significantly higher at lattice/horizontal turbines than at all other types combined (see Table 3.1).
[2] Detailed comparisons showed that mortality was significantly lower at guyed-pipe turbines than at all other types combined (see Table 3.1).

Mortality at windwall turbines (comprising side-to-side lattice/horizontal turbines) was lower than at non-windwall lattice/horizontal turbines and similar to mortality at the lattice/diagonal turbines. Because of the arrangement of turbines at windwall sites, we considered each pair of 60-ft and 140-ft turbines to be one single turbine. If we had counted each turbine individually instead of considering each pair to be one turbine, the number of turbines would have doubled and the mortality rate per turbine would have halved. Consequently, our calculated mortality rate for windwall sites may be overstated.

Table 3.7 compares mortality rates between lattice/horizontal turbines and all other turbine types combined (also referred to below as non-lattice/horizontal turbines) for the two variables we showed in our original report to be most strongly associated with mortality: position in row (end vs. non-end) and proximity to canyon (more than or less than 500 feet from a canyon). This analysis shows that lattice/horizontal turbines, end turbines, and turbines close to a canyon act separately on mortality, but the combined effect of two or more is multiplicative. Table 3.7 shows how mortality changes when any one of the three factors is held constant. Overall, the lowest mortality (2.2%) occurs when the turbines are not lattice/horizontal, not at ends of rows, and not close to a canyon. The highest mortality (30.8%) occurs when all three are present.

The mortality rate at non-lattice/horizontal turbines increased almost eight-fold, from 2.2 percent to 16.8 percent, when a turbine was both an end turbine and close to a canyon (Table 3.7). When lattice/horizontal turbines were both end turbines and close to a canyon, mortality increased almost six-fold, from 5.5 percent to 30.8 percent. These results are similar to what we found in our original analysis, in which we compared all lattice turbines (lattice/horizontal and lattice/diagonal combined) to all non-lattice.

Table 3.7 Results of chi-square test of raptor mortality by turbine type, position in row, and proximity to canyon.

	End of Row				
	Lattice/horizontal Turbines		All Other Turbine Types		
Close to Canyon**	Not End	End	Not End	End	Total
No	11/201 (5.5%)	4/26 (15.4%)	9/416 (2.2%)	3/74 (4.1%)	27/717 (3.8%)
Yes	9/92 (9.8%)	4/13 (30.8%)	8/172 (4.7%)	5/30 (16.7%)	26/307 (8.5%)
Total	20/293 (6.8%)	8/39 (20.5%)	17/588 (2.9%)	8/104 (7.7%)	53/1024 (5.2%)
			χ^2=9.69	P<0.003	

** A turbine is close to a canyon if it is within 500 feet of one.

Bivariate Analyses Excluding Guyed-pipe Turbines

As stated above, we believe that, because guyed-pipe turbines operated considerably less than any other turbine type, the low mortality rate at these turbines may have been more a function of low operating time than of any specific turbine characteristic. Consequently, data from guyed-pipe turbines may have produced an undue effect on the bivariate association of other variables with mortality. To compensate for this possible effect, we applied the same bivariate tests to all the above variables (except percent time in operation) after eliminating data from guyed-pipe turbines. Of the variables that were previously associated with mortality (see Table 3.1 for P values of tests *with* guyed-pipe data), rotor diameter (new P=0.06), rotor-swept area (new P=0.08), and blade pitch (new P=0.09) all lost their significant association. Of the variables that were not significantly associated with mortality when guyed-pipe data were included, tip speed was the only one that became significant (new P=0.03). Consequently, tip speed may indeed contribute to mortality.

Comparison of Variables — Multivariate Analysis

Only two of the new and original variables used in the multiple logistic analysis were significantly associated with raptor mortality: position in row (end vs. non-end) and proximity to canyon (Table 3.1). These two, with elevation, were significantly associated with mortality in our original analysis. As can be seen in Table 3.1, elevation was nearly significant (P<0.06) in this analysis. In our original analysis, structure density was nearly significant (P<0.07), but in this analysis it was not even close to significant (P<0.38). This is likely due to the association of structure density with the added variables.

The multivariate analysis puts all variables "in competition" with each other in predicting mortality. In some instances, one variable that is statistically significant in a bivariate test may be out-competed in predicting mortality by another variable that is also statistically significant in a bivariate test. This is particularly true when variables show a high degree of association with each other (see Appendix Table A.1 for correlations). Several variables that were significant in bivariate tests dropped out of significance in the multiple logistic analysis. For example, percent time in operation was significantly associated with mortality in a bivariate test but not in the multivariate test. This may be because it was highly correlated with other variables, including elevation and structure density. As in our original analysis, position in row and proximity to canyon were strongly associated with mortality and were not highly correlated with any of the original and new variables; thus, they remained significant in the multivariate analysis.

We used discriminant analysis to present a conservative and simple summary of our data. Both the discriminant and multiple logistic analyses yielded the same rank order of explanatory variable contributions. Discriminant analysis correctly classified 66 percent of the turbines that killed raptors and 70 percent that did not (Table 3.8). Although the discriminant analysis is predictive in a statistical sense, i.e., its predictive power is better than flipping a coin, it is not predictive in a practical sense because an excessive number of its predictions were wrong. For example, Table 3.8 shows that of the 324 turbines that the analysis predicted would kill raptors, 289 did not.

Table 3.8 Multivariate discriminant analysis model predictions for turbines that killed raptors and turbines that did not kill raptors.

Known Group		Predicted Group		Percent Correct
		Would Not Kill	Would Kill	
Turbines that did not kill raptors:	971	682	289	70.24
Turbines that killed raptors:	53	18	35	66.04
Total:	1,024	700	324	70.02

3.1.2 End Turbines

Location of Carcasses

We divided the area around the base of end turbines into four equal quadrants (Figure 2-2). Of 27 raptor carcasses found at end turbines, we found 13 (48%) within Quadrant A, 11 (41%) within Quadrants B and C, and 3 (11%) within Quadrant D. A chi-square test showed that this distribution was significantly different from an uniform distribution (Table 3.9; $P<0.02$); more raptor carcasses were found in the outside quadrant of end turbines.

Table 3.9 Results of chi-square test comparing location of bird carcasses at end turbines.

	Location of Carcass	
Turbine Quadrant**	**Observed**	**Expected**
Outside (A)	13	6.75
Sides (B,C)	11	13.50
Inside (D)	3	6.75
Total	27	27
	$\chi^2=8.33$	$P=0.015$

** See Figure 2-2.

End-turbine Mortality by Turbine Type

A Mantel-Haenszel chi-square test showed that end turbines were significantly associated with mortality within turbine types ($\chi^2=13.489$, $P<0.001$; Table 3.10). Mortality at end turbines was highest at lattice/horizontal turbines followed by lattice/diagonal, tubular, vertical-axis, guyed-pipe, and windwall turbine types. Mortality was two to four times higher at end turbines than at non-end turbines within all turbine types except windwall, where the numbers were too small to make a meaningful comparison.

