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Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales

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Abstract. Collisions with vessels are a serious threat to a number of endangered large whale species, the North Atlantic right whale (*Eubalaena glacialis*) in particular. In late 2008, the U.S. National Oceanic and Atmospheric Administration issued mandatory time-area vessel speed restrictions along the U.S. eastern seaboard in an effort to mediate collision-related mortality of right whales. All vessels 65 feet and greater in length are restricted to speeds of 10 knots or less during seasonally implemented regulatory periods. We modeled mortality risk of North Atlantic right whale when the vessel restrictions were and were not in effect, including (1) estimation of the probability of lethal injury given a ship strike as a function of vessel speed, (2) estimation of the effect of transit speed on the instantaneous rate of ship strikes, and (3) a consideration of total risk reduction. Logistic regression and Bayesian probit analyses indicated a significant positive relationship between ship speed and the probability of a lethal injury. We found that speeds of vessels that struck whales were consistently greater than typical vessel speeds for each vessel type and regulatory period studied; a use-availability model fit to these data provided strong evidence for a linear effect of transit speed on strike rates. Overall, we estimated that vessel speed restrictions reduced total ship strike mortality risk levels by 80–90% with levels that were closer to 90% in the latter two of the four active vessel speed restriction periods studied. To our knowledge, this is the most comprehensive assessment to date of the utility of vessel speed restrictions in reducing the threat of vessel collisions to large whales. Our findings indicate that vessel speed limits are a powerful tool for reducing anthropogenic mortality risk for North Atlantic right whales.

Key words: Bayesian risk analysis; endangered whales; *Eubalaena glacialis*; right whale; ship strike; speed restrictions; use-availability; whale-vessel collisions.

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Introduction

Violent collisions involving vessels and whales are a growing concern for marine resource managers. The outcome for the whale is often death or serious injury, including fractured bones, hemorrhaging, or propeller lacerations (Moore et al. 2004, Campbell-Malone et al. 2008). The occurrence of vessel strikes is a threat to a number of endangered large whale species (Clapham et al. 1999, Waring et al. 2011). In U.S. waters alone, tens of large whale deaths per year are ascribed to vessel strikes (Henry et al. 2012, van der Hoop et al. 2012), and globally the

number may be in the hundreds of deaths each year (Laist et al. 2001, Jensen and Silber 2003, Van Waerebeek et al. 2007). Not all dead whales are detected (particularly in offshore waters), and the cause of death for carcasses that are recovered cannot always be determined due to decomposition (Henry et al. 2012). Thus, the actual number of whales that succumb to vessel collisions is likely far higher than reported.

The North Atlantic right whale (*Eubalaena glacialis*) is particularly vulnerable to vessel strikes. In a population that contains fewer than 500 individuals, an average of about two known deaths have been documented each year for at least the last decade (Waring et al. 2011, Henry et al. 2012). This anthropogenic threat has slowed the recovery of this highly depleted species (Knowlton and Kraus 2001, Kraus et al. 2005, NMFS 2005).

A number of approaches have been taken to reduce the threat of vessel strikes to right whales. These actions include mariner awareness-raising programs and modifications of customary vessel operation practices that include vessel speed reductions and changes in vessel routing patterns (Vanderlaan and Taggart 2009, Silber et al. 2012).

Vessel speed has been identified as a contributing factor in the occurrence and severity of vessel collisions with various marine vertebrates (Laist and Shaw 2006, Hazel et al. 2007), large whale species in particular (Laist et al. 2001, Jensen and Silber 2003, Pace and Silber 2005, Vanderlaan and Taggart 2007). Impact forces involved in a collision increase with increasing vessel speed (Wang et al. 2007, Campbell-Malone et al. 2008, Silber et al. 2010) and the probability of death or serious injury of a whale involved in a collision increases as vessel speed increases (Pace and Silber 2005, Vanderlaan and Taggart 2007, Wiley et al. 2011). Gende et al. (2011) found that the encounter distance between whale and vessel is also influenced by vessel speed such that higher vessel speeds may increase the probability of a strike occurring. These various findings have prompted the use of vessel speed restrictions as a means of diminishing the threat of vessel strikes to endangered marine mammal species in various locations (NPS 2003, Laist and Shaw 2006, Tejedor et al. 2007).

To address the threat of vessel strikes to North Atlantic right whales, the U.S. National Oceanic and Atmospheric Administration's National Marine Fisheries Service (NMFS) issued regulations that limit vessel speeds in certain locations along the U.S eastern seaboard (NOAA 2008). The speed limits are in effect seasonally in prescribed areas (''seasonal management areas'', or "SMAs"). The SMAs were designed to correspond with the timing and locations of right whale migration, feeding, and nursery activities where they co-occur with high vessel traffic densities (typically near sizable port entrances and vessel traffic bottlenecks), while also minimizing economic impact to the maritime transport industry (Fig. 1). While in a management zone, all vessels 65 feet and greater in length are required to travel at 10 knots or less (speed over ground). Sovereign (e.g., U.S. military) vessels are exempted from the regulations.

