Modelling collisions between whales and ships. Assessing the potential for vessels to take avoiding action in response to sightings of whales.

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Abstract

A computer simulation model was developed in an attempt to understand the critical parameters needed to estimate the potential for vessels of different types, travelling at different speeds, to avoid collisions with large whales. The model incorporated three basic components; whale behaviour, the sighting process and vessel manoeuvrability. The behavioural component simulated whale movement, time of dive, time at the surface and production of visual cues such as blows. The sighting process component modelled the probability of detection of a blow from a whale at a particular location, and the vessel response component including response time and a model for the potential for altering course to avoid a sighting. In all cases, the simulation was run for a wide range of possible parameters to examine the sensitivity of the results to the assumptions that had been used. The behavioural and sighting process trials were expressed in terms of the distribution of radial distances to initial sightings of whales and the proportion of whales in the path of the vessel that were seen (this is the same as the parameter g(0) commonly referred to in the analysis of sighting surveys). A key assumption made for the purposes of the model is that the whales do not respond to the presence of the vessel.

Results indicated that the distribution of radial distances was mainly controlled by the detection probability function and largely unaffected by behavioural parameters and vessel speeds. In terms of estimating the proportion of whales that were detected for which an avoidance manoeuvre was effective, the key parameters that needed to be specified were the way in which the detection probability varied with range. Values chosen for detection probabilities were based on sighting survey data and were assumed to represent near optimum sighting conditions and a continuous lookout.

The results emphasise that even under optimum sighting conditions, with a fast response time and utilising the vessel's maximum manoeuvrability capacity, there is limited ability for large vessels to take effective avoidance action of large whales. Even under these ideal conditions, vessels over 200m are unlikely to be able to reduce the number of collisions by more than 30%. When time steamed at night and in poor sighting conditions is taken into account it is clear that other measures need to be considered in order to substantially reduce the number of collisions. This suggests that for models of interactions between vessels and whales there is a low sensitivity to assumptions used for collision avoidance by vessels.

Introduction

One possible method for estimating mortality due to vessel strikes is to model the combined distribution and movement patterns of whales and vessels in order to predict the number of potential collisions. The main uncertainties regarding such an approach are the responses of whales to vessels and the responses of vessels to whales. Both may have a large influence on whether a potential interaction results in an actual collision. Quantifying the response of whales to vessels remains a difficult problem, mainly due to insufficient data. This paper examines the potential of vessels to respond to whales, which is the easier part of the problem, but nevertheless a small step towards resolving some of the uncertainties.

Even a simple model that includes whale surfacing behaviour, the probability that a whale surfacing in a particular location will be seen and the results of a response by a vessel, can become quite complex. Without some kind of quantitative model it is very difficult to gauge the potential effectiveness of a vessel responding to a sighting in an attempt to avoid a collision. Such a model soon becomes too complex for analytical methods and so requires computer simulation. Some parts of the problem have already been well studied; manoeuvrability can be defined quite precisely for different vessel types and sizes. Whale behaviour remains a large unknown although some data are available from observational and telemetry studies. The process by which whales are detected visually and the way in which this is affected by range and conditions is still poorly understood and subject to large variability, but considerable efforts have been made to model the response during analysis of whale sighting surveys

For a vessel to attempt an avoiding action, a whale must first be detected and then a judgement made as to the best action to attempt to avoid a collision. If whales are travelling quite fast compared to the vessel then whale movement becomes a factor in determining that avoiding action. For a vessel travelling at 20 knots ($10ms^{-1}$) and a whale travelling at 3 knots ($1.5ms^{-1}$) detected at 2000m, the whale will move 300m as the vessel closes. Whale heading is difficult to judge even if the body is seen and most frequently the first sighting is just of the blow. Whale movements can also be erratic so it can be assumed that the vessel response will be based purely on whale location when seen, and not on any judgement of where the whale is likely to move. Once a manoeuvre has been initiated it is unlikely that it could be effectively altered based on subsequent sightings.

The possibility of stopping a vessel in response to a sighting of a whale has not been considered in the model for a number of reasons. Discussions with ship's officers have indicated that attempting to stop a vessel to avoid a whale would not be considered as a practical alternative to altering course. For larger vessels, the distance travelled before stopping is far in excess of the range at which whales can be detected. In addition, the model assumes no response of the whale to the vessel. Once vessel speed is reduced to be less than twice whale speed, assumptions about whale movement become a major unknown factor in estimating the number of collisions.