Table 3.10 Summary table of mortality at end turbines and non-end turbines by turbine type.

	Percent Mortality	
Turbine Type	**End Turbines**	**Non-end Turbines**
Lattice/horizontal Turbines	20.5 (8/39)	6.8 (20/293)
Lattice/diagonal Turbines	12.4 (2/13)	3.1 (4/128)
Tubular-tower Turbines	9.5 (4/42)	3.4 (6/177)
Vertical-axis Turbines	6.7 (1/15)	3.5 (2/57)
Guyed-pipe Turbines	3.6 (1/28)	1.6 (3/185)
Windwall Turbines	0.0 (0/6)	4.9 (2/41)

3.1.3 Perching

Perching Differences by Species

Table 3.11 presents the frequency of perching on turbines for those species that were observed perched within our sample sites. Our analysis shows that perching was more common among prairie falcons (*Falco mexicanus*), American kestrels, common ravens, and red-tailed hawks than among turkey vultures, ferruginous hawks (*Buteo regalis*), and golden eagles. Of birds observed within our sample sites, 42 percent of prairie falcons, 32 percent of American kestrels, 23 percent of common ravens, and 16 percent of red-tailed hawks were perched on turbines. Turkey vultures, ferruginous hawks, and golden eagles rarely perched on turbines (<1% to 4%). Northern harriers (*Circus cyaneus*) and rough-legged hawks (*Buteo lagopus*) were never observed perched on turbines. These data are from all seasons combined and all turbine types combined. The data also include repeat observations (multiple observations of the same bird in different scan periods) to reflect overall use of the area (see section 2.1.3). Comparing perching frequencies using repeat observations to those excluding repeat observations indicated that red-tailed hawks and common ravens perched on turbines for longer periods of time than other raptor species.

Table 3.11 Perching frequency by species, including repeat observations.

Species	Number Perched[1]	Number Observed[2]	Percent Perched[3]
American kestrel	58	184	32
Ferruginous hawk	2	103	2
Golden eagle	8	204	4
Prairie falcon	11	26	42
Red-tailed hawk	105	664	16
Turkey vulture	2	535	<1
Common raven	149	657	23

[1] Number of individuals observed perched on turbines within our sample sites.
[2] Total number of individuals observed within our sample sites (perched and not perched).
[3] Number perched divided by the total number observed.

Perching Differences by Season

Table 3.12 presents the seasonal summary of the frequency of raptor-perching on turbines within our sample sites. Perching frequency was highest in the fall, moderate in spring and winter, and lowest in summer when we included repeat observations and combined all raptor species and all turbine types. When we compared this to results excluding repeat observations, perching frequencies were similar, except in the fall when raptors appeared to perch on turbines for longer periods. Our original observation data were collected during one spring, one summer, and two winters and falls, but only data from the first year were used in this analysis.

Table 3.12 Frequency of raptor-perching on turbines by season, including repeat observations.

Season	Number Perched[1]	Number Observed[2]	Percent Perched[3]
Spring	48	493	10
Summer	4	301	1
Fall	65	348	19
Winter	18	230	8

[1] Number of individuals observed perched on turbines within our sample sites.
[2] Total number of individuals observed within our sample sites (perched and not perched).
[3] Number perched divided by total number observed.

Perching Differences Among Turbine Types

Table 3.13 shows the distribution of perching frequencies among turbine types. Perching frequency was highest within lattice/horizontal turbines (including windwall), followed closely by lattice/diagonal, guyed-pipe, and vertical-axis turbines. Perching on tubular turbine types was considerably lower. Again, we included repeat observations and combined all raptor species and all seasons. When we excluded repeat observations, perching was still highest at both lattice types, and was lowest at tubular turbines. Perching frequency was slightly lower at lattice/horizontal and vertical-axis turbines when repeat observations were excluded, suggesting that raptors may remain perched for longer periods at these turbine types than at others.

Table 3.13 Frequency of raptor perching by turbine type, including repeat observations.

Turbine Type	Number Perched[1]	Number Observed[2]	Percent Perched[3]
Lattice/horizontal Turbines[4]	90	659	13.7
Lattice/diagonal Turbines	13	105	12.4
Guyed-pipe Turbines	44	380	11.6
Vertical-axis Turbines	29	262	11.1
Tubular-tower Turbines	20	490	4.1

[1] Number of individuals observed perched on turbines within our sample sites.
[2] Total number of individuals observed within our sample sites (perched and not perched).
[3] Number perched divided by the total number observed (see section 2.1.3).
[4] Includes windwall turbines.

Perching at End Turbines

For all turbine types combined, perching frequency at end turbines was higher (16%) than at non-end turbines (11%; Table 3.14). When we calculated perching frequency for different turbine types, perching frequency was higher at end than at non-end turbines for three of the four turbine types: vertical-axis, lattice (all lattice types combined), and tubular. At guyed-pipe turbines, perching frequency was slightly higher at non-end turbines.

Table 3.14 combines all raptor species and all seasons and includes repeat observations. The difference in perching frequency at end and non-end turbines was similar both with and without repeat observations, *except* at vertical-axis turbines. At vertical-axis turbines, when repeat observations were included the difference in perching frequency at end and non-end turbines was striking. This difference markedly decreased when we excluded repeat observations, suggesting that some raptors may be perching for longer periods at vertical-axis turbines.

Table 3.14 Perching frequency at end and non-end turbines, including repeat observations.

	Percent Perched	
Turbine Type	**End Turbines**[1]	**Non-end Turbines**[2]
Lattice Turbines[3]	18.0 (18/100)	12.0 (65/540)
Tubular-tower Turbines	8.5 (6/71)	5.0 (10/199)
Vertical-axis Turbines	50.0 (9/18)	10.7 (6/56)
Guyed-pipe Turbines	10.2 (5/49)	11.8 (26/221)
All Turbine Types Combined	15.9 (38/238)	10.5 (107/1016)

[1] Number of individuals observed perched at end turbines divided by the number of end turbines within our sample sites.
[2] Number of individuals observed perched at non-end turbines divided by the number of non-end turbines within our sample sites.
[3] Due to small sample size (number of ends), this includes all lattice/horizontal, windwall, and lattice/diagonal turbines.