It can be difficult to determine with certainty if vessel speed limits and related management actions are achieving their intended objective of reducing whale strikes, particularly in the relatively short period since their enactment (Pace 2011, Silber and Bettridge 2012). Studies have used risk reduction models to assess the relative effectiveness of various vessel routing measures (Vanderlaan and Taggart 2009, Vanderlaan et al. 2009, van der Hoop et al. 2012). Others have provided estimates of vessel strike risk reduction resulting specifically from NOAA's vessel speed restrictions (Lagueux et al. 2011, Wiley et al. 2011). However, estimates arising from the latter studies were obtained by examining only limited aspects of the restrictions both temporally and geographically. Further, most assessments of risk to date have been made by simulating whale and vessel movement to quantify strike rates. Although this approach is useful for determining how likely a whale is to come in close proximity to a vessel, it cannot be used to account for whale avoidance behavior that can prevent vessel collisions.

In this paper, we attempt to model the effect of mandatory vessel speed restrictions along the U.S. east coast on comprehensive North Atlantic right whale mortality risk. This includes an assessment of risk associated with different years and management regimes (i.e., vessel speed restrictions in/not in effect). Our analysis includes three components: (1) estimation of the probability of lethal injury given a ship strike at different

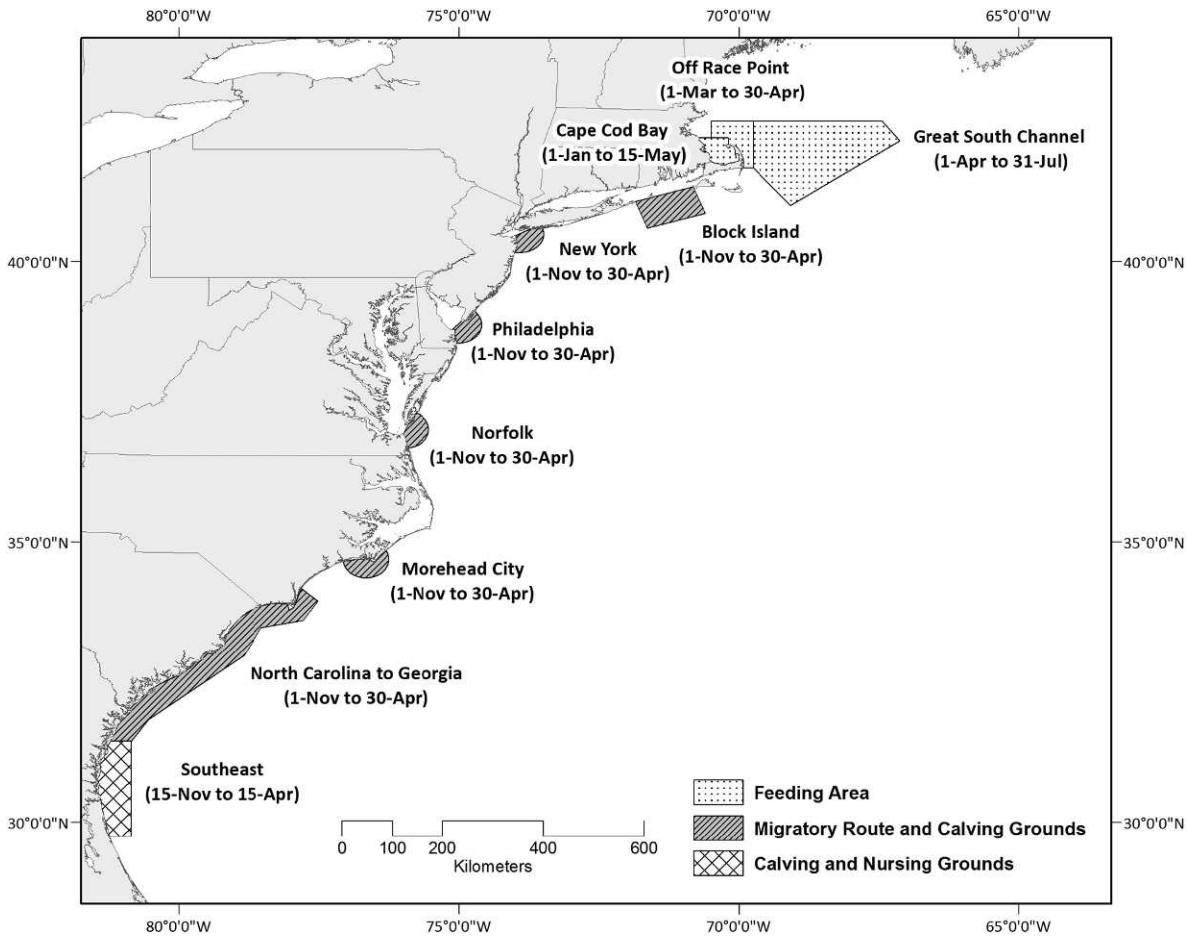

Fig. 1. Times and locations of vessel speed restriction seasonal management areas (SMAs) for North Atlantic right whales along the U.S. east coast.

