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Appraisal of Scottish Natural Heritage's Wind Farm Collision Risk Model and its Application

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1. EXECUTIVE SUMMARY

1. There are concerns over the potential impacts of wind farms on bird mortality rates due to turbine collisions. Scottish Natural Heritage (SNH) has produced a model to predict collision risk within the sweep area of the turbine rotors, assuming no avoiding action, based on input parameters derived from bird survey data (number of birds per unit time flying through the sweep area) and structural and operational variables describing the wind turbines. Mortality rates are determined by combining predicted collision risk with the numbers of birds at risk and bird avoidance rates when turbines are encountered.
2. This report critically evaluates the SNH collision risk model and its use with avoidance rates to predict bird mortality. Specifically the aims were: (i) To assess the underlying mathematics and assumptions of the model; (ii) To identify those input parameters which vary or are estimated, and which can have a large effect on the model outputs; (iii) To identify any flaws or limitations in the calculation of avoidance rates; (iv) To provide an aid to interpretation of model outputs for non-specialists including a checklist of input parameters for particular scrutiny and any caveats attached to these; (v) To provide recommendations for improvements to the model, its application and interpretation, including data requirements and survey methodologies to adequately parameterize the model, and to provide caveats for the use and interpretation of the model.
3. The model was found to be generally statistically sound. There were two features that could be improved upon. First, it would be more accurate to use a more precise method of integration such as Simpson's rule or the trapezoidal method rather than the simpler rectangular method employed. However, use of these more accurate methods made very little difference to model predictions in the examples here. Second, greater consideration needs to be given of the effects of overlapping rotors on collision risk, although a formal analysis would require a considerable degree of model development.
4. Input parameters to the collision risk model were varied in turn (within a realistic range) in order to assess the sensitivity of predicted collision risk to possible measurement errors. Variations in bird length and wing span had only small effects on collision risk. Bird speed was non-linearly related to collision risk and its variation had a greater effect on predicted collision risk than bird size. Predicted mortality increased exponentially at very low speeds (< 5m/s), but it is doubtful whether many birds fly at this speed.
5. There were non-linear effects of rotor diameter, rotation period and rotor blade pitch angle. Predicted collision risk increased exponentially with decreases in the former two variables. As these are known variables (rather than estimated) it should be possible for very accurate measurements to be used in the model.
6. The outputs from the collision risk models were combined with bird data to predict the mortality rate (assuming no avoiding action). Estimates are made of the number of birds at risk in a given time period (usually from observational survey data of birds flying at risk height through the proposed wind farm). Errors in bird counts and especially of the numbers at risk height will translate into directly proportional errors in predicted mortality rate.
7. The final calculation of mortality incorporates avoidance rates simply by multiplying (1 – avoidance rate) by collision risk and bird numbers at risk. Avoidance rates used in the examples presented were high (>0.90) and therefore resulted in a large adjustment to predicted mortality. Equally, small errors in avoidance rate were shown to result in large percentage changes in predicted mortality rates.
8. Further case studies were used to illustrate the effects of varying different parameters on predicted mortality. In each case, change in avoidance rate had the greatest effect on predicted mortality. In one example, a 10% change in all input parameters to the collision risk model and in numbers of birds at risk resulted in a 52% increase in predicted mortality. A 10% decrease in avoidance rate alone resulted in an increase of over 2000% in predicted mortality.
9. Avoidance rates are poorly known. Estimates are usually derived from the ratio of mortality (estimated by corpse searches) to birds in the risk area, both of which are subject to (sometimes considerable) error. This error will therefore have a large effect on predicted

mortality. Given the clear species and site-specific variations in mortality rates, it is deemed unacceptable to use avoidance rates derived from other studies without clear and rigorous justification.

10. It is imperative that further research is carried out on avoidance rates. It is suggested that remote survey methods using surveillance azimuth radar and thermal infrared imagery, for example, be used to assess the behaviour of birds encountering wind farms and any avoiding action taken. Ideally, this would be possible over a range of species and environmental conditions (seasonal, diurnal and weather variations).
11. Mortality is likely to be increased in poor visibility (e.g. at dusk or in poor weather), yet many surveys take place only when (human) visibility is good. Surveys are improved by use of remote technologies as outlined above, so movements under a range of conditions are known. Use of these techniques is not routine, but it is suggested that they should be part of any EIA.
12. Similarly, the relative sensitivity of collision risk to bird speed necessitates further research using remote technologies. In each case considered, bird speed was derived from a single source and was based on radar data for birds migrating. It is conceivable that there may be considerable variation in bird speed depending on species and prevailing conditions.
13. The collision risk model is a robust tool to predict collision risk in the absence of avoidance rates. However, the latter factor has a very large effect on predicted mortality. It is also very poorly studied. For these reasons, we are unable to recommend use of the collision risk model without further research into avoidance rates. The latter must be considered a very high priority.

2. INTRODUCTION

Concern over climate change has lead to an increased contribution of renewable technologies to energy generation, in particular in countries to which the Bern Convention applies (Langston & Pullan 2003). Wind power is currently the greatest contributor to renewable energy, yet the construction of groups of wind turbines (wind farms) is a contentious issue for several reasons. The potential impact on bird populations is one such concern, especially following high mortality rates of raptors in California, USA (Thelander *et al*. 2003) and Tarifa, Spain (Barrios & Rodriguez 2004). However, these are apparently exceptional cases and several other studies suggest that mortality due to collisions with turbines are relatively rare events (Langston & Pullan 2003, Percival 2005), although the number of such studies is relatively low compared to the number of wind farms.

It may be possible to estimate collision risk and therefore mortality rate given some key parameters on the placement, dimensions, structure and operation of wind turbines and the movements, abundance and behaviour of birds. This has lead to the development of a collision risk model (Band *et al*. in press). An advantage of such a model, if shown to be reliable, would be the ability to predict potential impacts of wind farm construction on bird mortality rates through pre-construction field surveys.

In this report we assess critically the model developed by Band *et al.* (in press). Avoidance responses of birds are not included in this model, but are required to determine predicted mortality rates (i.e. number of birds killed per unit of time). We also examine critically the estimation and use of avoidance rates in conjunction with the collision risk model. It should be noted that we consider only direct mortality caused by wind turbine collisions but we accept that there may be other indirect impacts on bird populations such as disturbance (Langston & Pullan 2003, Percival 2005) that are outside the scope of this report.

3. AIMS

1. To assess the underlying mathematics and assumptions of the model.
2. To identify those input parameters which vary or are estimated, and which can have a large effect on the model outputs.
3. To identify any flaws or limitations in the calculation of avoidance rates.
4. To provide an aid to interpretation of model outputs for non-specialists including a checklist of input parameters for particular scrutiny and any caveats attached to these.
5. To provide recommendations for improvements to the model, its application and interpretation, including data requirements and survey methodologies to adequately parameterize the model, and to provide caveats for the use and interpretation of the model.

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4. MODEL ASSESSMENT

The model considered in this report is that of the draft Scottish Natural Heritage (SNH) paper '*Windfarms and Birds: calculating a theoretical collision risk assuming no avoiding action*', hereafter abbreviated to *SNHWB*. (SNH, undated. See also Band *et al.*, in press). These papers provide a meticulously detailed account of the geometry and calculus involved in determining the likelihood of bird-strikes in the region of a wind farm, assuming certain conditions prevail. The aim of this report is to provide a critical assessment of the model and to consider statistical extensions that might further improve its performance.

Two stages are employed in a calculation of the numbers of birds likely to be killed in a specified period of time, assuming no avoiding action is taken (see below). Specifically:

Number of birds colliding with rotors = number flying through rotors (Stage 1) × probability of bird flying through a rotor being struck (Stage 2).

SNHWB also provides a spreadsheet outlining the arithmetic underlying Stage 2, reproduced here as Figure 1[†].

We express this model algebraically as:

(1) $$n_{hit} = n_{flying} \times P$$

Stages 1 and 2 are now considered in turn.

4.1 Stage 1. Numbers of Birds Flying Through Rotors

The SNH model considers two distinct circumstances, as follows:

i) Birds using the area are assumed to fly in parallel horizontal straight lines through the wind farm. We define notation and the model parameters as follows:

A 'risk window' of area W = height (h) × width (w) is identified and assumed parallel to the plane of the wind farm rotors and perpendicular to the trajectory of the birds (SNHWB page 2).

The wind farm consists of N identical rotors each of radius R.

The number of birds n flying through the risk window in unit time.

The total time T that the birds are active and liable to approach the risk window.

An estimate of the number of birds using the space in time T is then clearly nT and, as the area covered by the rotation of one rotor is πR^2, if there is no overlap in the projection of the rotors onto the plane of the risk window, the total area of the rotors is $A=N\pi R^2$, assumed to be < W, and these cover a proportion of the risk window $N\pi R^2/W$. We return to the issue of overlapping rotors later. Thus an estimate of the total number of birds passing within reach of the rotors is:

(2) $$n_{flying} = \frac{nTN\pi R^2}{W}$$

[†] Note that the species' identity was not given in the provided spreadsheet, but given the bird length and wingspan, it is assumed that the species is Golden Eagle *Aquila chrysaetos*.

It is immediately clear from the form of (2) which of the parameters are directly proportional to n_{flying}. Thus a proportional error in the prior estimation of n translates directly into an equal proportional error in n_{flying}; however n_{flying} increases in proportion to the square of the rotor radius (all other factors being equal). The SNHWB model assumes no avoidance action is taken by the birds; Band *et al.* (in press) introduce an externally derived multiplicative correction factor to adjust for this (avoidance rates are discussed in detail below). Clearly inaccuracy in this factor will also produce proportional error in the number of birds among the n_{flying} that evade the rotors and, hence, change the numbers killed accordingly.

ii) Birds fly randomly inside a volume enclosing the wind farm rotors. Again we define notation and parameters, namely:

A 'risk volume', V_w*, analogous to the risk window is given by the height (h) × the land surface area of the wind farm.*

The volume directly covered by a single rotor is $\pi R^2 d$*, where d is the rotor depth; given that a bird of length l will be vulnerable to a strike once its mid-point comes within a distance l/2 of the face of the rotor, a critical volume* V_r *is given by (SNHWB, p.4):*

$$V_r = N \times \pi\ R^2 \times (d + l)$$

The speed of the bird through the rotor, v.