Perching at Operating Turbines

Out of 187 records of raptors perched on turbines, only one was of a bird perched on an operating turbine. It was a red-tailed hawk perched on an operating windwall end turbine in January. This indicates that although raptors will perch on operating turbines, it appears to be a relatively rare event.

3.2 New Mortality Data

During our one-time follow-up field survey, we found a total of 20 bird carcasses, 15 of which were raptors: 11 red-tailed hawks, two American kestrels, one great-horned owl, and one barn owl. Non-raptors included two ducks, two rock doves, and one raven. Of the 15 raptors, we believe 13 were killed by collision with turbines. U.S. Fish and Wildlife Service necropsy results were used in our determination of cause of death. We only used data from turbine-related raptor mortalities that were within our sample sites in the analysis. This limited the data to 10 mortalities because three were not found within sample sites. We did not use mortality data collected by the windfarm companies because we were not confident of the cause of death and only one company submitted data.

The number of carcasses we found was relatively low. We believe this was probably due to vegetation density that obscured the discovery of older mortalities. Most carcasses we found appeared to be less than six months old. To correct for the small number of mortalities in some cells, we used the Fisher exact test.

3.2.1 Mortality at End Turbines

Using our new mortality data, end turbines were associated with a significantly higher raptor mortality rate (4%) than non-end turbines (0.6%; Table 3.15). In other words, mortality was more than six times as high at end turbines as at non-end turbines ($P<0.01$).

Table 3.15 Results of Fisher exact test comparing end and non-end turbines that killed raptors to those that did not.

	End Turbine		
Killed Raptor	**No**	**Yes**	**Total**
No	725 (99.5%)	144 (96%)	869
Yes	4 (0.6%)	6 (4.0%)	10
Total	729	150	879**
	P=0.003		

** This is less than the number of turbines in our original study because some of the turbines in our sample sites had been physically removed.

3.2.2 Proximity to Canyons

As in our original study, we defined a canyon as a narrow valley with relatively steep sides, such as a drainage, ravine, or draw, that provides updrafts or corridors for bird movements. Table 3.16 shows that in an analysis using proximity to a canyon as a discrete (i.e., yes/no) variable, raptor mortality was higher (2.2%) at turbines within 500 feet of a canyon than at turbines farther than 500 feet from canyons (0.7%). Although mortality was three times as high at turbines close to canyons, the difference was not quite statistically significant using the Fisher exact test (P=0.054). Using it as a continuous variable (i.e., actual distance in feet), a t-test showed that proximity to a canyon was significantly associated with mortality (P<0.05); turbines that killed raptors were an average of 673 feet (SD=864, n=10) from canyons; turbines that did not kill raptors were an average of 1310 feet (SD=1233, n=869) from a canyon.

Table 3.16 Results of a Fisher exact test comparing proximity to a canyon for turbines that killed raptors and those that did not.

	Close to Canyon[1]		
Killed Raptor	**No**	**Yes**	**Total**
No	603 (99.3%)	266 (97.8%)	869
Yes	4 (0.7%)	6 (2.2%)	10
Total	607	272	879[2]
	P=0.054		

[1] A turbine is close to a canyon if it is within 500 feet of one.
[2] This is less than the number of turbines in our original study because some of the turbines within our sample sites had been physically removed.

4.0 Discussion

Below, we offer possible explanations for what we observed in our data and analysis. We make no claim, however, to understand all the associations and contradictions, nor do we claim that we have considered all contributing factors, or that the significant relationships we present are actually causal. We interpret *P* values as indications of relationships rather than as strict probability statements. Our intent with the following discussion is to stimulate the flow of ideas. Moreover, we believe that many of the results we present, especially those where we found statistically significant relationships with mortality, should be further studied.

4.1 Variables Affecting Mortality

4.1.1 Percent Time in Operation

Our analysis suggests that turbines that operate more frequently may have more "opportunity" to kill birds. There are several inconsistencies in the data, however, that may minimize the importance of percent time in operation as a dominant factor in mortality. First, although percent time in operation appeared to be an important factor in mortality when all turbine types were combined, the association was lost when we separated the effect by turbine type. This suggests that percent time in operation may have been significantly associated with mortality primarily because of differences between turbine types. Second, windwall turbines operated the most frequently according to the conservative estimate, but had one of the lowest observed mortality rates. We speculate in section 4.2.3 that differential perching opportunities at windwall turbines may diminish the effect of percent time in operation. We believe, therefore, that percent time in operation is only one of several possible factors contributing to mortality.

Percent time in operation is a function of the wind speed at a particular site as well as of turbine design and operation characteristics (i.e., cut-in speeds and downtime). If percent time in operation is related to mortality, it may be because one or more of the following is true at a particular site: 1) consistently higher wind speeds, 2) lower cut-in speeds, or 3) less downtime. For example, given the same average wind speed, turbines that have lower cut-in speeds or spend less time "down" may pose a greater danger to birds because they operate more frequently.

Percent time in operation was highly positively correlated with elevation, suggesting that wind speeds may be higher at higher elevations. In our original study, we found a significant positive association between mortality and elevation. We questioned the biological significance of that association at the time, but the correlation between percent time in operation and elevation provides a missing element that makes that association more plausible.

Percent time in operation was also highly negatively correlated with structure density (the number of rows of turbines or transmission lines within 500 feet of a turbine). In other words, turbines operated more frequently when structure density was lower. This may partly be due to attenuation of wind associated with dense arrays of turbines. Attenuation of wind might, in turn, help explain why structure density was significantly negatively associated with mortality in our original analysis.

At present there is no mechanism to directly record the percent of time turbines operate; we can only derive estimates from indirect measures such as wind speed. Perhaps windfarm operators could be encouraged to devise a suitable, cost-effective method for recording the percent of time each turbine operates. This would greatly enhance our ability to assess the significance of this variable on raptor mortality.

4.1.2 Rotor Diameter and Rotor-swept Area

Rotor-swept area is a function of rotor diameter and has been considered by many biologists to be a potentially important factor in mortality (Dick Anderson pers. comm.). Both rotor diameter and rotor-swept area were significantly associated with mortality when all turbine types were combined (including guyed-pipe turbines). However, when guyed-pipe data were not included, neither variable was associated with mortality. This calls into question the importance of rotor diameter and rotor-swept area as contributors to mortality. The idea that larger rotor-swept area may contribute to higher mortality was also tested in a study in the Altamont Pass (Howell 1995); data from that study did not support the idea.

At the time of our original study, the largest rotor diameter of any of our sample turbines, 59 ft, was found on lattice/horizontal turbines. Today, there is a new generation of larger machines that have much larger rotor diameters (e.g., 110-170 ft) and correspondingly larger rotor-swept areas. The advantages or disadvantages of these new-generation machines relative to avian mortality are not known at this time.