vessel speeds; (2) estimation of the effect of transit speed on the instantaneous, per capita rate of ship strikes; and (3) a consideration of total risk reduction. The first component involves analyzing a dataset of ship strikes roughly twice the size as in previous work (e.g., Vanderlaan and Taggart 2007), while the second involves fitting a Bayesian model to describe the differences in observed ship speeds for vessels that struck whales from those which may or may not have struck whales. This latter approach differs conceptually from previous approaches to quantifying strike rates in that the effect of vessel speed on instantaneous strike rate is explicitly estimated via a statistical model. Finally, we jointly analyze all of these data sources to produce an estimate of mortality risk that simultaneously accounts for all sources of uncertainty.

Methods

Lethality of whale strikes

To explore the relationship between vessel speed and the lethality of vessel strikes, we examined records of known vessel strikes of whales in which sufficient information was provided to indicate with certainty both the speed of the vessel at the time of the strike and the severity of injury or fate (e.g., death resulted) of the whale involved in the collision. Records included all large whale species and all geographic areas worldwide.

In compiling vessel strike data for our analysis, we relied on the same data used in related

studies by Pace and Silber (2005) and Vanderlaan and Taggart (2007). The latter study used published sources (Laist et al. 2001, Jensen and Silber 2003) that detailed the historical record of vessels striking large whales ($n = 47$). Pace and Silber (2005) used these same data in addition to unpublished records of vessel/whale strikes ($n = 5$) not used by Vanderlaan and Taggart (2007). We began our compilation with the data set ($n = 52$) used by Pace and Silber.

By reviewing scientific literature and canvassing information from various stranding programs and data sources, we then compiled additional vessel strike records that occurred after the Pace and Silber (2005) study had concluded in May 2005, or were not previously documented in the Pace and Silber analysis. We included only those cases in which both the vessel speed and the fate of the whale were known with certainty. This yielded a total of 38 records not analyzed in previous studies. Unique records that met criteria for evaluation were derived from Neilson et al. (2012) for Alaskan waters ($n = 7$); NMFS' National Marine Mammal Stranding databases for the U.S. northeast ($n = 10$), northwest ($n = 2$), and southwest ($n = 7$) regions, national program ($n = 5$), and the Hawaiian Islands Humpback Whale National Marine Sanctuary ($n = 7$). A total of 90 records meeting the criteria identified above were used in our analysis. These data included records through September 2012.

For each record we recorded a binary response variable for whether injuries were lethal/not lethal, using the same criteria as in previous studies (e.g., Vanderlaan and Taggart 2007, Andersen et al. 2008). Records in which the whale was known to have died (e.g., carcass observed) or a severe injury was described (e.g., blood in the water, open or bleeding wounds observed) were classified as "lethal" (Vanderlaan and Taggart 2007). Individuals that were known to have survived (for example, where there were subsequent sightings of the living whale), who exhibited no apparent injury, or only minor injuries (e.g., visible non-bleeding wound, or no report of blood) were recorded as non-lethal "0" responses (i.e., we assumed these whales did not die as a result of the encounter). In making these determinations, we adopted the same classification of records utilized by Pace and Silber (2005), Vanderlaan and Taggart (2007), and Neilson et al. (2012). This left $n = 30$ records for which we made new injury determinations.

In total, our data set consisted of roughly double the number of observations previously used to estimate the relationship between vessel speed and the lethality of ship strikes (see, e.g., Vanderlaan and Taggart 2007), so we hoped to substantially increase precision of parameters describing the strike speed-mortality relationship. Two different analyses were performed. First, we analyzed the data using a simple logistic regression model where severity of injury ($Y_i = 1$, lethal injury; $Y_i = 0$, non-lethal injury) is modeled as a Bernoulli response variable with success probability M_i, where

$$\text{logit}(M_i) = \beta_0 + \beta_1 x_i.$$

Here, M_i gives the probability of a lethal injury for strike i, and x_i gives the speed (in knots) of the vessel involved in the collision. We provide estimates from this approach for historical consistency; several authors have used this formulation when addressing mortality associated with ship strikes (Pace and Silber 2005, Vanderlaan and Taggart 2007, Lagueux et al. 2011). For this approach, we conducted analysis with the 'glm' function in the R statistical language (R Development Core Team 2012).

