PREDICTING EAGLE COLLISION FATALITIES

The Service uses a Bayesian method (see Gelman et al. 2003) to predict the annual fatality rate for a wind-energy facility, using explicit models to define the relationship between eagle exposure (from pre-construction information and survey data), collision probability, and fatalities (verified during post-construction monitoring), and to account for uncertainty. The relationships between eagle abundance, fatalities, and their interactions with factors influencing collision probability are still poorly understood and appear to vary widely depending on multiple site-specific factors. The baseline model presented below is a foundation for modeling fatality predictions from eagle exposure to wind turbine hazards. In addition to generating the fatality estimate that will be a component of the Service's analysis of the permit application, the model also serves as a basis for learning and the exploration of other candidate models that attempt to better incorporate specific factors and complexity. The Service encourages project developers or operators to develop additional candidate models (both *a priori* and *post hoc*) for direct comparison with, and evaluation of, the baseline model and modeling approach. Our ability to learn over time and reduce uncertainty by incorporating new information into our modeling approach through an adaptive management framework enables us to improve site-specific estimation of eagle fatalities, reduce uncertainty in predictions, and, ultimately, improve management decisions relating to eagles and wind energy in a responsible and informed way. Rigorous post-construction monitoring is a critical component of evaluating model performance over time.

Variables used in the formulas below are summarized in Table D-1 for ease of reference. The total annual eagle fatalities (F) as the result of collisions with wind turbines can be represented as the product of the rate of eagle exposure (λ) to turbine hazards, the probability that eagle exposure will result in a collision with a turbine (C), and an expansion factor (ε) that scales the resulting fatality rate to the parameter of interest, the annual predicted fatalities for the project.

$$F = \varepsilon \lambda C$$

Using the Bayesian estimation framework, we define prior distributions for exposure rate and collision probability; the expansion factor is a constant and therefore does not require a prior distribution. Next, we calculate the exposure posterior distribution from its prior distribution and observed data. The expanded product of the posterior exposure distribution and collision probability prior yields the predicted annual fatalities.

Table D-1. Abbreviations and descriptions of variables used in the Service method for predicting annual eagle fatalities.

Abbreviation	Variable	Description
F	Annual fatalities	Annual eagle fatalities from turbine collisions
λ	Exposure rate	Eagle-minutes flying within the project footprint (in proximity to turbine hazards) per hr per km^2
C	Collision probability	The probability of an eagle colliding with a turbine given exposure
ε	Expansion factor	Product of daylight hours and total hazardous area (hr·km^2)
k	Eagle-minutes	Number of minutes that eagles were observed flying during survey counts
δ	Turbine hazardous area	Rotor-swept area around a turbine or proposed turbine (km^2)
n	Trials	Number of trials for which events could have been observed (the number of hr·km^2 observed)
τ	Daylight hours	Total daylight hours (e.g. 4383 hr per year)
n_{tur}	Number of turbines	Number of turbines (or proposed turbines) for the project

1. Exposure

The exposure rate λ is the expected number of exposure events (eagle-minutes) per daylight hour per square kilometer (hr· km^2). We defined the prior distribution for exposure rate based on information from several projects currently under Service review and projects described in Whitfield (2009). The mean (0.52) and standard deviation (1.44) for exposure based on those projects define the prior distribution for exposure rate as:

$Prior\ \lambda \sim Gamma(\propto, \beta)$, with shape and rate parameters of α = 0.13 and β = 0.25 (Figure D-1).

The prior distribution is meant to include the range of possible exposure rates for any project that might be considered.