The number of birds using V_w*, multiplied by the average flight time gives a bird-occupancy n within the period.*

Thus, if birds are assumed to pass through the rotor via the shortest route they clear the rotor in time $t=(d+l)/v$ and the bird-occupancy of that part of the volume susceptible to strike is nV_r/V_w. The number of birds flying through the rotors is therefore:

(3) $$n_{flying} = n\ V_r / V_w\, t$$

Either method can be used to estimate a value for n_{flying}, which can be used in equation (1), as a multiplier of P to derive the total number of birds hit. We discuss the estimation of P in the next section.

4.2 Stage 2. Probability of a Bird Flying Through a Rotor Being Struck

Assuming that a bird entering the area swept out by a rotor does so at a random point within its area a distance r ($r<R$) from the hub and angle φ from the vertical, then the pdf $f(r,\varphi)$ is given by:

(4) $$f(r,\varphi) = \frac{r}{\pi R^2} \qquad 0 < r < R,\ 0 < \varphi < 2\pi$$

Further, *SNHWB* assumes that a bird at location (r,φ) has a probability of being struck $p(r)$; that is it depends upon the distance from the hub but not the angle. The total probability P of a bird being struck, given that it enters the circumference of the rotor, is:

(5) $$P = \int_0^R \int_0^{2\pi} p(r)\ f(r,\varphi)\, d\varphi\, dr \quad \Rightarrow \quad P = \frac{2}{R^2}\int_0^R r\ p(r)\, dr$$

Note that for computational convenience, the *SNHWB* spreadsheet works not with r but with $x = (r/R)$, the distance from the hub as a proportion of the rotor radius, thus:

(6)
$$P = 2\int_0^1 p(r)\, x\, dx \qquad = \int_0^1 y(x)\, dx$$

This (with slightly different notation) is equation (1) of *SNHWB*, where $p(r)$ is as defined by equation (2) of *SNHWB*:

(7)
$$p(r) = (b\Omega / 2\pi v)\,[K\,|\pm c \sin\gamma + \alpha c \cos\gamma\,| + \theta\,]$$

where b= number of rotor blades
Ω=angular velocity of rotor (radians/second)
c=blade chord width
γ=blade pitch angle
R=rotor radius
l=length of bird
w=wingspan
β=bird aspect ratio (=l/w)
v=bird velocity
r=radius at the point bird passes through rotor
F=1 for flapping bird, $2/\pi$ for gliding bird
K=1 (for three dimensional rotor; set K=0 for one-dimensional model)

The sign of the $\sin\gamma$ term depends upon the direction of flight, upwind (+) or downwind (-).

The remaining term θ depends upon the relationship between the angle of approach α' of the bird (where $\tan^{-1}\alpha' = \alpha = v/r\Omega$) and $\theta = l$ for $\alpha < \beta$ and $\theta = w\alpha F$ for $\alpha > \beta$. This arises from the observation that one complete revolution of the rotor takes time $2\pi/\Omega$, thus for a rotor with b blades of constant separation two successive blades pass the same point after time $2\pi/b\Omega$. The bird, at velocity v, travels a distance $2\pi v/b\Omega$ in this time. A bird placed at random along such a length might or might not be struck by the blade; that part of the distance resulting in a strike is termed the 'collide length' and is indicated in a column of the *SNHWB* spreadsheet. Consider then a hypothetical bird with length only (w=0). Its collide length is simply the length of the bird l plus a contribution from the width and depth of the blade $c\sin\gamma + \alpha c\cos\gamma$ (see Band 1998, *SNHWB*) hence $\theta = l$. However, in practice even a bird whose body length evades the blade might be struck on the wings. Assuming a cruciform shape, with the wings equidistant between head and tail, it can be shown by trigonometry that once the wingspan reaches a value w such that $\alpha > \beta$, then the collide length is such that $\theta = w\alpha F$. This can be derived also by imposing the condition that the wingspan bisects the length upon the more general model discussed by Band (1998).

4.3 Numerical Integration

The algebraic complexity of y means that numerical approximation to (6) is the most practical way forward. Fortunately as y is a function of the single variable x this is readily accomplished to any required accuracy in a spreadsheet.

The spreadsheet accompanying *SNHWB* performs the numerical integration of (6) as follows: values of $y(x_i)$ are calculated where $x_i = 0.025+0.05*(i-1)$, for i=1…..20. For i=2,…20 the area under the curve is approximated by the total area of a series of rectangles of base length $(x_i - x_{i-1})$ and height $y(x_i)$. As $x \geq 0$, the rectangle calculated for x_1 has area = $x_1 * y(x_1)$. The total area, an approximation to P, is then the total area of these contributing rectangles (Figure 2). The area under the curve for the small range $0.975 < x < 1$ is disregarded.

There are, of course, a number of ways of numerically approximating a definite integral. As a validation exercise, we have repeated the approximation of P via (6) using (a) a trapezoidal rule and (b) a composite Simpson's rule approach (Lindfield & Penny 1995). In each case, the range of x (0-1) is divided differently to that above, into n subsections of equal width $h=1/n$. For the trapezoidal rule, denoting $y(x_i)$ as y_i, an approximation to P is thus

$$\tilde{P} = h\left(\frac{y_0 + y_n}{2} + y_1 + y_2 + ...y_{n-1}\right) \tag{8}$$

For the composite Simpson's rule values of y over pairs of adjacent subsections are approximated by a quadratic, then all pairs' contributions to the total integral are aggregated to give a further approximation to P, thus:

$$\tilde{P} = \frac{h}{3}cy^T \qquad \text{where } c = (1,4,2,4,2,\ldots.2,4,1) \text{ and } y = (y_0,y_1,y_2.\ldots.y_n) \tag{9}$$

Application of these two methods with n=20 to the data of the *SNHWB* 'upwind' spreadsheet example produces estimates 0.1702 (Trapezoidal) and 0.1711 (Composite Simpson's) – see Table 1. These values are minimally changed when n is increased to 40. Note that in the example provided by the SNHWB spreadsheet $y(x)$ tends for the most part to increase near-monotonically as x increases (Figure 2). It will be clear then that the rectangular approximations will tend to overestimate the areas under the curve as, in general, $y_n > y_{n-1}$. Thus in this example the omission of the strip for $x > 0.975$ is in part compensated for by overestimation of the area under the curve for low values of x especially, and in this example at least the simple rectangular approximation does not prove profoundly inaccurate. The combined inaccuracy resulting from these two sources will vary with the parameter values used and given their relative ease of programming in one dimension, therefore, for greater robustness consideration could usefully be given to adopting a more sophisticated quadrature method, such as the composite Simpson's.

4.4 Adjusting for Overlapping Rotors

The theory presented in *SNHWB* assumes that the numbers of birds flying through the rotors are given by equations (2) for the scenario of Stage 1(i) and (3) for that of stage 1(ii). This is irrespective of the extent to which separate rotors overlap in cross-section (*SNHWB*, p.2). This assumption appears reasonable in Stage 1(ii), where birds move randomly about the space, but less so at Stage 1(i), and Band *et al*. (in press) propose an arbitrary correction factor. Consider two identical, non-overlapping rotors of radius R; from (1) and (2)

$$n_{flying} = \frac{2nT\pi R^2}{W} \qquad \text{and} \qquad n_{hit} = n_{flying} \times P$$

However, as Stage 1(i) assumes birds fly horizontally through the planes of the rotors, if the projections of these two rotors onto the plane of the risk window overlap completely, the second of the rotors can only kill those birds that successfully passed through the first, leading to a total number of losses below that of non-overlapping rotors. More generally if two rotors overlap as in Figure 3, the total probability of a bird being struck given that it follows a trajectory that takes it through the shaded region $A \cap B$ is given by:

P(Bird is struck) = P(such a bird being struck by A) + P(bird previously evading A) × P(bird is then struck by B)

assuming that rotor A is the first encountered. Clearly unless the overlap is total the region of interest is now of a less accommodating shape than the circles A, B and required integrals of the kind

$$P = \iint_{A \cap B} p(r)\, f(r,\varphi)\, d\varphi\, dr$$

are likely to require solution by Monte Carlo integration techniques (e.g. Press *et al.* 1989).

4.5 Parameter Sensitivity

The straightforward arithmetic of equations (2) and (3) immediately identifies those parameters which are directly, or inversely, proportional to the numbers of birds flying into the rotors. The more complex calculus involved in estimating the strike probability P (equation (6)) does not lend itself to such direct interpretation. We consider the sensitivity of P to error/variability in its constituent parts via direct use of the spreadsheet accompanying SNHWB. Quantities denoted in bold in the spreadsheet are those defined earlier for use in (7), or simple transformations of them. Taking the example from SNHWB as a 'baseline' case, we then vary each parameter in turn (leaving the others unaltered) and plot the resulting estimate of *P* against the parameter in question, to assess the relationship between them and identify any to which *P* is especially robust over a realistic range of values.

The results suggest an approximately linear dependence of *P* upon chord width (Figure 4a) and number of blades (Figure 4b), either up- or down-wind. In contrast, *P* decreases approximately exponentially with bird speed (Figure 4c), rotor diameter (Figure 4d) and rotation period (Figure 4e). It seems likely that parameters relating to the mechanics of the rotor will be measured accurately, whereas those connected to the behaviour or ecology of the birds will be more prone to error. Figure 4c shows that while *P* becomes remarkably insensitive to variability in bird speed above around 15 metres/second, it increases rapidly as speed reduces below that. Thus any uncertainty in measuring the speed of a bird moving at around 5 metres/second (18 km/hour) translates into disproportionate error in the estimated value of *P*. Speeds of this kind are however well below that recorded by radar observations of migrating birds, for example, even for the smaller species (Campbell & Lack 1985). The relationship between *P* and pitch angle is unique among these examples (Figure 4f); below around 25 degrees strike probability increases upwind but decreases downwind, but increases in each case at higher angles.

We considered the effects of bird size in two ways; firstly, by increasing (separately) both length and wingspan in isolation. This was done over a small range of values only to avoid ludicrously proportioned birds (Figure 4g). Then we varied both dimensions simultaneously, but maintaining the relationship length = 0.39 × wingspan, where 0.39 is the 'bird aspect ratio' as employed in *SNHWB* (Figure 4h). Thus, in the latter scenario the 'size' of the bird changes but its 'shape' is held constant. Figure 4g shows that the change in probability per centimetre is considerably greater in terms of the length from head to tail of the bird than it is for wingspan. In fact, within the context of the parameter values employed here, *P* barely varied in response to changes in wingspan across a range 1.9-2.2 metres. Figure 4h shows a linear increase in P, approximately doubling as the length of the bird runs from 0.1 – 1.0 metres and wingspan from 0.26 – 2.56 metres (roughly a range in length from a warbler to a large bird of prey). It should be borne in mind of course that birds differing markedly in size are likely to differ in other features, such as flight speed, too.