Second, to integrate the relationship between ship speed and mortality into our comprehensive mortality risk analysis, we conducted a Bayesian probit regression analysis, which is similar to a logistic regression but uses the probit link function in place of the logit. In particular, we considered the model

$$\text{probit}(M_i) = \beta_0 + \beta_1 x_i. \tag{1}$$

The probit link function leads to some computational advantages when conducting Bayesian analysis; in particular, one can construct a collapsed Gibbs sampler as suggested by Albert and Chib (1993) to sample regression parameters. Defining $\mathbf{X}$ to be the design matrix where

$$\mathbf{X}' = \begin{bmatrix} 1 & 1 & \cdots & 1 \\ x_1 & x_2 & \cdots & x_N \end{bmatrix}$$

and augmenting the parameter space with $\tilde{Y}_i$ values for each observation, the algorithm proceeds as follows:

(1) Update $\tilde{Y}_i$ values according to a truncated normal distribution. If $Y_i = 1$, sample $\tilde{Y}_i \sim$ Normal ($[\mathbf{X}\beta]_i$, 1) with the constraint that $\tilde{Y}_i > 0$; if $Y_i = 0$, sample $\tilde{Y}_i \sim$ Normal ($[\mathbf{X}\beta]_i$, 1) with the constraint that $\tilde{Y}_i < 0$.
(2) Update the vector of regression parameters (in this case $\boldsymbol{\beta}' = [\beta_0\ \beta_1]$) according to $\boldsymbol{\beta} \sim$ MVN $((\mathbf{X}'\mathbf{X})^{-1}\mathbf{X}'\tilde{\mathbf{Y}}, (\mathbf{X}'\mathbf{X})^{-1})$, where MVN denotes the multivariate normal distribution. This formulation implies a flat, improper prior distribution for the regression coefficients.

Posterior predictions of mortality probability at pre-specified vessel speeds can then be produced by sampling from

$$M_k = \Phi(\mathbf{X}_k\beta) \tag{2}$$

where $\Phi(Z)$ denotes the cumulative distribution function of the standard normal distribution evaluated at Z, and $\mathbf{X}_k$ gives the design vector associated with predictions (e.g., $\mathbf{X}_k = [1\ x_k]$). We used this algorithm to sample the posterior distribution of model parameters and make posterior predictions; 11,000 such values were simulated, and we discarded the first 1,000 as a burn-in. We provide R code to conduct this analysis as an online supplement.

Strike rate analysis

In an analysis of vessel encounter rates with humpback whales, Gende et al. (2011) provided evidence that the likelihood of vessel-whale encounters increases with vessel speed. Others have used simulation to model the likelihood of whale-vessel intersections given assumptions about whale and vessel movement (e.g., Vanderlaan and Taggart 2007, van der Hoop et al. 2012). However, the degree to which whales are likely or able to move to avoid vessels of varying speeds has heretofore been a subject of uncertainty.

To investigate the relationship between whale strike rates and vessel speeds, we compared the speeds of vessels that struck whales to a larger population of vessel speeds. From a statistical perspective, these data sources are similar to use-availability data as commonly modeled in animal resource selection studies (see, e.g., Manly et al. 2002), where speeds that resulted in whale strikes can be viewed as "use" and random vessel speeds can be viewed as "availability."

For this analysis, we obtained randomly selected vessel speeds in SMAs along the U.S. east coast summarized for analysis by speed and vessel type (i.e., cargo, passenger, sovereign vessel types). Vessel operations in SMAs were monitored using the Automatic Identification System (AIS), a safety-at-sea navigation tool that transmits very high frequency (VHF) radio signals. All vessels 300 gross tons or greater making international voyages are required by the International Maritime Organization's (IMO) International Convention for the Safety of Life at Sea to maintain functioning and operational AIS capabilities. The same requirement applies to nearly all vessels 65 feet or greater sailing in U.S. waters. An AIS signal is transmitted several times per minute and contains both static (e.g., ship name, call sign, and hull specifications) and dynamic information that is unique to that particular voyage. Dynamic information includes vessel location, heading, and speed, and is automatically incorporated into the AIS signal by a global positioning system (GPS). Due to its signal transmission rate, AIS provides a detailed, continuously sampled, and precise record of vessel operations for a nearly complete census of vessels subject to the speed limits. Additional information about the function and characteristics of the AIS can be found in Aarsæther and Moan (2009) and Tetreault (2005); a description of methods used to acquire and parse AIS data for this study can be found in Silber and Bettridge (2010 and 2012).

Using the U.S. Coast Guard (USCG) network of AIS receivers, we obtained vessel operations data from 9 December 2008 to 31 July 2012. We randomly selected one speed value per SMA vessel transit. This sample was restricted to speeds that were >2 knots because AIS transmitters may continue to operate while vessels are at anchor or while in port. To generate a random population of such vessel speeds, we resampled these speeds with replacement, weighting each observation by the number of AIS records available per transit.