Because rotor diameter and rotor-swept area are so highly correlated, we refer only to rotor diameter through the remainder of this discussion.

4.1.3 Tip Speed

When all turbine types were combined, tip speed was not significantly associated with mortality ($P=0.28$); however, when we eliminated data from guyed-pipe turbines the association became significant ($P=0.03$). As we explained in section 3.1.1 Bivariate Analyses Excluding Guyed-pipe Turbines, we feel that inclusion of data from guyed-pipe turbines may have masked (i.e., statistically diluted) potentially important relationships. Tip speed may have failed to show significance when all turbine types were combined because the two turbine types that had the highest tip speeds (lattice/horizontal and guyed-pipe turbines) had opposite mortality rates, i.e., one was highest and one was lowest. The high tip speed of guyed-pipe turbines may be of minimal importance in mortality if the turbines seldom operate. We feel that excluding data from guyed-pipe turbines more accurately reflects the relationship between tip speed and mortality at the other turbine types.

4.1.4 Blade Pitch

Turbines with variable-pitch blades were associated with higher mortality than those with fixed-pitch blades when all turbine types were combined. We questioned this relationship, however, for the following reason. The significant association with mortality may have resulted from the fact that all lattice/horizontal turbines had variable-pitch blades and high mortality while all guyed-pipe turbines had fixed-pitch blades and low mortality. But we think that the low observed mortality at guyed-pipe turbines is related more to percent time in operation than it is to any other turbine characteristic, such as blade pitch. Indeed, when we removed guyed-pipe data from the analysis, blade pitch was no longer significantly associated with mortality. It is possible, therefore, that turbines at which observed mortality was highest, i.e., lattice/horizontal turbines, just happened to have variable-pitch blades.

We also questioned the relationship between blade pitch and mortality because it was difficult for us to provide a plausible biological explanation for the association. We first thought that mortality might be related to start-up time and start-up time might be related to blade pitch. We speculated that turbines with the capacity to position blades at an optimal angle to capture variable winds might have the potential for faster start-up times. Fast start-up times, in turn, might make it more difficult for a perched raptor to safely leave a turbine perch before the blades were turning at full speed, thus increasing the potential danger of collision. However, we have learned that other factors may be more important than blade pitch in determining start-up times, including blade weight and blade braking. Heavier blades would have more inertia and thus take longer to reach full speed, and some turbines have a braking mechanism that holds the blades stationary until the wind speed is high enough to generate electricity. For example, smaller machines with lighter blades that brake until cut-in speeds are reached (e.g., lattice turbines) have the capacity to start fast, whereas bigger machines with heavier blades that do not brake (e.g., tubular turbines) typically have slower start-up times. In addition, it is also possible that faster start-up times might actually startle a raptor and cause it to leave the turbine immediately, thus decreasing the chance of collision.

Another researcher (Ed Colson pers. comm.), however, has suggested that blade pitch may have a considerable influence on mortality because birds may find it more difficult to see the blades when approaching at certain angles. For example, the orientation of the variable-pitch blades when the turbine is rotating at top speeds is almost perpendicular to the horizon. If a bird is approaching at turbine height, the blade may be much less visible.

4.1.5 Position in Row and Proximity to Canyon

Position in row (end vs. non-end) and proximity to canyon were the only variables that were significantly associated with mortality in the multivariate analysis. As in our original analysis, each of these variables was strongly associated with mortality, and when both were present their combined effect on mortality was multiplicative. These two variables were also the only variables that continued to show a significant association with mortality by turbine type.

Our analysis of new mortality data indicated that both position in row and proximity to canyon were associated with mortality, thus supporting our original findings. European studies have also indicated that end turbines have a higher rate of mortality (Winkelman 1992a). Among 1993 and 1994 mortality records in Altamont Pass, 23 out of 56 (41%) dead or injured golden eagles were found near end turbines (Hunt 1994). One possible reason for higher mortality at end turbines is that end turbines may operate more frequently because of their proximity to canyons, where wind speeds are usually higher. Also, raptors such as golden eagles probably hunt more near canyons or draws using topography for contour hunting (Ron Jackman pers. comm.) and slope winds for lift. In section 4.2, we discuss additional reasons end turbines might be associated with higher mortality.

4.2 Perching

4.2.1 Perching at Operating Turbines

Because we only saw one raptor perched on an operating turbine during six seasons of field observations, we originally thought that perching at operating turbines would not contribute significantly to mortality. Hunt (1994) also found that raptors appeared to avoid perching on operating turbines; of the red-tailed hawks and golden eagles he observed perched on turbines, only two percent were perched on operating turbines. The rarity of birds perching on operating turbines suggests that most birds leave turbines soon after they begin to operate. However, some individuals apparently habituate to operating turbines. Hunt (1994) found that, of 15 red-tailed hawks observed perched on operating turbines, the majority stayed for an extended period. In addition, a mortality was recently observed when a red-tailed hawk appeared to try to perch on an operating turbine (Kenetech Windpower, Inc. 1994a). Perching or attempting to perch on operating turbines may be rare events, but so are turbine-related mortalities; they may be rare but highly related.

Although mortality was not significantly associated with rotor direction relative to wind (upwind/downwind) in our analysis, we wondered about the relative danger of upwind and downwind turbines to perching birds. We speculated that downwind turbines might be more dangerous to a bird *flying in* to perch on an operating turbine and that upwind turbines might be more dangerous to a bird *departing* an operating turbine. A bird preparing to land is usually flying into the wind. Downwind turbines face away from the wind and therefore toward a bird flying in to perch. Conversely, if a bird takes off into the wind from an upwind turbine it may have to pass through turning blades to take flight. These opposing effects may have diminished or canceled the influence of rotor direction on mortality in our analysis.

4.2.2 Differences in Perching Between Species and Seasons

The tendency of one species to perch on turbines more than another may explain why some species appear to be more susceptible to collision than another. In our original analysis of mortality, we found that American kestrels, red-tailed hawks, and golden eagles were killed more often than we would have predicted from their abundance in the study area. Turkey vultures and common ravens were killed less often than we would have expected. If perching on turbines puts a raptor at greater risk of collision, then the higher perching frequencies of American kestrels and red-tailed hawks may partly explain their higher relative mortality. In contrast, the turkey vultures' low perching frequency may contribute to its lower turbine-related mortality. Perching frequency does not, however, help explain observed mortality for golden eagles or common ravens. Golden eagles rarely perched on turbines, but their relative mortality was high, while common ravens often perched on turbines, but their relative mortality was low. Due to the low abundance of both prairie falcons and ferruginous hawks, such a comparison of perching frequency with mortality was not possible. Other species-specific characteristics that might put some species at greater risk, such as foraging behavior and flight characteristics, are discussed in Orloff and Flannery 1992.