4.6 Sensitivity to the Estimated Numbers of Birds in Unit Time

It follows from (1) that the number of birds killed is directly proportional to the number entering the risk window. We therefore now turn to the means of deriving this estimate. Inevitably this will require the estimation of bird numbers from surveys of limited duration. An example based upon Greylag Geese *Anser anser* recorded in the area of a proposed wind farm over a seven month period is presented by Band *et al.* (in press), and summarised here in Table 2.

We note that the numbers of birds using an area over a relatively long period may itself fluctuate with time. There is, for example, a wide range of monthly averages in Table 2. It is important therefore to consider the periods of time over which estimated averages are assumed to hold; for instance in Table 2 we use the monthly averages to produce estimates of birds using the space in each of the seven months. As each month has a very different length of total daylight, the total of these monthly numbers differs to a degree from that (9328) provided by Band *et al.* (in press), where the total winter daylight hours was multiplied by the arithmetic mean of the monthly birds per hour. Where there is a fluctuation in numbers between months, this latter figure provides a biased estimate of the total usage over the entire season.

Formally, we express this as follows. Let the fixed total numbers of hours' daylight in month i be n_i, with $\Sigma n_i = N$ over a seven month period, and let the arrival rate of birds in unit time be μ_i in month i. Then the expected total number of birds entering the risk window is $\Sigma n_i \mu_i$. Now if a smaller-scale survey yields estimated numbers of birds per hour c_i, then the expected value of c_i is μ_i and the expected value of $\Sigma n_i c_i$ is given by:

$$(10) \qquad E(\Sigma n_i c_i) = \Sigma n_i \mu_i$$

However, the mean value $\overline{c}_i$ of the c_i has expectation $\Sigma \mu_i/7$ and that of $N \times \overline{c}_i$ is given by

$$(11) \qquad E(N\overline{c}_i) = \frac{N}{7}\sum \mu_i$$

Clearly the expected values in (10) and (11) are equal if $n_i = N/7$, but are not in general. The desire to reduce bias therefore suggests it would be preferable to base results on a stratified random sample and calculation such as that in (10). The number and durations of time periods ("strata") are clearly at the discretion of the observer – statistically optimal divisions and the optimal assignation of effort in each are discussed by Cochran (1977). In general, for example, effort should be increased in periods with the most daylight hours, and those with the greatest variability in hourly counts. Note in Table 2, for example, that the February survey, based on only 38.5 hours duration, produced no geese at all and hence made no contribution to the summed monthly total, although the months either side produced reasonably high numbers. The fitting of a smooth curve to represent the relationship between bird count and season is a further option. Clearly logistical and financial constraints may prohibit the use of an ideal survey structure in practice.

5. CASE STUDIES

In this section, we assess the sensitivity of collision risk and the number of predicted collisions to error in the measurement of selected variables. Note that we term the probability of a bird passing through the rotors being hit (*P* in equation (6)) as 'collision risk'. The number of birds struck, as a function of collision risk, the number flying in the risk window and avoidance rates, is termed 'mortality rate' (assuming each bird hit dies) expressed over the time period specific to each case study.

The analyses focus on three types of variables. First, those that are site-specific and estimated in the field (flight rate, % birds at rotor height) and may therefore be subject to sampling error. Second, variables that are taken from standard references that may in fact vary. These are flight speed, bird length and wing span. Third, avoidance rates, which were not included in the models in Section 4, but which are incorporated in the estimates of mortality rates in the following four case studies.

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5.1 Bewick Swans at Cheyne Court

To obtain the estimated mortality rate, bird survey data that estimate the flight rate (birds/hour) and the proportion of birds at rotor height are simply multiplied by the collision risk and thus are directly proportional to the number of strikes. For Bewick's Swans *Cygnus columbianus* at Cheyne Court, there were an estimated 109 birds flying at risk height through the site (Percival 2002). This ultimately gave a predicted mortality rate of 0.06 over the period of risk (which was 180 days), determined by multiplying the collision risk (0145), the estimated number of birds at risk (109) and 1 minus the avoidance rate (0.9962). A summary of the key parameters used in the calculation of mortality rate is given in Table 3. A 10% error (for example) in the measure of the number of birds at risk leads to the same proportional error in the mortality rate, i.e. upper and lower estimates of 0.066 and 0.054. The number of hours of day light also has the same proportional effect on mortality rate. In the example data, this is given as 12 hours. However, over the course of a winter (taken as September – February in this case), daylight varies between eight and 13.5 hours. Using these figures as examples of maximum and minimum daylight gives predicted mortality of between 0.040 and 0.068.

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Less straightforward are the effects of factors influencing the collision risk, currently 0.145 (Table 3). Estimates of bird speed are based on radar data for migrating birds (e.g. Campbell & Lack 1985) which in the case of Bewick's Swan is 20 m/s. It seems reasonable to assume that these speeds will be relatively rapid, although no additional data on range of speeds achieved could be found for any species. The collision risk model was re-run substituting a range of values from 15 m/s (possibly slow take-off flight) to 22 m/s. Predicted collision risks are shown in Table 4. The slowest speed (a 25% decrease from the value used in the original model) results in an increase in collision risk from 0.145 to 0.184, which represents an increase of 27% in collision risk and therefore of birds hit.

Bird dimensions are well-known (e.g. Snow & Perrins 1998) and so realistic upper and lower estimates can be used in the models. Table 5 shows the effects of varying bird length and wingspan on collision risk. Even if exceptionally large or exceptionally small Bewick's Swans are considered, there is very little impact on collision risk showing that the model is not very sensitive to these parameters.

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In the collision risk model, no account was taken of possible avoiding actions of a bird when it encountered a turbine. The final output of that model was a collision risk of a bird flying through the site assuming no avoiding action, which in the case of Cheyne Court is 0.145 (Table 3). Estimates of avoidance (based on Painter *et al.* 1999) suggest that virtually all birds (a proportion of 0.9962) will take avoiding action. (Note that there are several issues concerning the application of avoidance rates derived from widely differing sites and species. These are addressed in Case Study 5.4 below). Predicted collisions are directly proportional to 1-avoidance rate. Since the avoidance rate used is very large (0.9962) collisions will be very sensitive to this. The final predicted mortality rate was 0.145

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(collision risk) × 139 (number of birds at risk) × 0.0038 (1 – the avoidance rate) = 0.06 birds over 180 days. However, a decrease of only 0.4% in avoidance rate, from 0.9962 to 0.9924, doubles the mortality rate. Avoidance rates for raptors calculated by Whitfield and Band (in prep.) varied between 1.00 and 0.87. If we take the lower avoidance value of 0.87, the mortality rate of Bewick's Swan increases over thirty-fold to 2.04 (i.e. 0.145 × 109 × (1 – 0.87)).

5.2 Golden Eagles at Ben Aketil and Edinbane

Estimated collision risk for Golden Eagle *Aquila chrysaetos* (without avoidance) at potential wind farm sites at Ben Aketil and Edinbane were 0.112 and 0.133 respectively (Madders 2004). A summary of the key parameters used in the calculation of mortality rate is given in Table 6. The effects of varying bird speed, bird length and wingspan on collision risk are given in Table 7. In common with the Cheyne Court example above, bird length and wingspan had relatively little impact on predicated collision risk. Decreases in bird speed (from 13 m/s to 10 m/s) had a relatively larger effect at Edinbane, from 0.133 to 0.156.

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Avoidance rates were taken as 0.995. Again, if we assume an extreme example of a relatively low avoidance rate of 0.87 then there are substantial effects on predicted mortality rate. At Ben Atekil, annual mortality would increase from 0.12 to 3.05 individuals. At Edinbane respective figures would be 0.55 and 14.25. This is clearly an extreme example – if avoidance rates really were so low, then there would clearly be serious impacts on local Golden Eagle populations. However, the sensitivity of estimated collisions to avoidance rates is such that a reduction from this value of only 0.005 (i.e. doubling the non-avoidance rate from 0.005 to 0.010) would double the mortality rate.

In a species such as Golden Eagle with a low reproductive rate, such an increase could have important impacts on populations (Whitfield *et al.* 2004). This raises a more general issue; species that exhibit low natural mortality rates with low reproductive potential (K-selected) are likely to suffer rapid declines in absolute numbers when subject to additive mortality. Since these species are typically also rarer (and therefore often of disproportional nature conservation value), this has a large proportional effect on patterns of overall abundance. In contrast, short-lived species with high reproductive potential may be able, through density dependent processes, to replace themselves more rapidly such that turbine collision mortality has little effect on overall population size over extended periods. Since these species are also abundant and widespread, the effect in proportional terms (though not necessarily to local populations) is likely to be slight. Whilst outside of the scope of this report, further research into the wider population impacts of increased mortality due to wind turbine collisions, especially on K-selected species such as Golden Eagle, is to be recommended.

5.3 Kittiwakes at Teeside

Thirdly, we repeat the above analysis for a much smaller bird that shows a higher collision risk, the Kittiwake *Rissa tridactyla*, using data presented in Percival (2004). Key variables are summarised in Table 8. As before, variations in measures of bird dimensions had very little effect on predicted collision risk (Table 9). Bird speed had a relatively larger effect: a lowering of the modelled speed from 10 m/s (used in the original model of Percival 2004) to 8 m/s increased collision risk from 0.183 to 0.226.

The avoidance rate used in this study was taken as 0.9962, as in the Cheyne Court example above, derived from Painter *et al.* (1999). Collision risk for the Kittiwake was estimated to be relatively high (18.3%) compared to the other case studies presented here. A lowering of –0.4% in avoidance rate results in a change in collision risk from 0.0007 (i.e. 0.183 × (1 – 0.9962)) to 0.0014. A total of 2036 birds were estimated to be in the area of which 4% (81.5) were estimated to be at risk height. Applying the avoidance rates to these figures results in a mortality rate of 0.057 birds per day under the published scenario and 0.114 birds per day with a collision risk of 0.0014.