The objectives of this work include estimating the value in posting extra lookouts on vessels, looking at the relative merits of searching further ahead with binoculars or considering the effect of faster response times. These factors will inevitably vary with the speed, size and other characteristics of the vessel. Given that the model is based on some rather crude assumptions about whale behaviours and whale detection processes, another aim was to explore the sensitivity of the model to a range of assumptions to assess the validity of any conclusions drawn with respect to the uncertainties of real life situations. The results of this simulation are also incorporated into the assumptions used in the ongoing development of an agent based computer simulation of interactions between North Atlantic right whales and vessels.

Methods

The model assumes that the vessel is transiting an effectively infinite area on a constant heading at a constant speed *v*. Within the area, whale density is assumed to be constant to the extent that a given box ahead of the vessel always contains a fixed number of whales. True whale headings are assumed randomly distributed and whales are assumed to travel in straight lines at a constant speed *w*. The model does not allow for any response to the vessel by the whale. The logic used to derive the probability distributions from which whale headings are drawn and the entry points along the side of the box is taken from Hiby (1982). The relative direction of movement φ is chosen at random from a probability density defined as

$$\frac{h(\psi, w, v)}{\int_0^{2\pi} h(\psi, w, v).d\psi}$$

Where w is the speed of the whale, v is the speed of the vessel and $h(\psi,w,v)$ is the total area bordering the square from which a whale moving in direction ψ can enter the square in a fixed time increment. A similar procedure using the proportion of areas is used to determine which boundary of the square the whale enters from. Once the boundary has been determined the actual position along the boundary is random.

Whales are assumed to come to the surface at regular intervals, for a fixed period, during which time they emit a fixed number of blows, which are taken to be the only visual cues. Each blow has a certain probability of being detected, which is a function of location. Only the initial detection of each whale is modelled. Once a whale has been 'detected' it continues to move until it leaves the box. Each time a whale leaves the box it is replaced by a new whale in order to maintain a constant density.

The probability *P,* that a whale surfacing at a particular location is detected, is modelled by the hazard probability function. The hazard probability is assumed to be a Logit link function of the hazard rate which is a linear combination of covariates relating to location.

$$P(r,\theta) = \frac{e^z}{1+e^z}$$

Where

$$z = a_0 + a_1 r + a_2 r^3 + a_3 \theta^2$$

The choice of functional form for the hazard probability function was based on sighting from surveys of minke whales (Cooke and Leaper, 1998). Although the sighting characteristics of larger whales and minke whales are very different, it is likely that the functional form of the probability detection function with range will be similar. Minke whales are one of the few species where survey data have been analysed to explicitly model the detection probability of each surfacing and simulation models have been used to investigate the relationship of g(0) with vessel speed (Schweder, 1991). The parameters were selected on the basis of data on right whale detections from surveys and other reports (Ohsumi and Kasamatsu, 1986; ∅ien, 1990; Leaper and Papastavrou, 1999) to attempt to give a similar distribution of radial distances to initial detections that might be expected in good sighting conditions with few whitecaps. Although this study used the right whale as the general model, the results are likely to be appropriate for other large baleen whales. These parameters were such that it was assumed that the detection probability was zero for radial distances greater than 4000m and angles relative to vessel's head of greater than 105°. All observers were assumed to be independent with the same individual detection probabilities. Hence if there are two observers A and B, the probability that a whale at (r, θ) is detected by at least one observer is

$$1-\left(1-P_A(r,\theta)\right)\left(1-P_B(r,\theta)\right)$$

Table 1. Base case sighting parameters

Parameter	Value
A_0	0
A_1	$-2/4000$
A_2	$-6/4000^3$
A_3	$\left(\frac{105}{180}\pi\right)^{-2}$
Dive time (secs)	400
Surface time (secs)	267
Number of blows during surface time	5
Number of observers	1
Whale speed	3 knots (1.5ms^{-1})
Vessel speed	20 knots (10ms^{-1})

Figure 2 shows the change in probability of detection with range and bearing for a single cue and these base case parameters.

There are essentially no data on which to model the likelihood of a typical alert watch keeper on the bridge of a vessel detecting a whale compared to an experienced observer on a sightings survey. The parameter values chosen are based on sightings surveys where the job of the observer is solely to look for whales and so it was assumed that on average these would be an upper limit on the detection probabilities of a vessel's watch keeper who has additional duties. Sightings surveys are also only usually conducted in good sighting conditions. The model could easily be run with other values for sighting parameters to simulate different conditions.