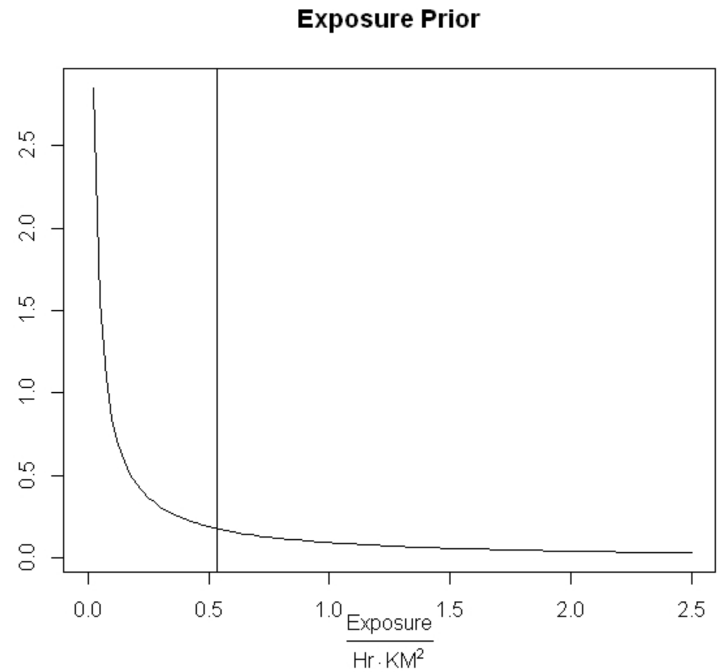

Figure D-1. The probability function Gamma(0.13, 0.25). This is the prior distribution for exposure rate, λ, based on a mean of 0.52 (indicated by the reference line) and standard deviation of 1.48. The distribution is positively skewed such that exposure is generally at or near 0 with fewer higher values.

Eagle exposure data collected during the pre-construction phase surveys (see APPENDIX C) can be used to update this prior and determine the posterior distribution that will be used to estimate the predicted fatalities. The Service may also be able to work with a project developer or operator on a case-by-case basis to use the prior λ distribution to generate a risk-averse fatality prediction for projects where no pre-construction survey data are available. Assuming the observed exposure minutes follow a Poisson distribution with rate λ, the resulting posterior λ distribution is:

$$Posterior\ \lambda \sim Gamma(\propto + \textstyle\sum_{i=1}^{n} k_i\,, \beta + n).$$

The new posterior λ parameters are the sum of α from the prior and the events observed (eagle minutes, k_i), and the sum of β from the prior and the number of trials, *n*, for which events could have been observed (the number of "trials" is the number of $km^2 \cdot hr$ that were observed). Note that by including realistic time and area data from the pre-construction surveys, the relative influence of the prior λ distribution on the resulting posterior λ distribution for exposure rate becomes negligible. In other words, with even minimal sampling, the data will determine the posterior distribution, not the prior. The posterior λ distribution can then be used to estimate the annual fatality distribution.

In addition, this posterior λ distribution can now serve as a prior distribution for the next iteration of the predictive model in an adaptive framework, at least for the project under consideration and potentially in a more general way as the posteriors from multiple sites are considered; in this way, we build ongoing information directly into the predictive process.

2. Collision probability

Collision probability *C* is the probability, given exposure (1 minute of flight in the hazardous area), of an eagle colliding with a turbine; for the purposes of the model, all collisions are considered fatal. We based the prior distribution on a Whitfield (2009) study of avoidance rates from four independent sites. A weighted mean and range of avoidance from those sites yielded a mean and standard deviation for collision probability of 0.0067, 0.0061, respectively. This in turn defined the prior *C* distribution as:

$Prior\ C \sim Beta(\nu, \nu')$, with parameters ν and ν′ of 1.2 and 176.7 (Figure D-2).

The prior *C* distribution attempts to include the range of possible collision probabilities across the set of potential sites to be considered.