We found that, when all raptor species were combined, raptors perched almost twice as much in the fall as in any other season, and seldom perched in the summer. This may be partly explained by seasonal differences in abundance of different species. For example, red-tailed hawks, which had a relatively high perching frequency, were most abundant in the fall and least abundant in the summer (as reported in Orloff and Flannery 1992), whereas turkey vultures, which seldom perched, were more abundant in the summer than in any other season. This may help explain the overall high perching frequency in the fall and overall low perching frequency in the summer.

4.2.3 Turbine-type Differences in Perching

Perching frequency was highest at lattice/horizontal (including windwall) turbines, followed closely by lattice/diagonal, guyed-pipe, and vertical-axis. Eleven to 14 percent of the raptors observed within these four types were perched on turbines. Only four percent of raptors observed within tubular turbine types were perching. When Hunt (1994) calculated perching frequencies by turbine type for red-tailed hawks and golden eagles combined, his "perchability index" followed the same order as that listed above.

The "perchability" of turbines may contribute to the relative rate of mortality at different turbine types. Raptors may be killed more frequently at turbines they find more perchable. Perchability, as we use it, is directly related to perching frequency. The low perching frequency (low perchability) at tubular turbines may partly explain the lower observed mortality rate at these turbines while the high perching frequency (high perchability) at lattice/horizontal turbines may partly account for the significantly higher observed mortality rate at these turbines. Moreover, because lattice turbine towers resemble the lattice transmission towers that raptors often use for nesting and perching, raptors may not recognize the potential danger of the one significant feature associated with lattice turbine towers that is not found on lattice transmission towers: the system of rotating blades (Ed Colson pers. comm.).

Raptors may be at risk of collision at lattice/horizontal turbines when they attempt to pass through spinning blades to perch on or depart from a perch anywhere in the upper half of the structure. Of the five horizontal cross arms on lattice/horizontal turbines, only the bottom two are well below blade level. Hunt (1994) found that 88 percent of the red-tailed hawks and golden eagles perched on turbines were perched on the three highest cross arms or on the catwalk platform at the top, all of which are within the rotor-swept area.

Although perching frequency at the other three turbine types—guyed-pipe, vertical-axis, and lattice/diagonal—was nearly as high as at lattice/horizontal turbine types, their mortality rates were considerably lower. Obviously, perching frequencies only partially explain the mortality rate at the different turbine types. Other perching-related and non-perching (turbine-specific) factors may interact with or override perching frequency to affect mortality. We present below several possible perching-related reasons for the contradictions we noted between perching frequency and mortality; we discuss possible non-perching factors in section 4.3 below.

A plausible explanation for the high perching frequency but low mortality at guyed-pipe turbines is that they operate much less frequently, on average, than other turbines in our sample sites. Birds may be more likely to perch on turbines that seldom operate and may be safer by doing so. Many turbines on the guyed-pipe sites were inoperative for extended periods. Moreover, birds perched at guyed-pipe turbines were often perched on the guy wires, which are mostly below the spinning blades, making them less vulnerable to collision with blades even if they were spinning.

Vertical-axis turbines are unique among turbine types: they resemble an egg beater. Because of this, they may present less danger to perching raptors than other turbine types. Birds observed perched on vertical-axis turbines were usually perched on the guy wires, which can be used for perching without birds ever having to pass through rotating blades to reach them. The horizontal cross arms that connect the blades to the vertical axis constitute another perching location on vertical-axis turbines. Although the cross arms are within the rotor-swept area, they rotate with the blades, so a bird would not be likely to attempt to perch on them while the blades were turning or to remain once the blades start turning. Since a bird already perched on a cross arm when it started turning would be likely to leave immediately, it would probably escape without injury.

The angled cross arms in the framework of lattice/diagonal turbines may be more difficult to perch on than the horizontal cross arms in the framework of lattice/horizontal turbines, but perching frequency was similar at these two types. The data suggested, however, that raptors remained perched longer at lattice/horizontal turbines than at lattice/diagonal turbines. The horizontal cross arms of lattice/horizontal turbines may be easier to perch on for extended periods, which may have contributed to the higher observed mortality at lattice/horizontal turbines. There may be two reasons for this: 1) staying longer may lead to greater habituation, causing a bird to be less cautious, and 2) the longer birds stay at a turbine the more likely they are to be there when blades start turning, perhaps leading to greater risk. If raptors are using turbines as night roosts, which the Avian Task Force suggested might be happening (Kenetech Windpower, Inc. 1994b), the effect of these two factors may be exacerbated.

For the perching analysis, we combined windwall and lattice/horizontal turbines because they are the same basic turbine design. In our mortality analysis, however, windwall turbines were considered a separate turbine type (for reasons we explained in section 2.1.1). The observed mortality rate at windwall turbines was half what it was at lattice/horizontal turbines, even though perching frequency was high at both. One possible explanation for this is that half of the turbine towers in the windwall sample sites are considerably taller than the regular lattice/horizontal turbines, with blade tips much farther from the ground. This increases the amount of safe perching area below the blades and consequently may lower the risk of collision.

Two possible limitations in the perching analysis by turbine type should be considered. First, the higher perching frequency at some turbine types may be a function of where the turbines are located. Some turbines may provide a better view of hunting areas than others and some sites may support more prey species than others. We corrected for this, however, by incorporating raptor use (by dividing the number of raptors observed perched by the number observed in each turbine type). Second, since some species have higher perching frequencies than others, differences in species-specific local abundance within turbine types may make one turbine type appear to have a higher perching frequency than another. Sample sites within turbine types are widely spread throughout the Altamont Pass, however, so we believe that differences in local abundance probably are not strongly affecting perching frequencies.

4.2.4 Perching at End Turbines

More raptors were observed perched at end turbines than at non-end turbines when all turbine types were combined. Hunt (1994) also found that, for red-tailed hawks, perching frequencies were significantly higher at end turbines. This may be one reason our observed mortality rate was higher at end turbines. End turbines may provide better perch sites because they often provide a better view of a canyon (or valley) where prey densities may be higher. This may be why proximity to a canyon was also significantly associated with mortality. Perching frequency was higher at end turbines than at non-ends for each of the turbine types except guyed-pipe. The exception of guyed-pipe turbines may be explained by the fact that guyed-pipe turbines had the lowest occurrence of turbines close to canyons, perhaps making both end and non-end turbines equally suitable as perch sites.