Observers were all considered as being positioned at the aft end of the vessel. This is probably correct for most larger vessels and will make little difference to the results from smaller vessels. The height of the observer was not included in the model due to lack of data on how observer height affects detection probabilities. The limited data that are available suggest that for the typical range of heights of vessel's bridges (15 – 30m) the variation in detection probabilities is likely to be small. The model could also be run with lookouts placed on the bow of the vessel in which case it may be necessary to include a term for observation height. No allowance has been made for blind spots ahead of the vessel because these are unique to a particular vessel specific but blind spots could be included if specific vessels were of interest.

Whale behaviour

The basic model used for whale behaviour is that whales dive for a certain period of the time followed by a period a surface during which time they make a certain number of regular cues (such as blows) which enable them to be detected. A key set of parameters is clearly dive time in relation to the time it takes the vessel to travel the distance corresponding to the maximum range of detection.

Definition of 'collision'

For the purposes of this study the dive behaviour of whales had to be simulated in order to model the probability of a whale being at the surface and possible to be detected visually. However, it is well known that the surfacing patterns of whales are highly variable. In deep water situations where dive depth is well in excess of the draft of the vessel, a whale at depth will not be at risk of collision. This complicates the interaction between the sighting process and the collision aspects of the model. This could result in the estimated collision rate being highly sensitive to assumptions about dive time; for example if a dive time was chosen such that all the whales seen at a particular distance ahead of the vessel were at depth as the vessel passed then no collisions would be recorded. Rather than trying to define a probability distribution for dive times it was thought more appropriate to consider that any whale which passed directly under the vessel was classified as a 'collision'. It would be possible to include vessel's draft as a parameter and multiply estimated collision rates by an estimate of the proportion of time whales spend within that distance of the surface

This model is also not intended to simulate the complex hydrodynamic forces close to the vessel's hull such as described by Knowlton *et al.,* (1998). The vessel is modelled as a crude rectangle with the length and beam of the desired vessel. A collision is classified as a bow collision if the whale crosses the side of the rectangle perpendicular to the heading and a side collision if the whale crosses the side of the rectangle parallel to the heading. The relative proportions of side and bow collisions are of value in validating and interpreting the simulation results. Data on the location of collisions would also be important if hydrodynamic forces were considered in more detail. Knowlton *et al*., (1998) also suggest that whales up to 15 – 20m outside of the beam of certain vessels may be drawn into collision situations by the hydrodynamic forces. These results indicate that it may be more appropriate to increase the collision zone beyond the beam of the vessel. The hydrodynamic forces due to a turning vessel trying to avoid a whale may also be significant.

Vessel manoeuvrability model

There are a number of standard parameters used to measure the ability of vessels to manoeuvre. These are described in Rawson and Topper (1991). Of key interest to this model is the initial response of the vessel to the start of a manoeuvre. For the purposes of avoiding a whale, the vessel is unlikely to turn through more than 45^o and so the commonly quoted values of advance and transfer for a 90^o turn or tactical diameter are not directly applicable.

For the purposes of defining a simple general model to describe the approximate location of the rectangular model of the vessel's hull during a turning manoeuvre, the following parameters were used:

Vessel length (L)
Vessel beam (B)
Vessel speed (V)

Position of pivot point (as a proportion of length aft of the bow, negative pivots are forward of the bow)
Initial turning (θ_L) (heading change in one vessel length travelled for a rudder angle of 30°)
Response time (time from first sighting to commencing manoeuvre)

It was assumed that forward speed remained constant during the turning manoeuvre. As a reality check other parameters were calculated from these input data. The initial turning rate (θ_R) in degrees per second is given by

$$\theta_R = \theta_L V / L$$

and the time to turn through 20° is $20/\theta_R$

These values may be compared to published values for particular vessels to check the accuracy of the simplified model. Figure 1 shows an example of the track of a vessel produced by the simplified model. In this case the pivot point is located ahead of the vessel resulting in the stern swinging a relatively long way to port during the turn to starboard. Location of the pivot point will depend on the trim of the vessel and to a lesser extent on the depth of the water. Simulation runs were conducted with different pivot point positions to examine the possible effects for each vessel type.