5.4 Seabirds at Kentish Flats

For the Kentish Flats study (Gill *et al.* 2002), the collision risk model was applied to several species. Avoidance rates, as is common, were derived from another study. In this final case study we examine critically the use of avoidance rates used by Gill *et al*. (2002).

Gill *et al.* (2002) present predicted mortality rates for four groups of species, terns, divers, Gannets *Morus bassana* and Black-headed Gull *Larus ridibundus*, derived from the collision risk model, survey data and avoidance rates taken from Winkelman (1992). A rate of 0.9998 is used for each example. This is the estimated rate of avoidance for passerines derived from Winkelman (1992) who presents a table of estimated mortality rates as a percentage of bird numbers for several categories. Winkelman (1992) actually presents a range of estimated mortality rates for a number of species groups (ducks, gulls, waders, passerines and others) based on four categories of survey data: nocturnal movements; nocturnal + daytime movements; noctural + daytime movements + all resting and feeding birds within 500m; and, all birds (movements, feeding, resting and breeding) within 500m. The value of 0.9998 has been derived from the latter group where passerines had an estimated maximum mortality rate of 0.02%.

Clearly there are several issues that should be raised here. First, it seems inappropriate to use the avoidance rate for passerines when all species considered at Kentish Flats were considerably larger. Second, it is questionable whether using the value for all birds in the vicinity is correct when it could be argued that a proportion of these are not 'at risk'. Third, despite the authors statement that the avoidance rate used is 'the worst case scenario', there are in fact many other higher mortality rates (see Table 12 in Winkelman 1992). Indeed, the authors seem to have used one of the lowest rates presented. For example, the maximum nocturnal mortality rate for passerines is 0.37%, giving an avoidance rate of 0.9963. Furthermore, Winkelman (1992) presents estimates from both 'certain and probable collision victims' and also from data including possible collision victims. Gill *et al.* (2002) use the former. This study would have been a good candidate for presenting a range of avoidance rates.

Table 10 presents estimated mortality rates from Gill *et al.* (2002) using an avoidance rate of 0.9998. Also presented are mortality rates based on avoidance rates from birds likely to be most at risk (nocturnal movements) and also from more appropriately-sized birds (so the rates for gulls have been used for Gannet, terns and Black-headed Gulls, and avoidance rates for ducks have been used for divers). Furthermore, we present estimates based on both certain/probable collision victims and possible collision victims. For most cases, the predicted mortality rates increased by a large percentage when using different estimates (e.g. 850 – 1700% increase in Black-headed Gull mortality). However, note that no nocturnal mortality was estimated for ducks, so assuming that ducks will be representative of avoidance rates for divers, their avoidance rate was estimated to be 100%. This demonstrates that using more appropriate data does not necessarily mean that predicted mortality will increase (of course, using data based on ducks to represent diver species, and indeed gull data to represent Gannet, is not likely to be valid due to the differences in size, speed and manoeuvrability, but it is useful for illustrative purposes). Although the percentage change in mortality rates is large, the actual mortality rate increase in terms of numbers of birds is still very small. For example, in Table 10 there is an 18-fold increase in predicted mortality rate of terns from the original estimates of Gill *et al.* (2002) when using revised estimates. In terms of individuals killed, this translates into one death on average every 373 years for the former scenario and one death every 20 years for the latter. Whether the difference here can be considered biologically significant is a moot point. Nevertheless, we feel that the avoidance rates used in Gill *et al.* (2002) are not the most appropriate. Use of similarly inappropriate avoidance rates in other studies could potentially have a much greater impact (and much greater biological significance) on predicted mortality rates.

6. DISCUSSION

6.1 Collision Risk Model

Although the calculations of the SNHWB spreadsheet appeared to show no great sensitivity to inaccuracy, there are aspects that could improve model robustness in general application. First, use of composite Simpson's or trapezoidal methods will be more accurate than the rectangular integration method used by Band *et al.* (in press). In the example, however, use of these alternative methods made very little difference to predicted collision risk. Nevertheless, there may be situations where the use of the rectangular method is not adequate. Given that application of the alternative methods requires only marginally more effort on the part of the modeller, remaining entirely compatible with a simple spreadsheet, it is recommended that they be used in future.

The probabilities of collision have previously been reported assuming either that rotors do not overlap, or that an arbitrary adjustment for overlap is made. When the birds are flying horizontally through the plane of the 'risk window', ignoring overlap will overstate the numbers of birds killed. Adjusting the estimates to model overlap directly is far from straightforward, and will require exact knowledge of the overlap extent and, probably, Monte Carlo integration techniques. Furthermore, birds experiencing a 'near-miss' may adjust their behaviour. This could be considered analytically by application of learning algorithms. Development of these techniques in relation to the collision risk model is worthy of further research. It should at least be acknowledged that using the collision risk model as it stands overestimates the collision rate in this case (see Section 4.1 (i)).

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Sensitivity analysis found that collision risk varied linearly or approximately linearly with respect to variations in most model parameters including bird length, wing span, flight rate and the proportion of birds at rotor height. Bird length and wing span are well known in the literature (e.g. Snow & Perrins 1998) and variations in them (within realistic bounds) have little effect on predicted collision risk. Of greater importance to predicted collision risk are flight rate and the proportion of birds at rotor height, both of which are estimated in the field and so subject to error. It is of course imperative to achieve the best estimates possible for these variables through rigorous field methods. This appears to have been achieved as far as possible in the examples considered, although often only in specific conditions (of weather and time of day for example). However, in many cases (and all of the case studies in Section 5), although mean values are used in the collision risk model, measurements of errors (SE or confidence intervals) are not given. These field estimates are subject to error and it would seem to be more circumspect to produce a collision risk range for any subsequent use of the model (based on upper and lower error estimates for example, where these can be calculated) rather than a single value. This could be extended to include likely maximum and minimum values for other constants in the model (bird length, wing span, speed but especially avoidance rate – see Section 6.2 below).

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Movements of birds show great variation (with regard to weather, season and diurnal rhythm for example), and it is likely that there can be considerable activity associated with movements from night time roosts and daytime feeding areas, but less at other times. Indeed, some of these movements may be crepuscular in nature and may even occur outside of daylight hours, yet often surveys are only carried out in good visibility. With regard to the Cheyne Court example (Case Study 5.1), swans often go to roost after dark, and may migrate at night, so daylight estimations may be inadequate for risk assessment calculations. There needs to be a more robust sampling regime to capture the scale of this variation than in the examples given, necessitating remote sensing approaches to data collection in future research on species likely to show nocturnal or crepuscular habits.

There were four variables that were non-linearly related to collision risk: rotor diameter, rotation period, pitch angle and bird speed. The former three variables are all associated with the turbines rather than the birds. Their accurate measurement is therefore essential, but should be easily achievable. Note that for rotor diameter and rotation period, the approximately exponential form of the relationship leads to increasingly large effects on collision risk as these values get smaller (Figs.

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4d and e). But also note that there is a compensatory effect of decreasing diameter on the number of birds flying through the rotor.

Bird speed (Fig. 4c) also shows an exponential-type relationship with collision risk. Slower bird speeds result in higher predicted collision risk. Collision risk increases rapidly below c. 5m/s. This is a very slow speed and below the slowest speed (6.5 m/s for roosting Swift *Apus apus*) reported in Campbell and Lack (1985). For the case studies considered here, the speeds used and the amount of variation applied in the sensitivity analyses (typically c. ±25%) were within the linear part of the trend in Fig. 4c. Such variation could have small but not necessarily trivial effects (e.g. a reduction of 10 m/s to 8 m/s resulted in a 4% increase in collision risk for Kittiwake). For the examples considered in the three case studies presented in Sections 5.1 – 5.3, flight speeds were taken from Campbell and Lack (1985) and were presumably approximated to the most closely related species if the particular species under scrutiny did not have a reported speed (e.g. Kittiwake speed is not reported and it appears that 10 m/s may have been based on Herring Gull *Larus argentatus*). Furthermore, Campbell and Lack (1985) base their data on migration flights detected by radar. It is possible that variation in flight speed between individual species is greater than implicitly assumed and also that migration speed differs from speeds that would be used in flights close to wind turbines (e.g. is take-off speed of Bewick's Swans the same as that detected by radar of migrating individuals?). Despite the relative insensitivity of this parameter, it would seem inappropriate to assume that literature-derived values for flight speeds are representative, especially when not derived from the same species, nor from situations analogous to those encountered in the vicinity of the wind turbines subject to review.

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Collection of more robust data to detect such variation would need to include, for instance, direct, real-time measurements of flight speed of a specific taxa under a realistic range of meteorological conditions. This would specifically need to include flight speeds recorded in a range of head, tail and cross winds, factors known to affect flight height, speed and behaviour, as well as reflect foraging or migratory movements which also impact on flight speed. Such measurements can be obtained using marine surveillance radar and are likely to influence species-specific avoidance rates as well.

There are two further factors that should be considered when assessing output from the collision risk model. First, the model only considers the sweep area of the turbine blade. However, birds may risk collision with other associated structures. Additional (but in all likelihood lower) collision mortality will accrue from collisions with other parts of the turbine superstructure and indeed meteorological masts and transformer stations associated with the development. Second, the model for birds flying directly through a wind farm (4.1 (i)) considers collision risk of a bird flying into the risk area at right angles to the plane of the turbine rotors. Turbines are orientated into the prevailing wind, whilst birds often pass through a given airspace in numbers and directions which are set partially by wind direction, but also other factors such as time of day, season, weather conditions etc. The collision risk of a bird flying into a turbine at an acute angle to the plane of the rotors will not be the same as the risk of a bird flying into the turbine at 90° to the plane of the rotors. This complicates the trigonometry and algebra considerably, but further model development incorporating the angle of potential collision should be considered. This could form the basis of a future research project.

The collision risk model is likely to be used by non-specialists who may not have the necessary statistical background to critically evaluate model outputs. We provide in Appendix I a brief guide to interpretation of model outputs. Use of the collision risk model, as any model based on field data, requires robust data collection. Also included in Appendix I is a table of input parameters and recommended data collection methods for key variables. However, it should be noted that use of the model (and therefore use of Appendix I) is only recommended when adequate estimates of avoidance rates are possible. This is addressed in Section 6.2.