Perching frequencies, however, do not entirely explain the differences in mortality rates between end and non-end turbines. When we combined all turbine types, the mortality rate at end turbines in our original analysis was nearly three times that at non-end turbines, whereas in the present analysis the perching frequency at end turbines was only one and a half times that of non-end turbines. Moreover, even though we do not think perching was a factor in mortality at vertical-axis turbines (as discussed in section 4.2.3), end-turbine mortality was still considerably higher in this turbine type. There seem to be, therefore, additional factors contributing to mortality at end turbines. This may be true for proximity to canyon as well.

Our data also show that more raptor carcasses were found in the outside quadrant of end turbines (Figure 2-2). Raptors may be more likely to land on or take off from the outside quadrant of end turbines because there is often more open space to maneuver and to gain altitude. Also, when a perched raptor is hunting adjacent canyons and valleys, it might be easier for it to descend on prey or return to the perch from the outside quadrant of an end turbine.

As a possible mitigation measure, it might be useful to place suitable alternative perches near selected end turbines (e.g., those at which a raptor has been killed) to diminish the frequency of raptors perching on these turbines, thereby reducing collision risk.

4.3 Mortality by Turbine Type

Our comparative analysis of mortality among the six turbine types indicates that lattice/horizontal turbines had a significantly higher observed mortality rate than all other turbine types combined, while guyed-pipe turbines had a significantly lower mortality rate than all other types combined. Our data lead us to believe that many factors contribute to mortality. One factor is not independent of the others, and some factors may dominate others under varying circumstances. A combination and interplay of factors probably determines the observed mortality rates at different turbines types. We discuss the factors that may be contributing to mortality at the different turbine types below.

There may be several reasons guyed-pipe turbines have the lowest observed mortality rate of any turbine type. Most importantly, guyed-pipe turbines operated far less frequently than any other turbine type, operating on average only 20 percent of the time. Other potential contributing factors include the fact that rotor diameter was smallest, structure density was highest (lower structure density was significantly associated with higher mortality in our original analysis), blades were fixed-pitch, and average elevation was lowest (higher elevation was significantly associated with higher mortality in our original analysis). See Appendix Table A.2 for mean values of variables. Frequency of operation may diminish the importance of characteristics that might otherwise be expected to increase mortality, such as high tip speed and high perching frequency. Although tip speed was highest at guyed-piped turbines, its importance may be diminished if turbines seldom operate.

The features of lattice/horizontal turbines that may be contributing to the high mortality rate include high percent time in operation, high tip speed (the second highest in our sample), large rotor diameter (the largest in our sample), variable-pitch blades, and low structure density (the second lowest in our sample) (Appendix Table A.2). Elevation was moderately high at lattice/horizontal turbines, but was comparable to three other turbine types. Perching frequency was also highest at lattice/horizontal turbines.

Lattice/horizontal and lattice/diagonal turbines all have lattice-type towers, but they are different in several ways that may be influencing their association with mortality. Lattice/horizontal turbines have a faster tip speed, larger rotor diameter, and lower structure density than lattice/diagonal turbines. Moreover, percent time in operation is four to five percent higher at lattice/horizontal turbines (using conservative estimates). All these factors may have contributed to the higher observed mortality at lattice/horizontal turbines.

Interestingly, when we separated lattice/diagonal turbines into their two types, Enertech and Vestas, the mortality rate was much higher at Vestas turbines (6.9%) than at Enertech turbines (1.5%), almost as high as at lattice/horizontal turbines (8.4%). Vestas and Enertech turbines were grouped together because they are structurally similar. They have a few potentially important differences, however, that may account for differences in observed mortality rates. The values for tip speed, rotor diameter, and structure density at Vestas turbines were intermediate between those at Enertech and lattice/horizontal turbines, which may account for the intermediate mortality rate. Vestas and lattice/horizontal turbines also have a catwalk platform around the nacelle (the box around the generator) that increases perching opportunities near the blades. Percent time in operation and elevation were notably higher at Vestas turbines than at either lattice/horizontal or Enertech turbines.

The observed mortality rate at windwall turbines was half that at lattice/horizontal turbines. Because windwall turbines are structurally identical to lattice/horizontal turbines except for turbine height and arrangement, tip speed and rotor diameter do not help explain the difference in observed mortality between these two turbine types since tip speed and rotor diameter have identical values. In fact, because percent time in operation (conservative estimate) and elevation were highest at windwall turbines, we might expect the observed windwall mortality to be higher than at lattice/horizontal turbines. This inconsistency might be explained by the height of the taller, 140-ft turbines, which results in the availability of more perches well below the rotating blades than the shorter lattice/horizontal types, possibly making windwall sites safer (we discussed this in section 4.2.3 above).

Tubular turbines have four attributes that may explain, at least in part, their relatively low observed mortality rate. First, average tip speed for tubular turbines was considerably lower than for most other turbine types (see Appendix Table A.2). Second, elevation was relatively low among tubular turbine sites. Third, as indicated previously, the perching frequency at tubular turbines was considerably lower than at any other turbine type. Fourth, although *average* rotor diameter was almost as high at tubular turbines (56 feet) as at lattice/horizontal turbines (59 feet), it was 52 feet or less at well over half the tubular turbines (63%).

We do not believe that either percent time in operation or structure density, both being comparatively moderate at tubular turbines, had a noticeable effect on mortality at tubular turbines. Although for tubular turbines, percent time in operation went from second lowest using the conservative estimate to highest using the liberal estimate, the operating time that created this increase was time when the tip speed was relatively low, i.e., 65 to 75 mph, which may pose less danger than faster tip speeds. In fact, this may be why conservative estimates of percent time in operation, which include only the higher tip speeds, were more strongly associated with mortality than liberal estimates. Tubular turbines also have a relatively slow start-up time, which may give perched birds more time to leave or may make them more wary before blades begin to turn at higher rpm.

The relatively low observed mortality at vertical-axis turbines may be partly due to their unique design, which reduces the danger of spinning blades to perching birds (we discussed this in section 4.2.3 above). Consequently, perching-related injuries are unlikely. Although average rotor diameter among vertical-axis turbines was almost as large as among lattice/horizontal turbines, the turbine designs are so different, they are not comparable for these purposes. The values for all other variables that were significantly associated with mortality were moderate and do not help us explain mortality at vertical-axis turbines.

As we discussed in our original report, comparisons of observed mortality among turbine types are confounded by several factors. Two that concern us are 1) differential scavenging rates and 2) the distribution of turbine types in the WRA. Differential scavenging rates could change our estimate of mortality among turbine types. If scavengers removed carcasses more quickly in one area and we did not find them, we would conclude that mortality was low in that area. Interestingly, scavenging rates were among the highest at lattice/horizontal turbines, suggesting that mortality at lattice/horizontal turbines might actually have been underestimated. Because turbine types are not randomly distributed with respect to habitat characteristics within the Altamont Pass WRA, the proportion of significant habitat and structure features, such as number of end turbines and turbines close to canyons, differs for each turbine type. This unequal distribution of certain features may have affected mortality rates among turbine types.