Table 2. Parameters for generalised vessel types used in model

Type	Length (m)	Beam (m)	Draft (m)	Speed (knots)	Pivot point	Initial turning
160,000 ton tanker	340	56	22	15	-0.15	6
30,000 ton container ship	200	30	12	20	0.15	6
7,000 ton coastal tanker	130	20	7	12	0.15	6
4,000 ton ferry	75	15	4	15	0.30	10
500 ton fishing boat	30	8	3	10	0.30	9

The base case response time from the initial sighting to commencing the avoidance manoeuvre was taken as 30 seconds. This was considered to be the minimum realistic time to examine the sighting through binoculars, report it and initiate a manoeuvre.

The sighting model was run first to generate a set of simulated locations of initial sightings, together with whale travel direction and stage in the dive sequence that could potentially result in collision situations. A simulated avoidance manoeuvre was then undertaken for each of these sighting locations to see if a collision resulted. In the initial simulation the avoidance manoeuvre was simply to turn away to the maximum extent possible from the side on which a sighting occurred. If data on whale heading and movement could be judged then these manoeuvres could be slightly refined to take this into account but it is considered unlikely that it would be possible to predict whale movement patterns at sea from a single sighting.

In each case the simulation was run for 10^8 simulation steps (each step is equivalent to 1 second of real time) through an area with a density of 0.03 whales/km^2. Each run with a different set of parameters took about one hour on a desktop PC.

Results

Figure 3 shows the proportion of whales detected by perpendicular distance for the base case parameters. Data from sightings surveys are commonly presented in this format and this plot is included for comparison with such surveys. In terms of collisions it is the value of g(0) that is of interest. Base case values are given in table 3.

Table 3. Values of g(0) values for base case with one variable parameter

Variable parameter	g(0)
Number of observers	
Obs =1	**0.46**
Obs =2	0.61
Obs =3	0.67
Vessel speed (ms^{-1})	
V= 5	0.70
V = 7.5	0.55
***V* = 10**	**0.46**
Dive time	
Dt =200	0.65
Dt =400	**0.46**
Dt = 600	0.35
Surface time	
St=130	0.45
St =267	**0.46**
St =400	0.40

Lines in bold indicate identical base case runs

Figure 4 shows the proportions of whales that are first detected on each blow in the surfacing sequence. This is for the base case of 5 blows in each surfacing sequence. The plot shows the mean over all the case given in table 3 but the shape of this distribution was not affected substantially by other parameters. There may frequently be cases where the first blow is seen but not with enough confidence to initiate an avoidance manoeuvre. In these situations the observer may wait to see a second blow. This waiting time can be incorporated in the mean response time but an additional correction needs to be applied for whales which are seen on the last blow in the sequence. This would result in 24% of the sightings made not being acted upon unless they were sufficiently close that the body of the whale could be seen. In many cases where a blow is seen with the naked eye, the body of the whale may well be visible with binoculars.

Figures 5a – 5d show the distribution of radial distances for whales detected in a 20^{o} sector ahead of the vessel for the base case parameters with one variable. Figure 5a shows that increasing the number of observers does substantially change the shape of the distribution whereas changing the dive time, surface time or vessel speed have only minor effects on the relative proportions detected at different distances. These results suggest that the simulation output should be relatively robust to assumptions about dive cycle parameters. It should be noted however that these results are for a fixed number of cues per cycle. Variation in the cue rate per cycle has a similar effect to variation in the number of observers since, for example doubling the cue rate is approximately equivalent to doubling the number of observers. The dive cycle parameters were based on a limited set of data collected in the Bay of Fundy and Scotian Shelf (Leaper *et al*., 1999). Hain (1997) used generally lower surface times (30 – 60 seconds) to estimate probability of detection of right whales during aerial surveys in Cape Cod Bay but similar dive times (60 – 360 seconds). The lack of sensitivity of the overall results to changes in surface time suggests that the choice of data used to model surface time will not have a large effect on the resultant distribution of simulated sighting locations.

Table 4 shows the proportions of collisions that would otherwise have occurred which were avoided by altering course. These are referred to as the percentage 'success' for the base case parameters for each general vessel type given in table 2. Figure 7 also shows how these values vary with vessel speed. This still leaves the question of how the speed of the vessel is related to the total number of collisions per kilometre travelled that are likely to occur. In this simulation, which does not allow for any whale response to approaching vessels, the simulated collision rate without avoiding action by the vessel will always increase with decreasing vessel speed. For the purposes of determining which vessels could usefully post extra lookouts and attempt avoiding action, the percentage 'success' in avoiding collisions is more relevant than the overall collision rate. This value should also be much less sensitive to assumptions about whale reaction to vessels since the proportion of whales that find themselves close to the vessel but successfully avoid a collision is unlikely to be affected by whether the vessel is manoeuvring. In all cases, the success of the avoiding action decreased approximately linearly with vessel speed with the gradient of the slope being steeper for smaller vessels. The irregularity of the plots indicates variation caused by the simulation process and could be improved by running the simulation for longer in each case.