6.2 Avoidance Rates

The original collision risk model assumed no avoidance behaviour by birds when they encountered a wind turbine. Incorporating avoidance behaviour is achieved by multiplying predicted collision risk by (1-probability of avoidance). As estimates of avoidance are typically very high (>0.990 in most case studies), this has a very large influence on the predicted collision rate and small variations in avoidance rates can lead to relatively large changes in predicted collisions. Determination of avoidance behaviour has been done by back-calculation using estimates of actual mortality (Whitfield & Band in prep.). These mortality estimates themselves rely on a number of assumptions, but authors have tended to err on the side of caution and use 'worse case scenario' estimates. Such calculations have usually estimated avoidance rates as being high, but the lowest estimate given by Whitfield and Band (in prep.) was 0.87 for American Kestrel *Falco sparvarius*. Such a low rate of 0.87 applied to the case studies considered here had a very large effect on predicted collisions.

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Bird surveys at wind farm sites are typically carried out in good weather conditions and in daylight. Avoidance behaviour, however, is likely to vary according to conditions: it seems reasonable to expect that avoidance rates would be much reduced at times of poor visibility, in poor weather (themselves depending in part on season) and at night (e.g. Winkelman 1992, Still *et al.* 1996). This may, as Madders (2004) points out, be offset to some extent by lowered bird activity, at least in raptors, but probably not in other species such as waterbirds (see Section 6.1). Poor weather may also have the effect of lowering the cloud base causing the compression of large numbers of birds on migration to a corridor low over the sea or land, funnelling more birds into the risk area.

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A further factor that could influence avoidance rates at night is attraction to lights on the turbines. The power companies are obliged to put aircraft navigation lights on all wind turbines, and there are restrictions imposed on floodlighting and other lights because of the visual impacts. Offshore turbines also require navigation lighting for shipping. There is an extensive literature on the effects of lights on birds (e.g. Gauthraux & Belser 1999, Manville 2000), which shows that in conditions of poor visibility, birds tend to be drawn towards, and circle in the vicinity of, continuous lights, which may represent an attraction and therefore substantially affect avoidance rates.

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Avoidance rates have been calculated by dividing the estimated actual mortality rate by number of birds 'at risk' (e.g. flying through the area at turbine height). Potential improvements to bird survey methods, particularly at night and in poor visibility could include remote sensing survey technologies (see page 28 below). Calculation of post-construction mortality rates has typically relied on corpse searches (Langston & Pullan 2003), which for off-shore and coastal wind farms involve tideline searches (e.g. Winkelman 1992, Still *et al.* 1996, Painter *et al.* 1999). There are clearly potential biases in estimating mortality in this way due to searching efficiency, removal of corpses by scavengers, injured birds leaving the area before death, 'obliteration' of birds struck by turbines (especially smaller species) and, for coastal locations, corpses being washed out to sea. Adjustments to mortality rates have been made to try and compensate for these factors. Nevertheless, there is clearly likely to be much local variation in these features: the scavenger community is likely to differ locally; searching efficiency depends on the size of the bird and the vegetation in the surrounding area (Winkelman 1992); at coastal sites, local tide and weather conditions will affect recovery rates (Painter *et al.* 1999). Furthermore, post-mortem examination has been used to assess mortality caused by turbine collision and compared to background mortality (where major physical injury has been taken as evidence of collision). It is possible, however, that birds may be driven to the ground due to the downforce of the wake rather than an actual collision (Winkelman 1992). Given these factors, it is probably very unwise to use mortality rates (and therefore avoidance rates) derived from studies in different locations or indeed from different species as is often the case (see Case Study 5.4 above). Rather avoidance rates should be derived from the same species and from localities as similar as possible to the location under consideration.

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Given the above caveats, the ideal situation would be to study actual avoidance behaviour of birds rather than infer avoidance based on two variables (mortality rates and bird counts) both of which are

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subject to (sometimes considerable) error. This error, even though small, can have relatively large effects on predicted mortality. This is illustrated by the example in Table 11 using data from Case Study 5.1 (Bewick's Swans at Cheyne Court). By varying each parameter in turn by 10% (either increasing or decreasing depending on which direction increases the predicted mortality rate), it can be seen the effect error in each parameter can have on the outputs. Clearly, the effect of variation in avoidance rate is far higher than any other variable in the collision risk model. Even when all other parameters were changed by 10%, the predicted mortality was estimated only at 0.091 (a 52% increase from the original 0.06), compared to 1.63 for a change in avoidance rate (a 2613% increase). There is clearly an urgent need to increase research into avoidance rates in order to measure them as accurately as possible.

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Spatially explicit patterns of avoidance shown by birds can be generated under a range of meteorological, light, diurnal and seasonal conditions using relatively crude surveillance azimuth radar (e.g. conventional marine radar, Kahlert *et al.* 2004). This has been successful in measuring the level of avoidance shown by migrating waterbirds (mainly eiders and dabbling ducks) to an extant offshore wind farm in Denmark. Furthermore, statically mounted thermal infrared imagery (especially in terrestrial situations) can be used to view rotating turbines in a way that could potentially directly record actual collision rates, mortal wounding events associated with air vortices and safe passage of birds through the turbine sweep area to generate such data, potentially at the species or species group level (Desholm 2003). Archived imagery from such devices can also show the specific avoidance behaviour shown by individuals of particular species that can further inform the development of meaningful parameterisation of avoidance behaviour probabilities. Use of such remote technologies is essential if we are to be able to provide useful precision on estimates of a parameter that makes such a huge difference to predicted collision risk in this model application.

More than this, it is important to gather data on avian flight volume in the vicinity of a wind farm, both pre- and post-construction, in such a way that avoidance responses at a range of spatial scales can be detected. This is because the range of avian avoidance behaviours may be manifest from minor adjustments of migration course at large distances (e.g. several kilometres) right through to last minute sudden avoidance of turbine blades in close proximity (e.g. a few centimetres). Without any knowledge of these responses, much of the value of a rigorous modelling approach is lost on informing the EIA process. Without some assessment of avoidance rates, the model's only utility would be in offering crude comparative data, which would largely reflect relative differences in flight altitude distribution and volume and which could be inferred from these data without resort to modelling.

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7. CONCLUSIONS AND RECOMMENDATIONS

Whilst the ultimate collision probabilities generated from the collision risk model approach are theoretically robust, their modification by the probability of avoidance shown by different species of bird is specifically ignored by the present formulation and ill-served with available real data at the present time (as mentioned in SNH undated and Band *et al.* in press). Since these parameter probability values could theoretically vary between 0 and 1, and most assessments suggest that they are nearer 0.995, we suggest that the value of the current model is questionable until such time as species-specific and state-specific (i.e. different bird activities and behaviours under a range of conditions) avoidance probabilities can be better established. Even relatively small scale change in this probability has potentially enormous effects on the sensitivity of the model.

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We make specific recommendations for improvement of the collision risk model, but more importantly, list some key areas of research in estimation of avoidance rates that should be carried out before the collision risk model is applied. For this reason, we prioritise the recommendations by first considering avoidance rates, then the collision risk model.

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1. Avoidance rate studies should be carried out as a matter of urgency. Currently, inferring avoidance rates from survey data and estimated mortality (themselves subject to error) is not adequate. Even small errors here can have large effects on predicted mortality rates such that, no matter how robust the estimates of collision risk in the absence of avoiding action, the final predicted mortality is meaningless. **We cannot therefore recommend the use of the SNH model without further research into avoidance rates.** Indeed, Band *et al.* (in press), who developed the collision risk model concur with this statement in stating '*For the collision risk model to predict accurately measures of collision mortality, it is essential that more information is collected on avoidance*'. Potential methodologies for this are given in detail in Section 6 and include use of surveillance azimuth radar and thermal infrared imagery.
2. Survey methods are crucial in determining the numbers of birds at risk. There is scope for a thorough review of survey techniques at wind farm sites. Methods should always include surveys at periods when birds are likely to be more vulnerable to collisions and so should encompass a range of seasonal, diurnal and weather conditions. Remote sensed technologies should be used as a matter of course.
3. In addition to surveys in the immediate vicinity of the wind farm site, consideration should be given to the wider impacts of large-scale avoidance at the regional scale (e.g. at the scale of several kilometres) as well as at a local level.
4. Collision risk is relatively sensitive to bird flight speed. In all case studies reviewed, flight speed is derived from empirical studies, usually of migration flight (and not necessarily of the species under consideration in the EIA). Remote sensed technologies again should be used to consider flight speeds under a range of conditions.
5. Collision risk was sensitive to fixed variables associated with turbine rotors (rotor diameter, rotation speed, pitch angle of blade). Their measurement should be precise, but this is readily achievable.
6. All measures are subject to error although this is rarely acknowledged, even when means are used. Where error is estimated, it is recommended that upper and lower limits as well as means are used in calculations to acknowledge measurement error and to give a range of collision risks and ultimately mortality estimates.
7. Collision risk model calculation should preferentially use trapezoidal or more advanced integration methods rather than the current simple rectangular method.
8. It should be acknowledged that adjustment for the overlap of rotors on collision risk is not made accurately. An accurate adjustment is not a trivial task and would require further research possibly involving Monte Carlo integration techniques.

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X	Prob(collision)	y(x)	c	cy^T
0.00	1.000	0.000	1	0.000
0.05	0.994	0.099	4	0.398
0.10	0.547	0.109	2	0.219
0.15	0.440	0.132	4	0.528
0.20	0.394	0.158	2	0.315
0.25	0.341	0.170	4	0.682
0.30	0.289	0.173	2	0.346
0.35	0.250	0.175	4	0.700
0.40	0.220	0.176	2	0.352
0.45	0.196	0.176	4	0.704
0.50	0.175	0.175	2	0.351
0.55	0.158	0.174	4	0.694
0.60	0.142	0.171	2	0.342
0.65	0.154	0.201	4	0.803
0.70	0.145	0.203	2	0.405
0.75	0.136	0.204	4	0.815
0.80	0.127	0.204	2	0.408
0.85	0.119	0.203	4	0.812
0.90	0.112	0.201	2	0.403
0.95	0.105	0.199	4	0.795
1.00	0.098	0.195	1	0.195
AREA (=P)				0.171

Table 1 Calculation of the probability of a strike for the parameter values used in the SNHWB example spreadsheet (upwind case), based on the composite Simpson's rule.

x is the distance from the rotor centre as a proportion of the radius *R*, *y(x)* is given by equation (6) and c is the constant multiplier of y arising from Simpson's Rule (see equation (9)). Values of *y* given can be used to provide an alternative estimate via a trapezoidal rule of 0.1702 (see text).