For two reasons, however, we believe that the non-random distribution of turbine types within the WRA would not substantially affect observed mortality among turbine types. First, as can be seen in Table 3.7, we were able to compensate for this potential influence for two of the most significant variables (position in row and proximity to canyon), by isolating the effects of these two from the turbine type that had the highest observed mortality. Table 3.7 shows that mortality was higher at lattice/horizontal turbines than at all other turbine types combined when the other two variables were held constant. For example, when neither end turbines nor turbines close to canyons was present, mortality was still 2.5 times higher at lattice/horizontal turbines. Second, our data indicated that the relative proportion of end turbines or turbines close to canyons within a turbine type was not a reliable predictor of mortality between turbine types. For example, the proportion of end turbines was lowest at both lattice/horizontal and guyed-pipe turbines, yet these sites had extremely different mortality rates, and tubular turbines had the highest proportion of turbines close to canyons, yet a relatively low mortality rate. There seems to be little correspondence between the proportion of end turbines or turbines close to canyons and mortality within a turbine type.

Unlike the position in row (end vs. non-end) and proximity to canyon variables, the association with mortality of all other significant variables was primarily a function of differences *between* turbine types and not *within* turbine types. These other variables were significantly associated with mortality when all turbine types were combined but not when they were analyzed by turbine type in two-way ANOVAs. This may be in large part explained by the limited variability within turbine types of many of the turbine-specific variables. Consequently, it is difficult to isolate the effect of the variables that may be contributing to mortality from the turbine type itself (see section 4.4 below).

4.4 Study Limitations and Qualifications

We caution readers to consider the following qualifications before drawing conclusions about or interpreting the results of our analysis. First, we considered this present study an extension of our original exploratory analysis (Orloff and Flannery 1992). There are still many things that are not known and have not been explored that might shed light on the problem of raptor collisions with wind turbines. We simply analyzed the variables we thought might affect mortality to attempt to narrow the search for causal agents. Although any causal agent should be statistically associated with mortality, the statistical association of a variable with mortality does not necessarily mean it caused the mortality. We do not presuppose that any of the variables we found to be significantly associated with mortality were actually causing bird deaths. Lattice/horizontal turbines, for example, were associated with significantly higher mortality than the other turbine types, but to assume that some lattice turbine feature caused mortality might be incorrect; it is possible that lattice turbines are associated with some other non-turbine feature that predisposes them to a higher mortality rate (such as where they are situated topographically).

Second, turbine types are not randomly distributed with respect to habitat characteristics within the Altamont Pass WRA. Consequently, it is difficult to determine whether differences in mortality among turbine types are related to the turbine type itself or to topographic features more commonly associated with one turbine type than another. For example, it is possible that mortality at a particular turbine type might be different if turbines within that type were situated in a different location and were therefore associated with different habitat features.

Third, in our original analysis individual turbines had their own values for each of the variables irrespective of turbine type or sample site, e.g., proximity to a canyon was specific to each turbine. In this present analysis, variable values were often identical within sample sites, turbine types (e.g., all tubular turbines are upwind), and sometimes even across turbine types (e.g., both guyed-pipe and lattice/diagonal turbines have fixed-pitch blades). Because of this, there was little inherent variability in some of the variables, particularly within turbine types. It is difficult to separate the effect of a variable on mortality from the effect of a turbine type when all turbines of a certain type have the same value for that variable.

Finally, we advise caution in drawing conclusions from our *P* values. In this exploratory analysis (and our original analysis as well) we have used *P* values as objective measures to prioritize variables that may deserve further study and not to make definitive probability statements. Because we conducted so many statistical tests, it is inevitable that some variables would be significantly associated with mortality statistically when an association does not actually exist. If 20 independent statistical tests were performed at $\alpha=0.05$ on data that were not actually different, one out of those 20 tests would be expected to show a significant difference.

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Appendix Table A.1 Correlation table.

	First Turbine Row	Position on Slope	Structure Distance[1]	Rotor Solidity	End Turbine	Canyon Distance	Proximity to Canyon	Structure Density	Elevation (in feet)	Number of Slopes
First Turbine Row	1									
Position on Slope	0.262	1								
Structure Distance[1]	0.374	0.32	1							
Rotor Solidity	0.225	0.241	0.312	1						
End Turbine	0.016	-0.031	-0.042	0.024	1					
Canyon Distance (ft)	0.142	-0.292	-0.08	-0.315	0	1				
Proximity to Canyon	0.029	0.277	0.077	0.237	0.001	-0.53	1			
Structure Density	-0.338	-0.247	-0.629	-0.246	0.021	-0.02	-0.007	1		
Elevation (ft)	0.254	0.401	0.249	0.265	-0.071	-0.368	0.219	-0.23	1	
Number of Slopes	0.17	0.643	0.282	0.3	-0.025	-0.267	0.26	-0.315	0.505	1
Killed Raptor	0.048	0.008	0.045	0.041	0.109	-0.055	0.097	-0.087	0.087	0.027
Elevation (HL)[2]	0.317	0.347	0.202	0.196	-0.051	-0.16	0.128	-0.31	0.916	0.45
Lattice/horizontal	0.087	0.193	0.431	-0.095	-0.044	0.001	0.025	-0.543	0.196	0.195
Lattice/diagonal	-0.15	-0.253	-0.263	-0.19	-0.055	-0.082	-0.113	0.178	0.07	-0.1
Tubular	0.056	0.04	-0.025	0.613	0.078	-0.278	0.173	0.179	-0.049	-0.069
Guyed-pipe	-0.072	-0.149	-0.373	-0.499	-0.012	0.399	-0.146	0.366	-0.424	-0.197
Windwall	0.13	0.181	0.233	-0.03	-0.008	-0.065	0.019	-0.201	0.271	0.154
Vertical-axis	-0.038	0.011	0.007	0.264	0.054	-0.026	0.045	0.052	0.077	0.075
Upwind/Downwind	0.051	0.059	-0.12	0.66	0.052	-0.299	0.15	0.134	0.098	0.055
Fixed Pitch[3]	-0.203	-0.285	-0.631	-0.266	0.038	0.087	-0.096	0.627	-0.324	-0.334
Free Yaw[4]	0.069	-0.019	0.164	-0.468	-0.131	0.223	-0.142	-0.268	-0.015	0.077
Turbine Height	0.178	0.096	0.196	0.359	0.06	-0.074	0.066	-0.124	0.201	0.082
Rotor Diameter	0.228	0.329	0.589	0.687	-0.001	-0.348	0.194	-0.57	0.42	0.381
Rotor-swept Area	0.248	0.336	0.612	0.707	-0.007	-0.335	0.196	-0.581	0.398	0.392
Tip Speed (max)	0.151	0.181	0.301	-0.289	-0.068	0.287	-0.052	-0.372	-0.015	0.189
Tip Speed (avg)	0.138	0.148	0.29	-0.311	-0.08	0.291	-0.067	-0.37	0.003	0.187
Turbine Spacing	0.087	-0.062	0.093	0.54	0.068	-0.138	0.093	0.075	-0.032	-0.009
Raptor Use[5]	0.212	0.144	0.282	0.189	-0.011	0.216	0.012	-0.172	0.134	0.094
% Time (Liberal)[6]	0.217	0.238	0.228	0.539	-0.009	-0.29	0.163	-0.236	0.603	0.294
% Time (Conserv.)[7]	0.293	0.279	0.403	0.504	-0.079	-0.167	0.13	-0.486	0.754	0.438