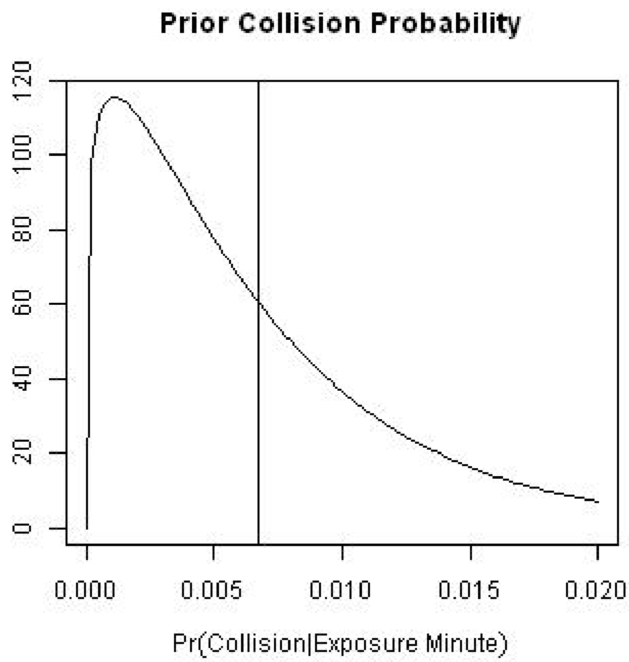

Figure D-1. The probability function for the collision probability prior, a Beta(1.2, 176.7) distribution with a mean of 0.0067 (indicated by the reference line) and a standard deviation of 0.0061. The distribution is positively skewed such that most collision probabilities will be small.

At the time of pre-construction permitting, the prior *C* distribution will be used to estimate the annual predicted fatalities. After construction, post-construction monitoring can be used to determine the posterior *C* distribution by updating the prior *C* distribution.

Assuming the observations of fatalities follow a binomial distribution with rate *C*, the posterior distribution of the rate *C* will be a beta distribution (the beta distribution and the binomial distribution are a conjugate pair):

$$Posterior\ C \sim Beta(\nu + f, \nu' + g),$$

where f is the number of fatalities estimated from the Stage 5 post-construction monitoring, and g is the estimated number of exposure events that did *not* result in a fatality. The posterior distribution for C cannot be calculated until a project has been built, has started operations, and at least one season of post-construction monitoring has been completed. Once determined, the posterior C distribution can then be used to generate a prediction for annual fatalities and can serve as a prior C for the next iteration of the predictive model.

3. Expansion

The expansion factor (ε) scales the resulting per unit fatality rate (fatalities per hr^{-} per km^2) to the daylight hours, τ, in 1 year (or other time period if calculating and combining fatalities for seasons or stratified areas) and total hazardous area (km^2) within the project footprint:

$$\varepsilon = \tau \sum_{i=1}^{n_t} \delta_i,$$

where n_t is the number of turbines, and δ is the circular area centered at the base of a turbine with a radius equal to the rotor-swept radius of the turbine; we define this as the hazardous area surrounding a turbine. In this model, to simplify data requirements and assumptions, we consider both eagle use and hazardous area as 2-dimensional areas. Alternative models that consider 3-dimensional space could also be considered, though the expansion factor should be adjusted accordingly. The units for ε are $hr \cdot km^2$ per year (or time period of interest).

4. Fatalities

Now we can generate the distribution of predicted annual fatalities as the expanded product of the posterior exposure rate and the prior collision probability (once post-construction data is available, the posterior collision probability would be used to update our fatality distribution).

$$F = \varepsilon \cdot posterior\ \lambda \cdot prior\ C$$

We can then determine the mean, median, standard deviation, and 80% quantile (this will be the upper credible limit) directly from the distribution of predicted fatalities.

5. Putting it all together: an example

The Patuxent Power Company example below illustrates the calculation of predicted fatalities from exposure data from a hypothetical project site. This data will normally come from the field surveys in Stage 2, but for the purposes of this example, we have generated fabricated observation data. The advantage of simulating data in such an exercise is that we can manipulate model inputs to critically evaluate the performance of the model. Additional examples are provided at the end of this document to illustrate the general approach and clarify specific considerations that may apply to certain projects.