Month	Daylight hours	Birds/Hr	Birds/Month
January	396	2.29	906.84
February	378	0.00	0.00
March	465	3.64	1692.60
April	495	0.64	316.80
October	418	0.6	250.80
November	382	10.99	4198.18
December	372	4.29	1595.88
Total	2906		8961.10

Table 2 Estimated numbers of Greylag Geese using a wind farm over a seven month period. Data from Band *et al.* (in press).

Species	Bewick's Swan
Length	1.21 m
Wingspan	1.96 m
Speed	20 m/s
No. at risk	109
Time span	180 days
Collision risk	0.145
Avoidance rate	0.9962
Mortality rate	0.06

Table 3 Selected parameters used in and arising from the collision risk model applied to data from Bewick's Swans at Cheyne Court. Only parameters associated with birds are presented. Data were derived from Percival (2002) where further details of model parameters can be found.

Mean speed	*P*
15	0.184
17	0.165
20	**0.145**
21	0.140
22	0.136

Table 4 The effect of bird speed (m/s) on collision risk *P* in Bewick's Swans at Cheyne Court. Values used in the original model are given in bold.

Length	***P***	**Wingspan**	***P***
1.10	0.141	1.80	0.145
1.15	0.143	1.90	0.145
1.21	**0.145**	**1.96**	**0.145**
1.25	0.147	2.16	0.147
1.30	0.149	2.30	0.148

Table 5 The effect of bird length and wing span (m) on collision risk *P* in Bewick's Swans at Cheyne Court. Values used in the original model are given in bold.

Species	**Golden Eagle**	
Site	**Ben Aketil**	**Edinbane**
Length	0.85 m	0.85 m
Wingspan	2.20 m	2.20 m
Speed	13 m/s	13 m/s
No. at risk	230	1005
Time span	1 year	1 year
Collision risk	0.112	0.133
Avoidance rate	0.995	0.995
Mortality rate	0.12	0.55

Table 6 Selected parameters used in and arising from the collision risk model applied to data from Golden Eagles at Ben Aketil and Edinbane. Only parameters associated with birds are presented. Further model parameters derived from wind turbine variables are given in Madders (2004).

Bird speed	***P***	**Length**	***P***	**Wingspan**	***P***
Ben Aketil					
10	0.130	0.80	0.109	2.0	0.110
13	**0.112**	**0.85**	**0.112**	**2.2**	**0.112**
15	0.105	0.90	0.115	2.4	0.114
Edinbane					
10	0.156	0.80	0.13	2.0	0.131
13	**0.133**	**0.85**	**0.133**	**2.2**	**0.133**
15	0.124	0.90	0.136	2.5	0.137

Table 7 The effect of bird speed (m/s), bird length and wing span (m) on collision risk *P* in Golden Eagles at Ben Aketil and Edinbane. Values used in the original model are given in bold.

Species	**Kittiwake**
Length	0.39 m
Wingspan	1.08 m
Speed	10 m/s
No. at risk	81.5
Time span	1 day
Collision risk	0.183
Avoidance rate	0.9962
Mortality rate	0.057

Table 8 Selected parameters used in and arising from the collision risk model applied to data from Kittiwakes at Teesside. Only parameters associated with birds are presented. Further model parameters derived from wind turbine variables are given in Percival (2004).

Bird speed	***P***	**Length**	***P***	**Wingspan**	***P***
8	0.226	0.35	0.179	0.98	0.183
9	0.202	0.37	0.181	1.03	0.183
10	**0.183**	**0.39**	**0.183**	**1.08**	**0.183**
11	0.167	0.41	0.185	1.13	0.183
12	0.155	0.43	0.187	1.18	0.184

Table 9 The effect of bird speed (m/s), bird length and wing span (m) on collision risk *P* in Kittiwakes at Teesside. Values used in the original model are given in bold.

Bird data	**All in area**		**Nocturnal movements**		**Nocturnal movements**	
Collision victims	**Probable**		**Probable**		**Possible**	
Species	**Avoidance**	**Mortality**	**Avoidance**	**Mortality**	**Avoidance**	**Mortality**
Divers	0.9998	0.0024	1.000	0	0.9991	0.0108
Gannet	0.9998	0.0006	0.9982	0.0053	0.9963	0.0109
Black-headed Gull	0.9998	0.0006	0.9982	0.0051	0.9963	0.0104
Terns	0.9998	0.0027	0.9982	0.0241	0.9963	0.0496

Table 10 Avoidance rates and predicted annual mortality of birds (individuals per year) at Kentish Flats. Bird data from ‘All’ is that presented in Gill *et al.* (2002). Two other scenarios are presented based on a high risk period (nocturnal), one for avoidance rates based on probable mortality caused by wind turbine collision and one on possible mortality.

Input variable	Baseline'	Baseline ± 10%	Collision risk	Revised collisions	% increase
Max. chord (m)	5	5.5	0.153	0.063	5.621
Pitch angle ()	30	33	0.15	0.062	3.550
Bird length (m)	1.21	1.331	0.151	0.063	4.240
Wingspan (m)	1.96	2.156	0.147	0.061	1.479
Bird Speed (m/s)	20	18	0.158	0.065	9.073
Rotor diameter (m)	92	82.8	0.15	0.062	3.550
Rotation period	3	2.7	0.158	0.065	9.073
Bird count	109	120	0.145	0.066	10.200
Avoidance rate	0.9962	0.897	0.145	1.628	2613.192

Table 11 Effects of 10% variation in input parameters on predicted mortality rates of Bewick’s Swans at Cheyne Court. Variables were changed by 10% (increased or decreased) so that mortality rates increased. Baseline data is that used in Case Study 5.1. The original collision risk was 0.145 and the original number of predicted collisions was 0.06.

CALCULATION OF COLLISION RISK FOR BIRD PASSING THROUGH ROTOR AREA

Only enter input parameters in bold

K: [1D or [3D] (0 or 1)	**1**	
NoBlades	**3**	
MaxChord	**2.431**	m
Pitch (degrees)	**30**	
BirdLength	**0.82**	m
Wingspan	**2.12**	m
F: Flapping (0) or gliding (+1)	**1**	
Bird speed	**13**	m/sec
RotorDiam	**52**	m
RotationPeriod	**2.97**	sec
Bird aspect ratioo: β	0.39	

Calculation of alpha and p(collision) as a function of radius

			Upwind:			Downwind:		
r/R radius	c/C chord	α alpha	collide length	p(collision)	contribution from radius r	collide length	p(collision)	contribution from radius r
0.025	0.575	9.45	24.90	1.00	0.00125	23.50	1.00	0.00125
0.075	0.575	3.15	8.77	0.68	0.00511	7.37	0.57	0.00429
0.125	0.702	1.89	6.20	0.48	0.00602	4.49	0.35	0.00436
0.175	0.860	1.35	5.31	0.41	0.00723	3.22	0.25	0.00438
0.225	0.994	1.05	4.83	0.37	0.00844	2.41	0.19	0.00421
0.275	0.947	0.86	4.02	0.31	0.00860	1.72	0.13	0.00368
0.325	0.899	0.73	3.45	0.27	0.00871	1.27	0.10	0.00319
0.375	0.851	0.63	3.01	0.23	0.00878	0.95	0.07	0.00275
0.425	0.804	0.56	2.67	0.21	0.00881	0.79	0.06	0.00260
0.475	0.756	0.50	2.38	0.19	0.00879	0.80	0.06	0.00295
0.525	0.708	0.45	2.14	0.17	0.00873	0.80	0.06	0.00325
0.575	0.660	0.41	1.93	0.15	0.00862	0.79	0.06	0.00351
0.625	0.613	0.38	2.05	0.16	0.00997	1.08	0.08	0.00523
0.675	0.565	0.35	1.92	0.15	0.01009	1.09	0.08	0.00572
0.725	0.517	0.33	1.80	0.14	0.01016	1.09	0.08	0.00616
0.775	0.470	0.30	1.69	0.13	0.01019	1.09	0.08	0.00656
0.825	0.422	0.29	1.59	0.12	0.01018	1.08	0.08	0.00691
0.875	0.374	0.27	1.49	0.12	0.01011	1.06	0.08	0.00722
0.925	0.327	0.26	1.39	0.11	0.01001	1.04	0.08	0.00748
0.975	0.279	0.24	1.30	0.10	0.00986	1.02	0.08	0.00770

Overall p(collision) = **Upwind** **17.0%** **Downwind** **9.3%**

Average **13.2%**

Figure 1 The spreadsheet provided by *SNHWB* detailing input parameters to the collision risk model for Golden Eagle.

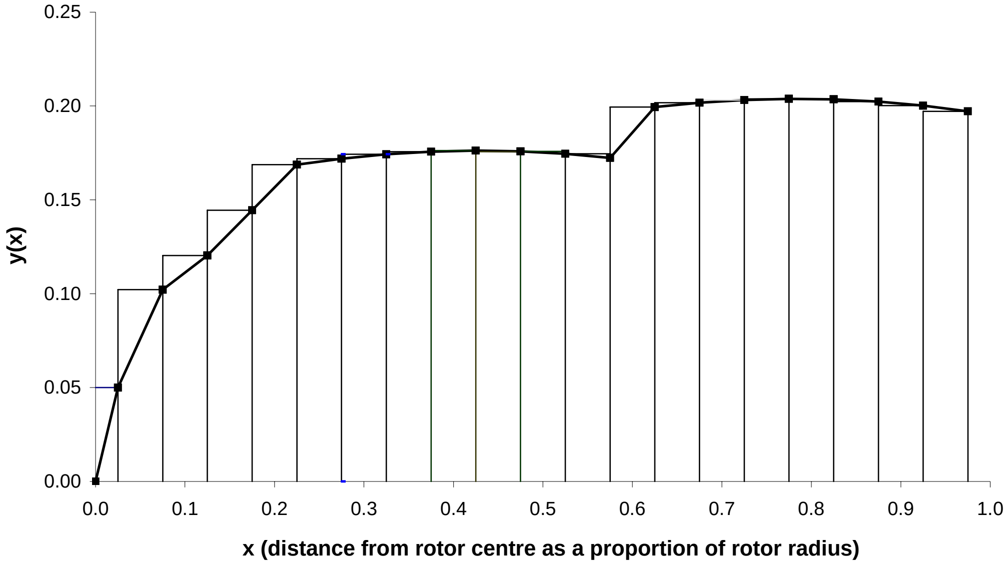


Figure 2 Numerical integration via the *SNHWB* spreadsheet. y(x) is defined in Equation 6 (see text).