For analysis of instantaneous per capita strike rates, we limited strike records to the U.S. east coast and to vessel types that were comparable to the categories available in the AIS data. Strike records were derived from published large whale

ship strike databases (Jensen and Silber 2003) and those maintained by NMFS stranding personnel. We restricted analysis to cargo vessels ($n = 1$ strike), passenger vessels ($n = 1$ strike), and to sovereign vessels (e.g., USCG operated vessels ($n = 10$ strikes)). Strike records were obtained over a wider time frame than AIS data; $n = 6$ were from 2000–2009, $n = 4$ were from 1990–1999, and $n = 2$ records came from 1950–1980. There is little indication that the speeds of vessels changed appreciably even over this relatively long horizon. We did not include strikes with small private vessels or whale watching vessels as these types of vessels were seldom identifiable in the AIS database. Although it may have been possible to isolate random transit speeds associated with particular whale watching vessels, we anticipated that these would not adequately represent the activities being conducted when whale strikes occurred (since whale watching vessels are actively searching for whales during portions of their transits). Since the fate of whales was not necessary for analysis of strike rates, we included records where the fate of the animal was unknown. A simple comparison of strike speeds from our vessel strike database to transit speeds randomly sampled from our AIS database in different regulatory periods suggested that strikes occurred when vessels, in each vessel category studied, were traveling faster than average vessel speeds (Fig. 2).

To formalize the relationship between vessel speed and strike rates, we start by defining the per capita, instantaneous rate at which whales are struck, λ_i. In particular, we express it as a function of vessel speed, x_i, with a log link. We considered both linear and quadratic functional forms for the effect of vessel speed on strike rate:

$$\text{Model 1: } \log(\lambda_i) = \alpha_0 + \alpha_1 x_i \tag{3}$$

$$\text{Model 2: } \log(\lambda_i) = \alpha_0 + \alpha_1 x_i + \alpha_2 x_i^2.$$

Letting $[X|Y]$ denote the conditional distribution of X given Y, we can describe the likelihood of observing strike speeds $\mathbf{x}$ for a particular combination of vessel type and regulatory period as

$$[\mathbf{x}|\mathbf{y} = 1, \alpha] = \frac{[\mathbf{y} = 1|\mathbf{x}, \alpha][\mathbf{x}]}{\int [\mathbf{y} = 1|\mathbf{x}, \alpha][\mathbf{x}] d\mathbf{x}}$$

where $y = 1$ if a particular vessel speed resulted in a strike. Here, $[\mathbf{y} = 1 \,|\, \mathbf{x}, \boldsymbol{\alpha}]$ is the joint probability that the observed vessel strike speeds resulted in strikes, and can be given as

$$[\mathbf{y} = 1|\mathbf{x}, \boldsymbol{\alpha}] = \prod_{i=1}^{S} 1 - \exp(-\lambda_i).$$

The component $[\mathbf{x}]$ denotes the probability density function for vessel speeds independent of whether or not those vessels struck whales. We follow Lele and Keim (2006) in approximating the denominator as

$$\int [\mathbf{y} = 1|\mathbf{x}, \alpha][\mathbf{x}] d\mathbf{x} \approx \frac{1}{B} \sum_{j=1}^{B} [\mathbf{y} = 1|\mathbf{x}_j^*, \alpha]$$

where $\mathbf{x}_j^*$, $j \in 1, 2, \ldots, B$ denotes a randomly sampled vessel speed from our transit database. This formulation has the advantage that we can use the empirical distribution of transit speeds as opposed to a fitted model, a desirable property since observed vessel speeds often were multimodal and/or bore little resemblance to parametric distributions. We set $B = 10{,}000$ in subsequent analysis.

The parameter α_0 controls the proportion of vessel speed observations that result in reported whale strikes. This parameter is not identifiable using the previous setup; however, inference can still be drawn regarding α_1, the effect of vessel speed on strike rates (Lele and Keim 2006). We used maximum likelihood to estimate parameters for the linear and quadratic models for strike rates, employing AIC (Burnham and Anderson 2002) for model selection. We then used the model with highest support in a Bayesian analysis of strike rates, imposing diffuse Normal(0,100) prior distributions on regression parameters (i.e., the α values). For this purpose, we used Markov chain Monte Carlo (Gelman et al. 2004) to sample from the joint posterior. When implementing this approach, we used separate data models for $[\mathbf{x}]$ for each combination of vessel type (cargo, passenger, sovereign) SMA speed restriction active/inactive period. An R script to conduct this analysis is provided in the Supplement.

Joint risk analysis

To estimate a total risk reduction value, we again sampled AIS data transmitted between 9 December 2008 and 31 July 2012 by cargo, tanker,