Table 4.

Type	Length	Beam	Speed (knots)	Pivot point	Initial turning	Response time	No. of observers	% 'success'
160,000 ton tanker	340	56	15	-0.15	6	30	1	3%
30,000 ton container ship	200	30	20	0.15	6	30	1	20%
7,000 ton coastal tanker	130	20	12	0.15	6	30	1	36%
4,000 ton ferry	75	15	15	0.30	10	30	1	39%
500 ton fishing boat	30	8	10	0.30	9	30	1	60%

Discussion

The values obtained for the proportion of collisions that were successfully avoided can be considered as upper limits for situations without extra dedicated lookouts and there are many factors that could cause the ability of vessels to avoid collisions with whales to be much lower. It would be difficult to put generalised lower limits on these values that could be close to zero in some circumstances. The cases examined are generally optimum i.e. good sighting conditions, instant identification and appropriate avoiding action. In many situations such as at night, sea state 4 and above, or reduced visibility, the effectiveness of taking avoiding action will be much reduced or not possible at all. A suggested correction factor when attempting to compare the effectiveness of vessel manoeuvring to other measures such as routing would be to multiply the percentage success rates from the simulation by 0.2. This figure is based on the assumption of darkness precluding a visual watch for 50% of the time and weather conditions only allowing an effective watch for 40% of the daylight hours. For some scheduled routes that operate mainly in daylight, this may not be appropriate. Hain (1997) analysed weather conditions in Cape Cod between January and March and found that 22% of days had wind speeds of 10 knots or less and 50% of days had wind speeds of 14 knots or less. These figures suggest that, allowing for fog as well as wind strength, 40% of daylight hours with good sighting conditions may be rather optimistic for Cape Cod Bay and areas such as the Great South Channel may well be much lower.

The modelling exercise described clearly has a number of limitations but it does allow an investigation of the sensitivity of the effectiveness of avoiding action to the assumptions that need to be made about whale and vessel behaviour. The overall results are most sensitive to the detection probabilities. The selection of a 4km maximum range of detection was based on naked eye searching and could be improved upon if observers scanned ahead close to the trackline using binoculars. Southern right whales have been detected at distances of as great as 4.5nm (8.3km) by observers using binoculars on sighting surveys, however even on these surveys, mean detection range was only 2.4 nm (4.4km) (Ohsumi and Kasamatsu, 1986). During Norwegian naked eye surveys in the North Atlantic the maximum radial distance to sightings of humpback and fin whales was around 5km. In around 70% of these sightings the initial cue was reported as the blow only (∅ien, 1990).

Another key limitation of this study is that only single animals were considered. Where whales occur in groups, avoiding one individual may increase the probability of collision with another. The model could be extended to investigate this. In most cases with a group of whales, the most likely scenario is that there will be whales to both sides of the animal that is first detected. This would result in the effectiveness of altering course away from a sighting being much reduced. An exception to this would be if an active group was cohesive enough that the full extent of the group could be seen and avoided. This may be the case with some courtship groups. In this situation the group may be seen at a greater range with a higher probability than a single individual and avoidance action may be much more effective.

Although the model runs were specifically based on right whales, the results would likely be similar for most large baleen whales and the model could easily be run with parameters tuned to the particular species in a given area. The results suggest that for large vessels, models to predict collision rates that do not take into account vessel response will not be substantially biased compared to the other uncertainties involved.

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Figure 1. Track of 'model' vessel. In this example the pivot point is forward of the hull.