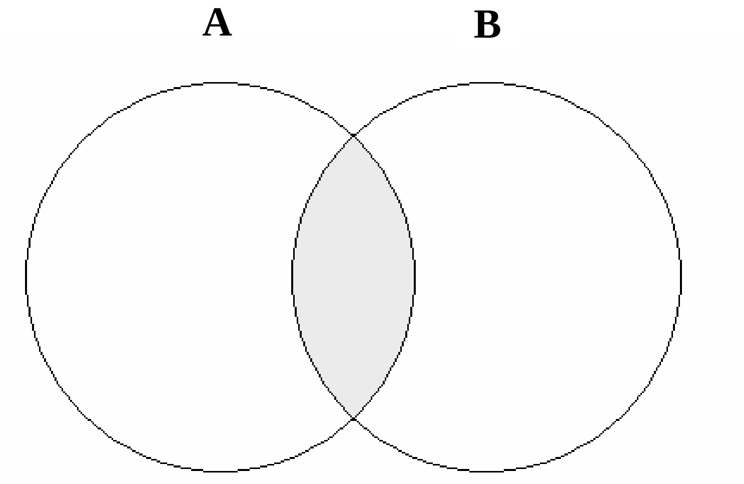
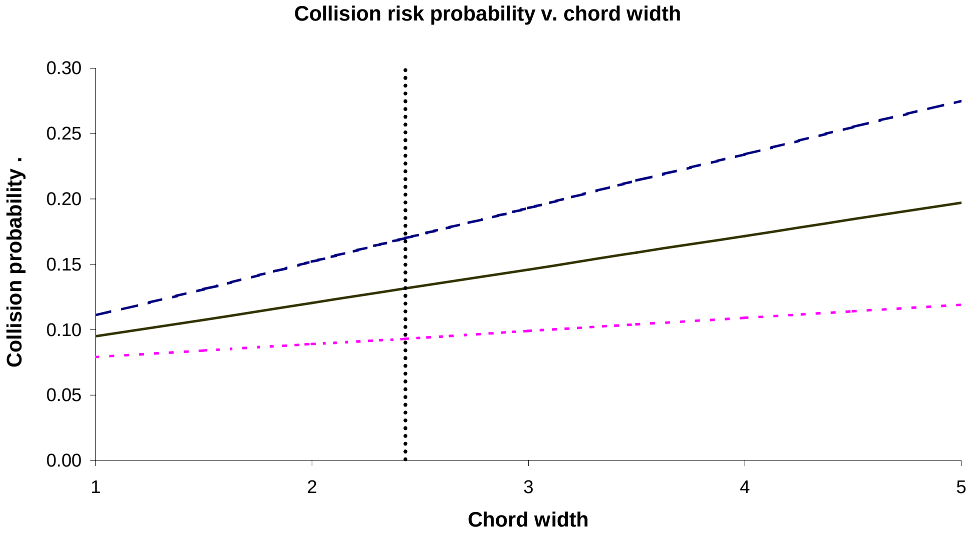


Figure 3 Representation of two partially overlapping wind farm rotors.

(4a)



(4b)

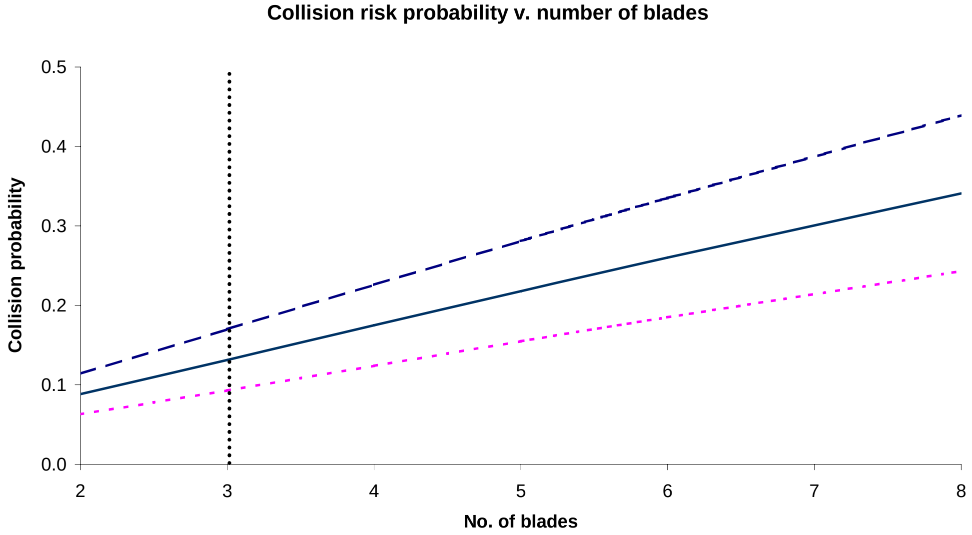
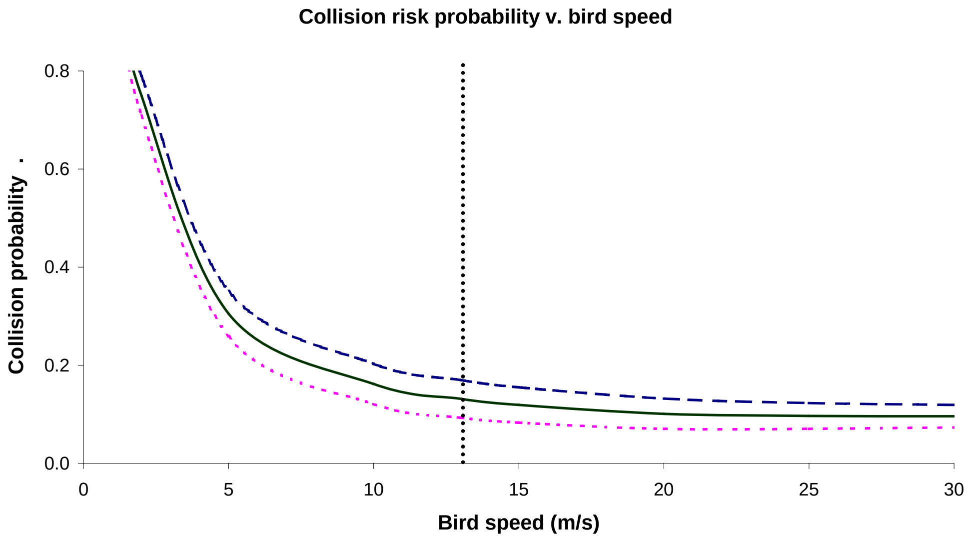


Figure 4 Effects on collision risk of variations in parameters used in the collision risk model (based on the SNHWB spreadsheet). The upper dashed line represents the 'upwind' scenario, the lower dotted line the 'downwind' scenario and the solid middle line the average between the two. In each case, original values (Fig. 1) remain constant apart from the parameter in question. Original parameter values are denoted by a vertical line.

(4c)



(4d)

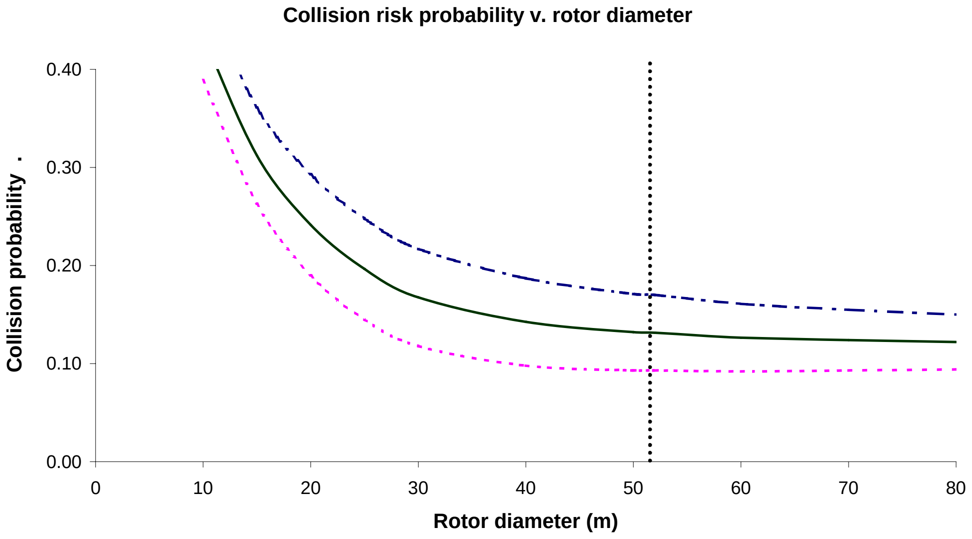
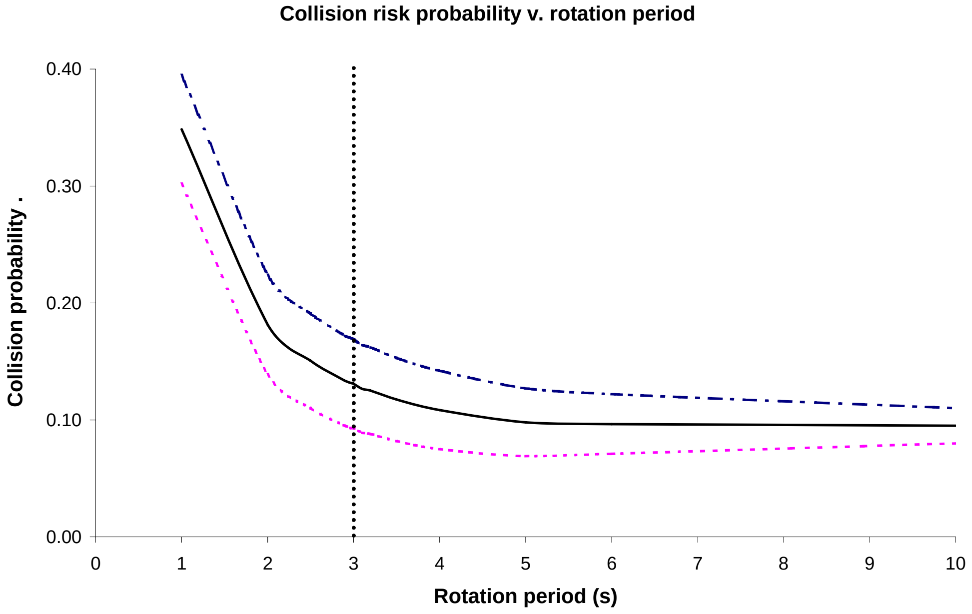


Figure 4 Continued.