> **Patuxent Power Company example** - Patuxent Power Company conducted surveys for eagles at a proposed location for a small- to medium-sized wind facility (18 turbines, each with a 50 meter rotor diameter) following the recommended methods in the ECPG (see Table D-2). They conducted 168 counts at 7 points and 60 eagle-min of exposure were observed. Each count was 2-hr in duration, and covered a circular area of radius 0.8 km. Thus, 675.6 $km^2 \cdot hr$ were observed in total.

Table D-2. Exposure data for Patuxent Power Company example. In this hypothetical example, 168 counts were performed. Each count was 2-hr in duration and covered a 0.8 km radius circle. Thus, the total time and area sampled was 675.6 km^2·hr. In that time, 60 exposure events (eagle-min) were observed.

Visit	P1	P2	P3	P4	P5	P6	P7	Total
1	0	0	2	0	2	0	1	5
2	0	0	1	0	0	0	1	2
3	0	1	2	0	0	0	1	4
4	0	1	0	0	0	1	1	3
5	0	1	0	1	0	1	1	4
6	0	0	1	1	0	0	1	3
7	0	1	0	0	0	1	1	3
8	0	0	0	0	0	1	0	1
9	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0
11	1	0	1	1	0	0	0	3
12	0	1	0	0	1	0	0	2
13	0	0	1	0	0	0	1	2
14	2	0	0	0	0	0	2	4
15	0	0	0	2	2	0	1	5
16	0	0	0	1	0	0	0	1
17	0	0	0	2	0	0	0	2
18	1	0	1	1	0	0	0	3
19	0	0	0	1	0	2	0	3
20	0	0	2	0	1	0	0	3
21	0	0	0	0	1	0	0	1
22	1	0	0	0	0	0	1	2
23	1	0	0	3	0	0	0	4
24	0	0	0	0	0	0	0	0
Total	6	5	11	13	7	6	12	60

b. Exposure

The posterior distribution for the exposure rate is:

$Posterior\ \lambda \sim Gamma(\widetilde{\alpha}, \widetilde{\beta})$, remember $Prior\ \lambda \sim gamma(0.13, 0.25)$; Figure D1, where,

$$\tilde{\alpha} = \alpha + \sum_{i=1}^{n} k_i = 0.13 + 60\ eagle\ minutes = 60.13\ eagle\ minutes$$

$$\tilde{\beta} = \beta + n = 0.25 + (168\ counts \times 2\ hr \times \pi(0.8\ km)^2) = 675.8\ km^2 \cdot hr$$

Thus,

$$Posterior\ \lambda \sim Gamma(60.13, 675.8)$$; the units for λ are per hr^{-} per km^2.

The posterior distribution is shown in Figure D-3. The mean and standard deviation of exposure rate are 0.09 and 0.01, respectively. Note that there is little influence of the prior on this posterior, because the sampling effort was substantial.

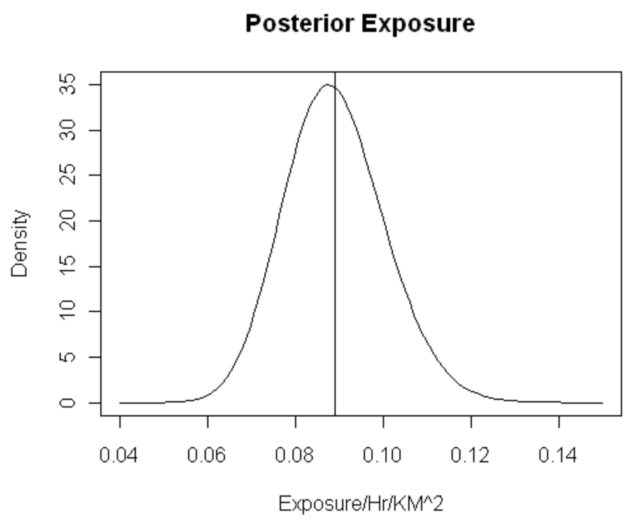

Figure D-2. The posterior distribution for exposure rate. This gamma distribution has a mean (indicated by the reference line) of 0.09 and a standard deviation of 0.01.

b. Collision Probability

We do not have any additional information about collision probability, *C*, so we will use the prior distribution, which has a mean of 0.0067 and a standard deviation of 0.0061.