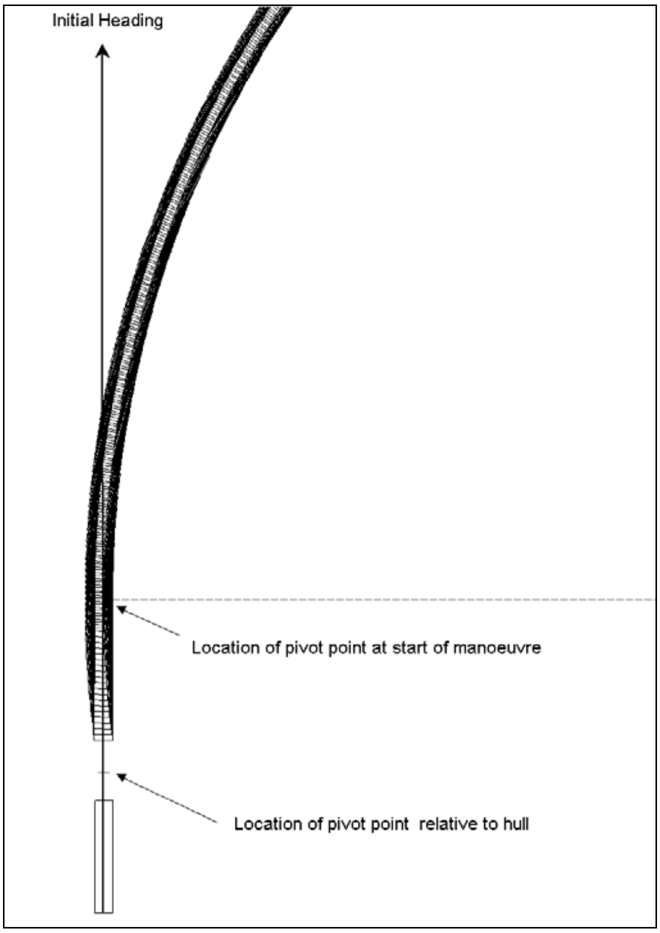

Figure 2. Base case probability of sighting a single cue (blow) from a whale at a given radial distance and bearing relative to vessel's head

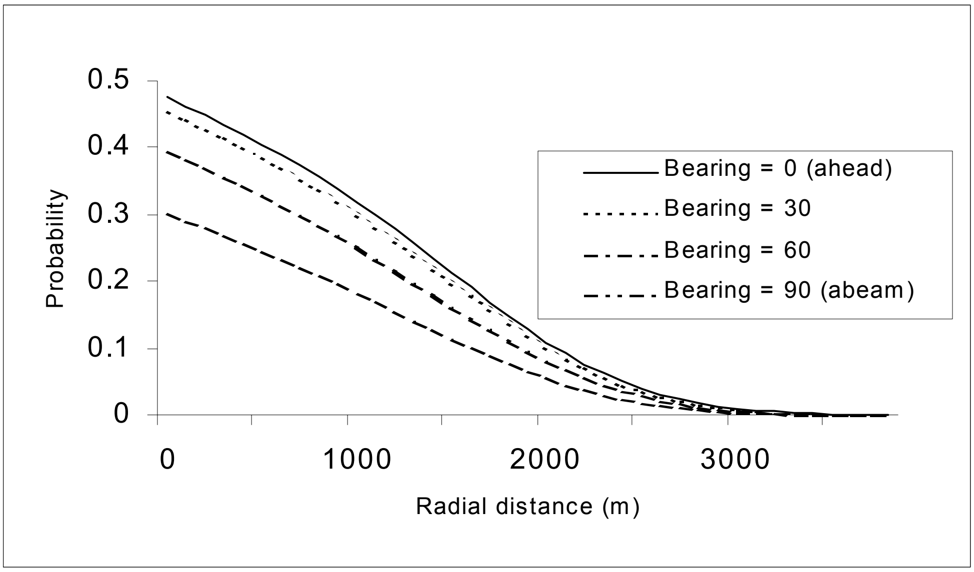

Figure 3. Base case distribution of sightings by perpendicular distance from vessel's track