(4e)



(4f)

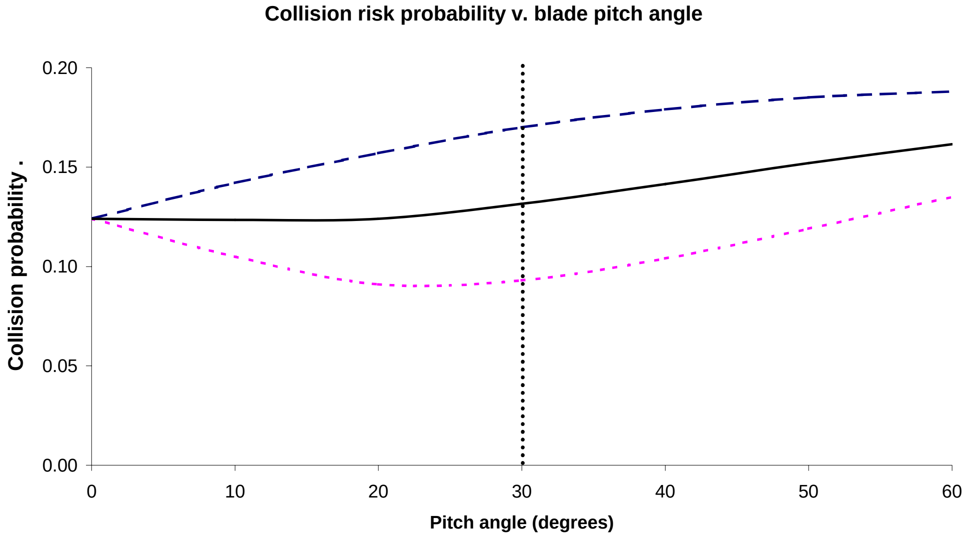
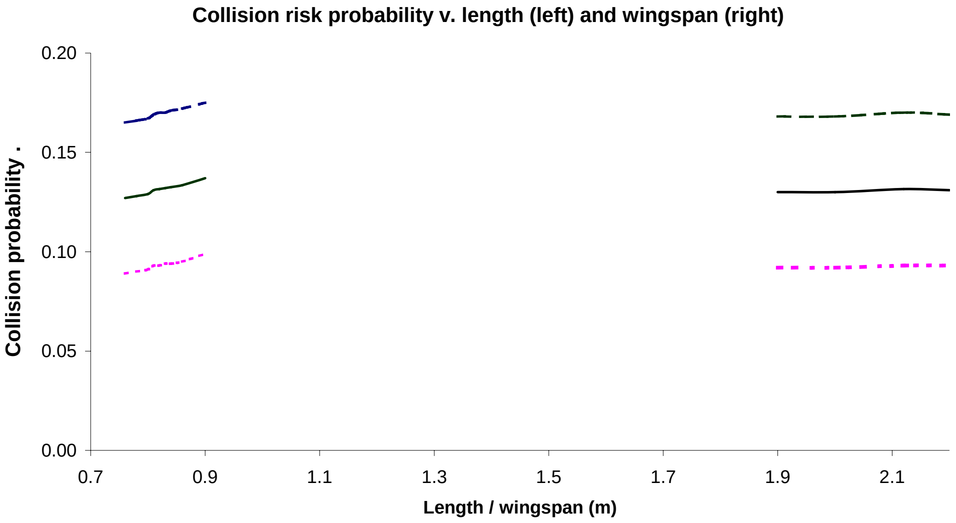


Figure 4 Continued.

(4g)



(4h)

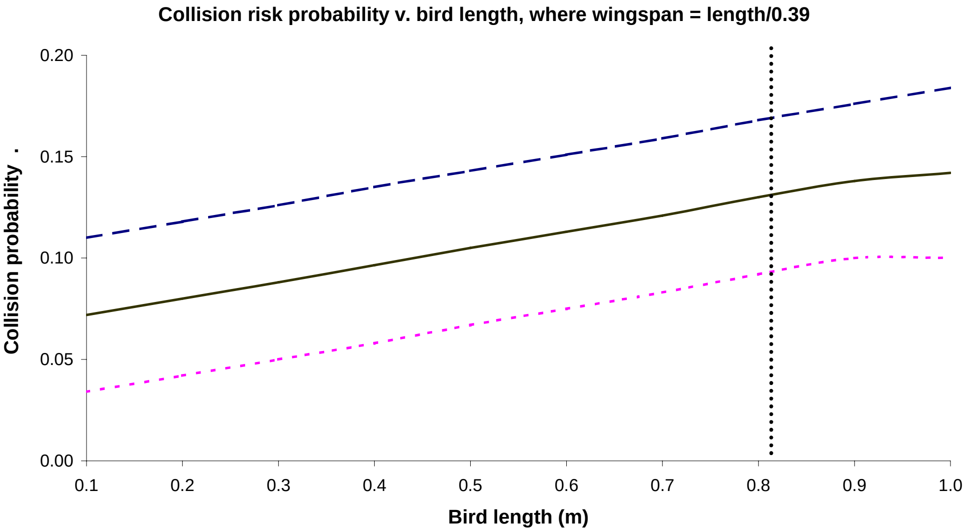


Figure 4 Continued.

APPENDIX I AID TO INTERPRETATION OF COLLISION RISK MODEL PARAMETERS AND OUTPUTS

The collision risk model uses measurements from the proposed wind turbines, data on bird size and speed and bird survey data to predict the probability of an individual bird colliding with a turbine rotor blade. This probability is not of great use itself as it assumes that birds do not take avoiding action when encountering a turbine. In order to predict mortality rates (numbers of birds killed over a given time period), the probability needs to be multiplied by the number of birds at risk per unit time and the rate at which an individual bird will take avoiding action when encountering a turbine. The avoidance rate is a crucial measure and yet it is the parameter about which least is known. Estimates of avoidance rate are usually derived from the ratio of mortality (estimated by corpse searches) to birds in the risk area, both of which are subject to (sometimes considerable) error. This error will have a large effect on predicted mortality. Because of this, the following brief account of the use of input parameters to the collision risk model should be considered provisional until much more detailed research has been carried out into avoidance rates.

Any error in bird survey data or measurement of wind turbines, bird speed or size could lead to errors in the predicted mortality rate. The utmost accuracy should be sought for any input parameters to the model, but the number of birds at rotor height and flight speeds are especially important. Table A1 lists the input parameters required to estimate mortality rates along with the ‘Ideal’ and ‘Standard’ data collection methods. The former gives the most accurate recommended method that could be used. The latter shows the method that is commonly employed in wind farm Environmental Impact Assessments (EIAs). Note also that the conditions covered are those that are recommended rather than those that are actually covered in many published EIAs. Comments on each input parameter are given below:

Rotor diameter – This is a structural variable and should be constant for a given wind farm. An accurate measurement (e.g within 0.5m) should be obtainable.

Rotation period – This may vary according to wind farm operations. If this is the case, a range of rotation periods should be used in the collision risk model covering all operational scenarios.

Pitch angle – As Rotation Period.

Max. chord – As Rotor Diameter.

Bird length and wing span – The model is not highly sensitive to variations in bird length. Values from the literature can be used, but a range of values should be used, particularly when there is a relatively wide variation within a species (sex or age differences for example).

Bird speed – Collision risk can be sensitive to bird speed. Values from the literature may not be adequate where they are unrepresentative of flight under different conditions. Also it is not advisable to assume bird speeds are similar between different species just because they are approximately the same size. If bird speeds from the literature are used in the collision risk model, a caveat should always be made that the data used may not be representative of actual speeds at the site. Note should also be made that speeds may vary according to conditions of wind speed and direction and visibility. Ideally, bird speeds should be ascertained under a range of conditions using remote survey technologies.

Bird numbers at risk height – This is a crucial measure in the field and incorporates methods of counting birds and methods of determining bird height, often at some distance from a potential site and with few reference points. Guidelines for recommended field methods are currently being devised by SNH (SNH 2005) which should be consulted before designing field surveys for EIAs. However, it should be noted that visual estimation will only be possible in good conditions whereas collision risk is likely to be higher when visibility is poor. For this reason, the ideal survey methodology would incorporate remote technologies such as infra-red detection in order to assess movements at night or in poor visibility. Where this is not possible, caveats should be placed on the interpretation of survey data, including an acknowledgement that the data cannot be extrapolated to conditions not experienced during the surveys.

Avoidance rate – Avoidance rates cannot be estimated under normal survey protocols. Avoidance behaviours may be studied under a range of conditions using remote technologies. Given that mortality rates vary according to individual sites and species, it is deemed unacceptable to use avoidance rates derived from other studies without clear and rigorous justification. This should include a demonstration that species, weather conditions, topography, wind turbine design and wind farm layout (for example) are sufficiently similar for an analogy to be drawn. However, even if this was possible, the original derivation should be critically examined for possible errors. Unless there is a very strong case for so doing, avoidance rates should not be used until further research is carried out. The value of the collision risk model is therefore dependent on greatly improved estimates of avoidance rates.

Reference

SNH (2005) *Survey methods for use in assessment of the impacts of proposed onshore wind farms on bird communities*. Draft v. 6.3.2, January 2005

Variable	**Data collection**		**Conditions covered**
	Ideal	**Standard**	
Rotor diameter	Direct measurement	Direct measurement	n/a (constant)
Rotation period	Direct measurement	Direct measurement	All operational scenarios
Pitch angle of blade	Direct measurement	Direct measurement	All operational scenarios
Max. chord	Direct measurement	Direct measurement	n/a (constant)
Bird length	Derive from literature	Derive from literature	All ages and both sexes
Wingspan	Derive from literature	Derive from literature	All ages and both sexes
Bird speed	Remote survey technologies	Derive from literature	All seasonal, diurnal and weather variations
Bird numbers at risk height	Survey data and remote survey technologies	Bird survey	All seasonal, diurnal and weather variations
Avoidance rate	Remote survey technologies	Derive from other reports	All seasonal, diurnal and weather variations

Table A1 Input parameters needed to calculate mortality rates using the SNH collision risk model and avoidance rates. Data collection methods are given where ‘Ideal’ gives the most accurate recommended method that could be used and ‘Standard’ shows the method that is commonly employed in wind farm EIA’s.