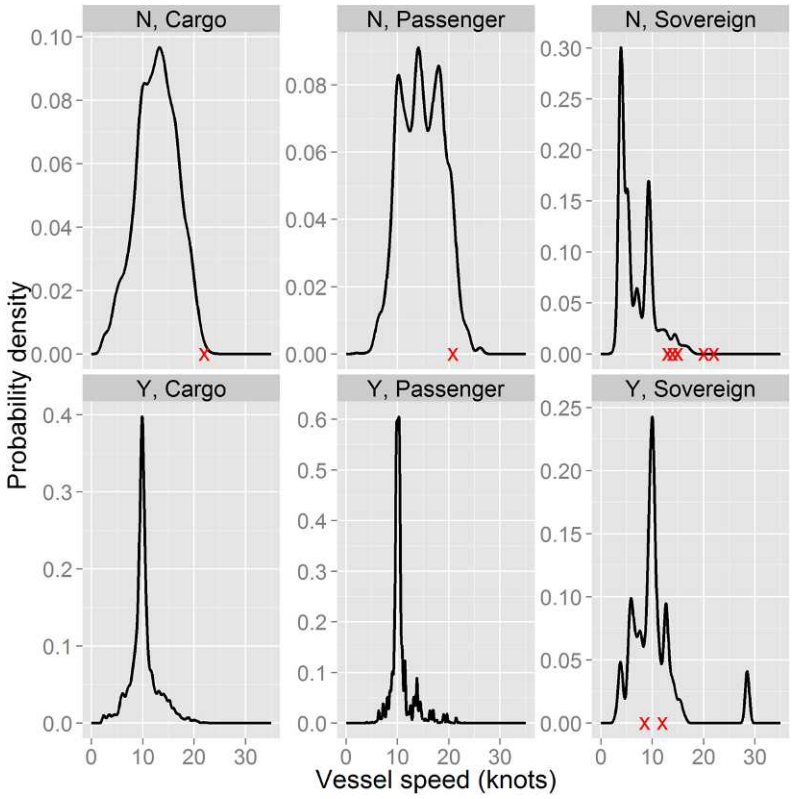

Fig. 2. A comparison of randomly sampled ship speeds from our Automatic Identification System (AIS) database (black kernel densities) to speeds at which vessels struck whales (represented by X's). Data are partitioned by vessel type ("Cargo", "Passenger", or "Sovereign") and by whether the data point occurred during periods when Seasonal Management Area (SMA) speed restrictions were ("Y") or were not ("N") in effect. Each panel represents a distribution of 10,000 randomly sampled ship speeds which are used to define separate availability datasets in the strike rate analysis (strike rate itself is only modeled as a function of ship speed).

and passenger vessels with lengths of 65 feet or greater (a total of tens of millions of individual speed records). We analyzed vessel speed information for 73,319 trips in SMAs at times in which speed restrictions were in effect and for 68,099 trips in the same geographic areas defined by SMAs when restrictions were not in effect. A single mean speed was computed for each trip. Vessel speed analyses were limited to transits that were at least one nautical mile in length, had at least five AIS records, and an average transit speed of >2 knots.

We formulated alternative expressions for relative mortality risk associated with R time periods with different management regulations. Assuming that the risk of mortality is temporally and spatially homogeneous within time period r, the probability that a single whale, chosen at random, is lethally injured can be given as

$$p_r = 1 - \exp(-T_r h_r)$$

where T_r gives the time interval and h_r gives a constant hazard rate associated with period r. The hazard rate h_r is fundamental to survival analysis (cf. Cox and Oakes 1984) and measures instantaneous mortality risk. In practice, we expect variability in h_r over time and space, but little information exists to quantify changes in spatial distributions of whales over the entire east coast. Assuming that this distribution remains relatively constant, comparisons of constant h_r over different management regimes may still prove illuminating. In particular, the relative risk of morality in management period r relative to some reference period 0 may be written as

$$R = h_r/h_0 \quad (4)$$

with values of $R > 1$ indicative of increased risk associated with a management action, and $R < 1$ indicative of reduced risk. In practice, there is considerable uncertainty in the hazards associated with each period because of uncertainty about mortality and strike rates, so that R is best viewed as a probability density function. Further, managers may be interested in different functional forms of h_r since these may provide different interpretations of the effect of management actions.

Ultimately, the mortality hazard throughout the management area (i.e., over all SMAs) in a given time interval is the sum of independent hazards associated with different transits (which are at different speeds and of different lengths). If we wish to directly compare the realized mortality risk in different management periods (i.e., speed regulation in effect/not in effect), we can approximate the mortality over each management period using a single, constant hazard during regulation period r:

$$h_r = \sum_{t=1}^{N_r} \lambda_{tr} D_{tr} M_{tr} / T_r.$$

Here, λ_{tr} is the instantaneous striking hazard for transit t in regulation period r (assumed here to be constant for the entire transit), D_{tr} is the duration of the transit, and M_{tr} gives the probability that a whale is lethally injured given that it is struck during transit t in period r. This formulation describes actualized change in mortality risk, but is dependent upon N_r, the number of transits in regulation period r, as well as the duration of such trips. Thus, changes in the total number of transits over time (or the duration of such transits) will affect interpretation of R. This formulation is also problematic for right whales because vessel speed regulations were temporally staggered based on location (Fig. 1) so T_r is not well defined.

Although absolute increases and decreases in risk can be of interest, managers may also be interested in standardized risk, or changes in risk associated with a management action while controlling for variables not under control of management. For instance, if the number and durations of transits varied markedly between regulation periods due to extrinsic factors, realized risk may give an unclear picture of the effects of regulations. In this case, managers may still be interested in changes in mortality risk that would have resulted had the number of transits remained constant. To make this estimate, we suggest calculating relative risk using

$$h_r^* \propto \sum_{t=1}^{N} \lambda_{tr}^* \Delta_{tr}^* M_{tr}^*$$

where λ_{tr}^*, Δ_{tr}^*, and M_{tr}^* are random draws for strike rate, vessel transit duration, and mortality probability (see below). We refer to risk computed using this approach as standardized risk.