$Prior\ C \sim Beta(1.2, 176.7)$; see Figure D-2.

c. Expansion

The expansion rate, ε, is the number of daylight hours in a year (τ) multiplied by the hazardous area (δ) around the 18 turbines proposed for the project:

$$\varepsilon = 4{,}383\ hr \cdot \pi(0.025\ km)^2 \cdot 18\ = 154.9\ hr \cdot km^2$$

d. Fatalities

To determine the distribution for the predicted annual fatalities, the exposure and collision risk distributions need to be multiplied by each other and expanded. The resulting distribution cannot be calculated in closed form; it is easiest to generate it through simulations. In this example, after running 100,000 simulations, the predicted distribution for annual fatalities (Figure D-4) has a mean of 0.092 and a standard deviation of 0.085. The 80% quantile is 0.15 eagle fatalities per year.

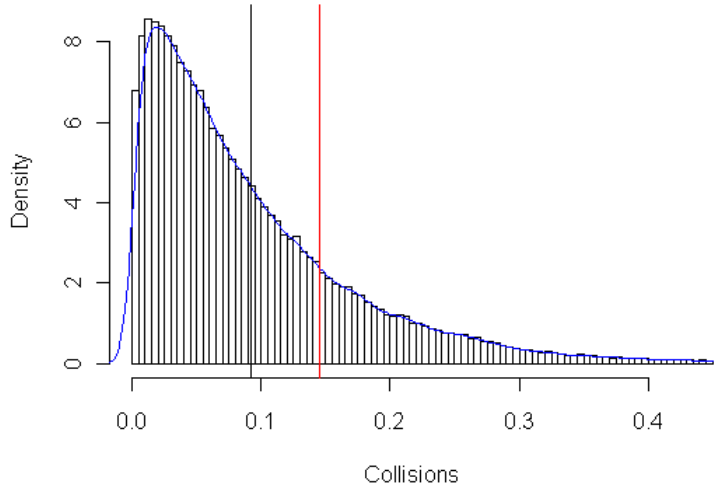

Figure D-3. The probability distribution for predicted annual fatalities. The mean (0.092) and 80% quantile (0.15) are represented by the reference lines (black and red, respectively). The standard deviation is 0.085.

The Service's baseline model for the proposed Patuxent wind facility predicts that 80% of the time that annual fatalities would be 0.15 eagles or fewer, suggesting that an eagle collision fatality would be predicted to occur at the project site every 6-7 years on average. The facility had a medium amount of eagle activity at the site, but the small size of the project kept the predicted fatality numbers lower than they would have been for a larger project in the same location. Ideally, we would consider other candidate models alongside the baseline model presented here and compare their relative performance using data collected in Stage 5.

6. Additional considerations

This initial estimate of fatality rate should not take into account possible conservation measures and ACPs (e.g. changes in turbine siting or seasonal curtailments); these will be factored in as part of Stage 4. Additionally, any loss of production that may stem from disturbance is not considered in these calculations, but should be added to these estimates and later adjusted based on post-construction monitoring as described in Stage 5. This stage and Stage 5 of the ECP will require close coordination between the project developer or operator and the Service.

The Service is working on the development of additional tools to assist project developers or operators with estimating predicted fatalities given different inputs and allowing for the flexibility to incorporate other factors into additional candidate models. We encourage project developers or operators to begin coordinating with the Service early in the process (Stage 1 or Stage 2) so that we can collaboratively develop a suite of candidate models to consider.

Literature Cited

Gelman, A., Carlin, J. B., Stern, H. S., and D. B. Rubin. 2003. Bayesian Data Analysis, 2nd ed. London, Chapman & Hall.

Whitfield, D. P. 2009. Collision avoidance of golden eagles at wind farms under the 'Band' collision risk model. Report from Natural Research to Scottish Natural Heritage, Banchory, UK.