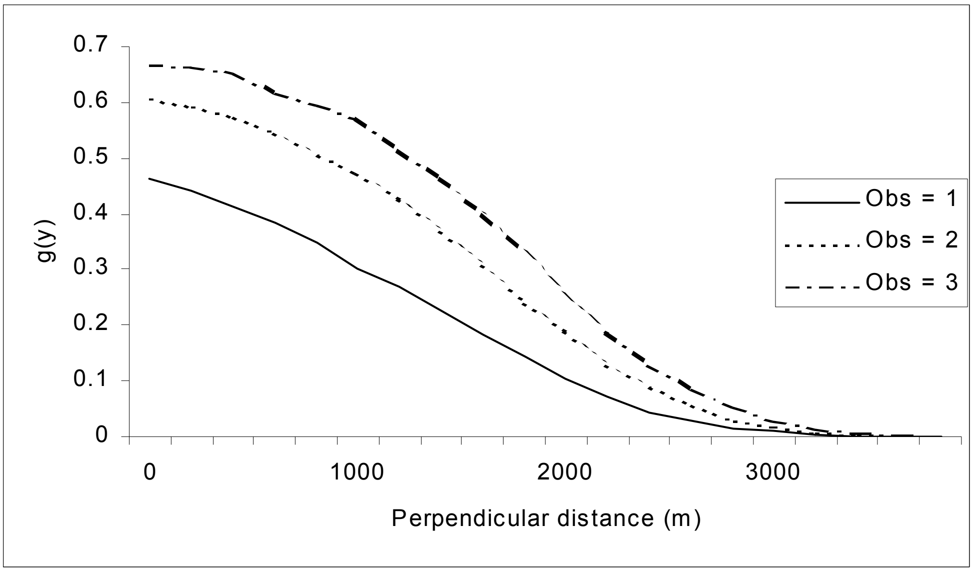

Figure 4 Proportions of whales first detected at blow *n* in surfacing sequence that subsequently resulted in a collision

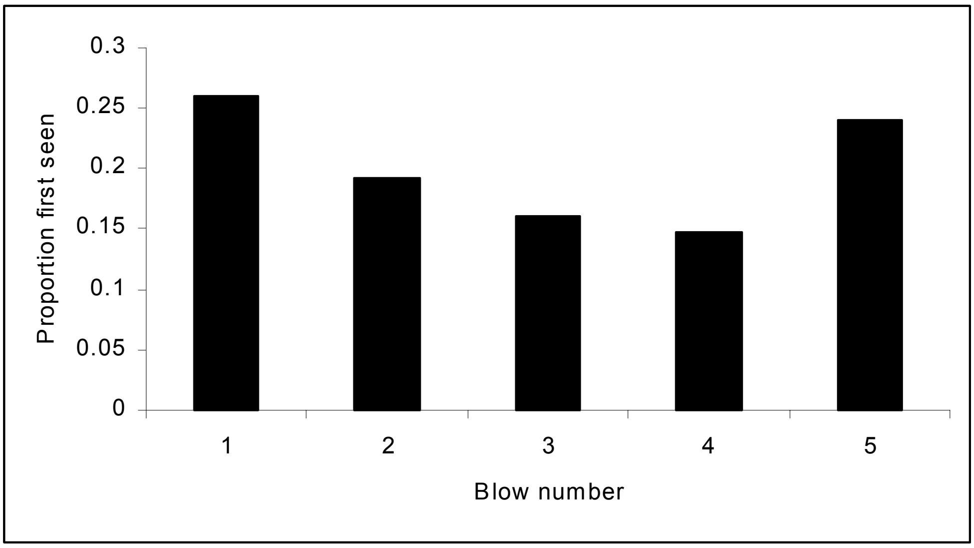

Figure 5a. Proportions of sightings in 20° sector ahead of vessel by radial distance categories