Since we have empirical data on the length and speed of transits by management period and models for how whale mortality (M) and strike rate (λ) change as a function of transit speed (Eqs. 1 and 3) it is a relatively simple matter to calculate comprehensive risk reduction associated with speed restrictions. To properly account for uncertainty in these relationships, we computed a posterior distribution for the standardized risk ratio R (Eq. 4) by incorporating uncertainty in the estimated lethality-vessel speed relationship and the estimated strike rate-speed relationship. Again letting $[X|Y]$ denote the conditional probability distribution of X given Y, and bold symbols denote vectors of parameters, we start by symbolically writing the joint posterior distribution of R and transit speed and mortality parameters given the data as

$$\begin{aligned}&[R, \mathbf{M}, \Delta, \beta, \theta, \alpha_1 | \mathbf{S}, \mathbf{Y}, \mathbf{Z}, \mathbf{x}] \\ &\quad = [R|\mathbf{M}, \Delta, \alpha_1][\mathbf{M}|\theta, \beta][\beta|\mathbf{Y}][\Delta|\mathbf{Z}, \theta][\theta|\mathbf{S}][\alpha_1|\mathbf{x}].\end{aligned}$$

Here, $\mathbf{S}$ denotes vessel speed data for different management periods, $\mathbf{Z}$ denotes transit length data, and $\mathbf{Y}$ denotes strike/mortality data as analyzed in our Bayesian probit analysis. The posterior distribution depends on simulated vessel speed values θ, which are assumed to be distributed according to $[\boldsymbol{\theta}|\mathbf{S}]$, and simulated transit durations, Δ. The latter depend upon both the empirical distribution of transit length values $\mathbf{Z}$ and upon vessel speed (given a particular transit length Z_i, and speed θ_i, duration can be calculated as Z_i/θ_i). Posterior predictions of lethality at different vessel speeds associated with the component $[\mathbf{M}|\boldsymbol{\theta}, \boldsymbol{\beta}][\boldsymbol{\beta}|\mathbf{Y}]$ may be generated via Eq. 2, while posterior values of α_1 can be sampled from the strike rate analysis.

Given these values, we express the standardized risk ratio as

$$[R|\mathbf{M},\Delta,\lambda] = \frac{\sum_{t=1}^{19,345} \lambda_{tr}^{*}\Delta_{t}^{*}M_{tr}^{*}}{\sum_{t=1}^{19,345} \lambda_{t0}^{*}\Delta_{t}^{*}M_{t0}^{*}} = \frac{\sum_{t=1}^{19,345} \exp(\alpha_1^{*}\theta_{tr}^{*})\Delta_{t}^{*}\Phi(\beta_0^{*}+\beta_1^{*}\theta_{tr}^{*})}{\sum_{t=1}^{19,345} \exp(\alpha_1^{*}\theta_{t0}^{*})\Delta_{t}^{*}\Phi(\beta_0^{*}+\beta_1^{*}\theta_{t0}^{*})}. \quad (5)$$

Note that the non-identifiable strike rate parameter α_0 cancels out of the above expression. As correlation between transit lengths and vessel speeds was low (Pearson correlation coefficient $\rho = -0.03$), we used independent probability density functions for both quantities. In particular, we drew vessel speed values $\boldsymbol{\theta}$ from the AIS-generated empirical distribution of vessel speeds within sampling regime r, and simulated Δ_t^* based on draws from the empirical distribution of observed transit lengths $\mathbf{Z}$ over the whole study period. We selected the limits of summation, 19,345, because it was the average number of transits occurring within a six month period. As results were somewhat sensitive to high speeds outside the range of strike rate and/or mortality analyses, we replaced any randomly selected transit speed above the 99th percentile of transit speeds (22.5 knots) with a value of 22.5 knots.

To summarize comprehensive risk ratios, we generated 10,000 posterior predictions using Eq. 5. Separate predictions were made for each year (1–4) of the study and for control and treatment periods for each strike rate scenario. We also analyzed pooled control and treatment data (pooling over years).

Results

Using logistic regression analysis, we detected a significant positive relationship between ship speed and the probability of a lethal injury ($\hat{\beta}_1 = 0.217$; SE 0.058; $p < 0.001$); the intercept was estimated as $\hat{\beta}_0 = 1.905$ (SE 0.821). The Bayesian probit analysis produced an almost identical relationship to the logistic regression analysis (Fig. 3), with posterior means of $\beta_0 = -1.067$ (SE 0.452) and $\beta_1 = 0.124$ (SE 0.030). As with logistic regression, there was substantial evidence for a positive effect of vessel speed on strike lethality (the posterior sample for β_1 was greater than zero for all realizations). Owing to several new observations of serious injury vessel strikes at lower vessel speeds (e.g., one each at 2 and 5.5 knots), the relationship between lethality and strike speed was less extreme than the one produced by Vanderlaan and Taggart (2007) and used in previously published risk analyses (Fig. 3).