	Killed Raptor	Elevation (HL)[2]	Lattice/ horizontal Turbine	Lattice/ diagonal Turbine	Tubular Turbine	Guyed-pipe Turbine	Windwall Turbine	Vertical-axis Turbine	Upwind/ Downwind	Fixed Pitch
Killed Raptor	1									
Elevation (HL)[2]	0.088	1								
Lattice/horizontal	0.102	0.268	1							
Lattice/diagonal	-0.017	0.104	-0.277	1						
Tubular	-0.014	-0.177	-0.361	-0.208	1					
Guyed-pipe	-0.076	-0.404	-0.355	-0.205	-0.267	1				
Windwall	-0.009	0.278	-0.152	-0.088	-0.114	-0.112	1			
Vertical-axis	-0.013	0.066	-0.19	-0.11	-0.143	-0.141	-0.06	1		
Upwind/Downwind	-0.001	0.037	-0.436	0.201	0.828	-0.323	-0.138	-0.173	1	
Fixed Pitch	-0.087	-0.349	-0.73	0.379	0.333	0.486	-0.231	-0.29	0.45	1
Free Yaw	0.023	0.068	0.401	0.231	-0.714	0.297	0.127	-0.475	-0.559	-0.224
Turbine Height	-0.022	0.211	-0.364	-0.134	0.202	-0.283	0.724	0.381	0.159	-0.186

	Killed Raptor	Elevation (HL)[2]	Kenetech Lattice Turbine	Zond/Seawest Lattice Turbine	Tubular Turbine	Guyed-pipe Turbine	Windwall Turbine	Vertical-axis Turbine	Upwind/ Downwind	F F.
Rotor Diameter	0.097	0.403	0.473	-0.092	0.216	-0.864	0.15	0.16	0.255	-0.716
Rotor-swept Area	0.096	0.376	0.465	-0.12	0.215	-0.822	0.147	0.151	0.244	-0.728
Tip Speed (max)	0.034	0.058	0.533	-0.501	-0.632	0.432	0.169	-0.113	-0.73	-0.527
Tip Speed (avg)	0.032	0.082	0.521	-0.4	-0.709	0.418	0.165	-0.075	-0.767	-0.537
Turbine Spacing	-0.01	-0.113	-0.396	0.018	0.332	-0.296	-0.126	0.742	0.255	-0.092
Raptor Use	0.053	0.174	0.266	-0.301	0.165	-0.154	-0.126	0.002	-0.018	-0.264
% Time (Liberal)	0.071	0.598	0.058	0.186	0.445	-0.704	0.088	-0.025	0.615	-0.102
% Time (Conserv.)	0.095	0.808	0.363	0.085	-0.027	-0.619	0.188	0.093	0.196	-0.521

	Free Yaw	Turbine Height	Rotor Diameter	Rotor-swept Area	Tip Speed (maximum)	Tip Speed (average)	Turbine Spacing	Raptor Use[5]	% Time in Operation (Lib.)[6]	% Time in Operation (Conserv.)[7]
Free Yaw	1									
Turbine Height	-0.383	1								
Rotor Diameter	-0.152	0.304	1							
Rotor-swept Area	-0.116	0.296	0.996	1						
Tip Speed (max)	0.681	-0.186	-0.077	-0.03	1					
Tip Speed (avg)	0.736	-0.194	-0.084	-0.038	0.991	1				
Turbine Spacing	-0.595	0.447	0.311	0.322	-0.445	-0.424	1			
Raptor Use	-0.08	-0.024	0.233	0.244	0.098	0.068	0.089	1		
% Time (Liberal)	-0.379	0.292	0.643	0.612	-0.494	-0.51	0.222	0.137	1	
% Time (Conserv.)	0.033	0.251	0.7	0.686	0.012	0.036	0.058	0.151	0.768	

1 Structure distance is the minimum distance to the next closest turbine row in feet.
2 High or low.
3 Pitch is either fixed or not fixed.
4 Yaw is either free or not free.
5 Raptor use as indicated by mean number of raptors seen per 10-min scan period.
6 Liberal estimate of the percent of time turbines operated. See methods.
7 Conservative estimate of the percent of time turbines operated. See methods.

Appendix Table A.2 Table of mean values for continuous variables discussed in text.

Variable	Lattice Horizontal (n=332)[1]	Lattice Diagonal (n=141)	Windwall (n=47)	Tubular (n=219)	Vertical-axis (n=72)	Guyed-pipe (n=213)
% Time in Operation (liberal)	41.12	46.01	45.16	50.96	38.9	22.49
% Time in Operation (conservative)	41.12	37.37	45.16	34.17	38.9	20.25
Rotor Diameter (ft)	59	50.13	59	56.39	58	36
Rotor-swept Area (ft^2)	2733.98	1973.72	2733.98	2497.44	2642.09	1017.88
Maximum Tip Speed	152	97.15	152	98.26	120	154
Average Tip Speed	152	97.15	152	85.94	120	154
Rotor Solidity	8664	7338.1	8664	13801.6	12960	5390
Turbine Height (ft)	60	63.97	140	80	100	59.44
Turbine Spacing	80	98.88	80[2]	116.99	180	79.81
Number of Raptors per Scan Period	1.193	0.894	0.941	1.175	1.094	1.013
Canyon Distance (ft)	1336.5	1077.7	965.4	666.7	1218.1	2312.6
Structure Density	1.602	3.071	1.447	2.95	2.764	3.394
Elevation (ft)	835.9	792.2	1218.3	684.7	835.1	389.9

[1] *n* is the number of turbines of this type in our sample sites.
[2] Measured from one *pair* of turbines to the next.