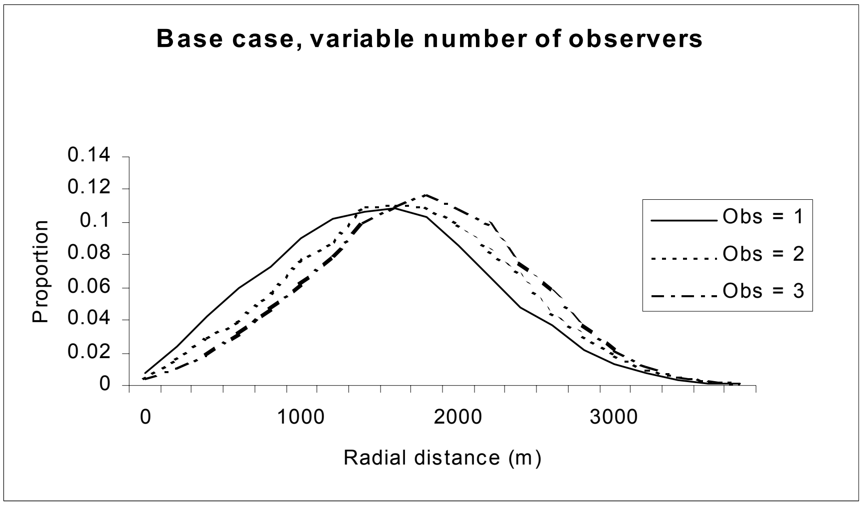

Figure 5b

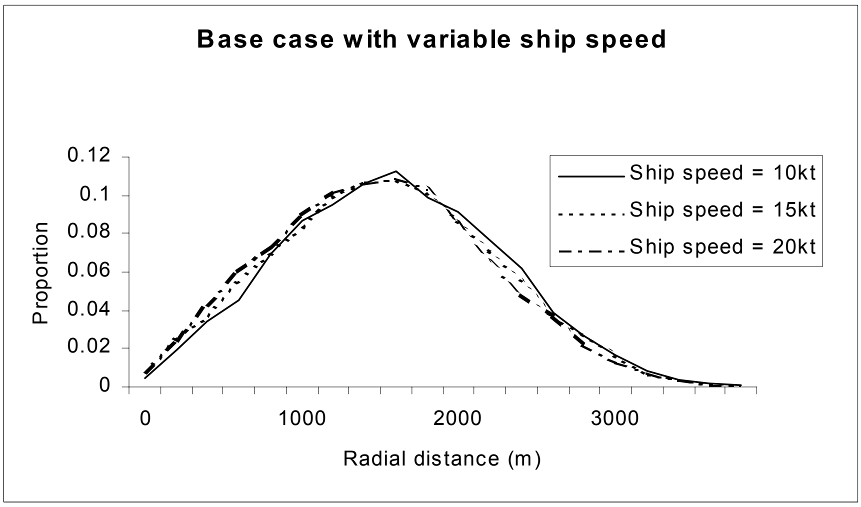

Figure 5c

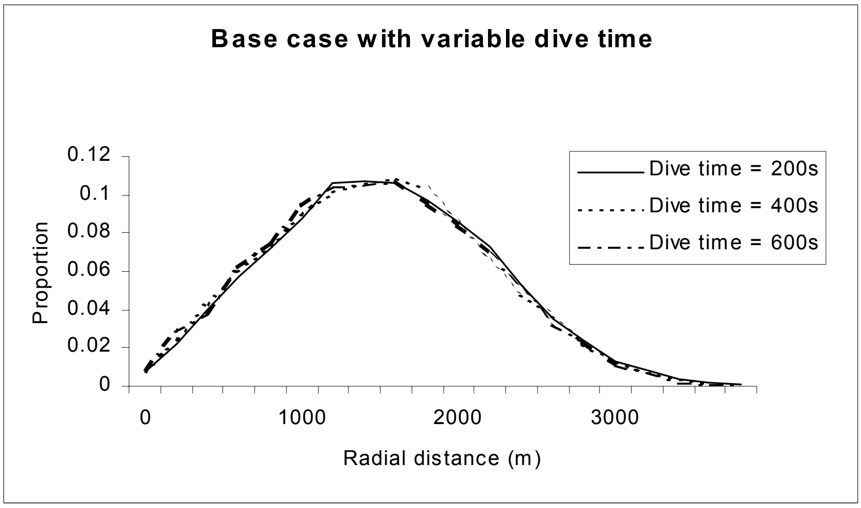

Figure 5d

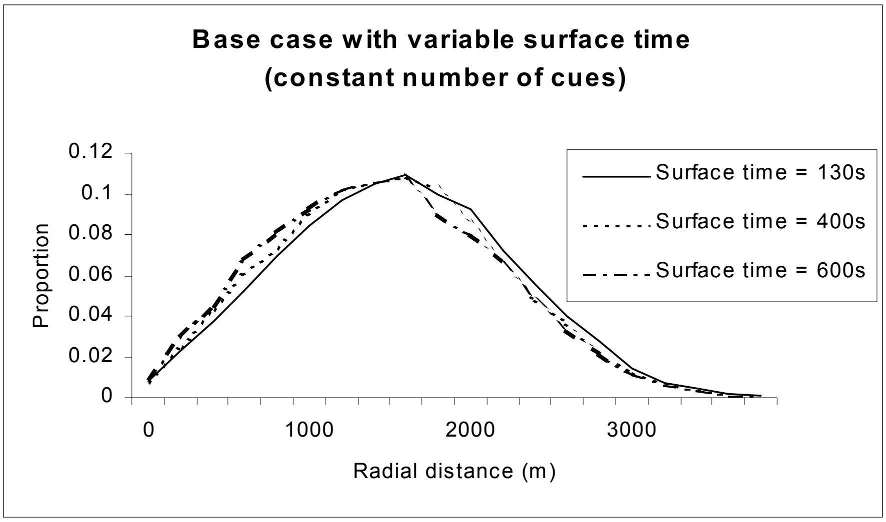

Figure 6. Collisions that were successfully avoided as a proportion of the total that would have occurred if no avoiding action was taken for generalised vessel types across a range of speeds.