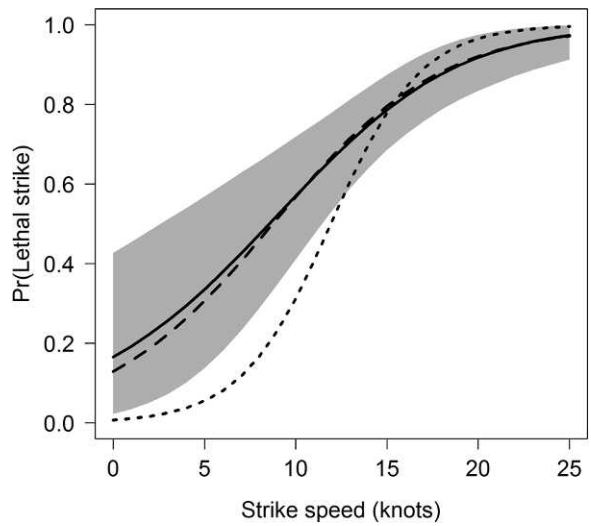

Fig. 3. Probability of a lethal whale strike given strike speed. The dashed line gives predictions from a logistic regression, the solid line gives posterior mean estimates from a Bayesian implementation of probit regression, and the dotted line gives logistic regression estimates reported by Vanderlaan and Taggart (2007). The gray area represents a 95% credible interval from the Bayesian analysis.

The speeds of vessels that struck whales were consistently greater than typical vessel speeds for each vessel type and regulatory period (Fig. 2). Accordingly, maximum likelihood fits of the use-availability model for strike speeds provided strong evidence for a linear effect of transit speed on strike rates ($\hat{\alpha}_1 = 0.49$, SE = 0.09); however, there was insufficient evidence to support a quadratic effect ($\Delta AIC = 1.1$). We therefore used a linear formulation for the effect of transit speed

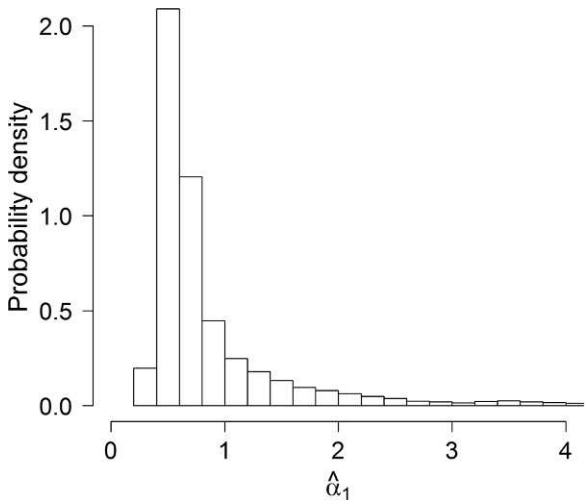

Fig. 4. Estimated posterior density function for α_1, the effect of vessel speed on the log of the instantaneous rate at which vessels strike whales. A value greater than zero indicates that instantaneous strike rate increases with vessel speed.

on strike rates in our Bayesian analysis. The posterior distribution for $\hat{\alpha}_1$ was substantially greater than zero (Fig. 4), providing further evidence that strike rates increase as a function of vessel speed.

Estimates of comprehensive risk reduction suggest a large decrease in standardized mortality risk associated with vessel speed restrictions (Fig. 5). In particular, control periods (i.e., when SMAs were not in effect) all had similar risk levels, while treatment periods (i.e., when SMAs were in effect) resulted in a risk reduction of 80–90%. Examining individual years separately (Fig. 5), it appeared that risk reduction was on the order of 80% for the first 2 years of vessel speed restrictions, and closer to 90% for the final 2 years of regulation. Pooling over years and simply comparing risk between treatment periods when speed regulations were in effect versus control periods when regulations were not in effect, the posterior mean mortality risk level in treatment periods was 14% of that in control periods (95% credible interval 5.6–29.0%), representing an 86% reduction.

Discussion

Various measures, focused primarily on changes in vessel routing patterns and reductions of vessel speed, have been employed to reduce the threat of vessel collisions with North Atlantic right whales. Routing changes that result in lowered co-occurrence of vessels and whales is the most desirable approach in most settings (Silber et al. 2012, van der Hoop et al. 2012), and several studies have provided estimates of vessel strike risk reduction afforded by established routing modifications (Firestone 2009, Vanderlaan and Taggart 2009, Vanderlaan et al. 2009, Lagueux et al. 2011). However, changing vessel routes is not always feasible due to navigational safety constraints, particularly in coastal waters.

Arguments for lowering vessel speed to limit the threat of fatal vessel collisions with both large whales (Laist et al. 2001) and manatees (*Trichechus manatus*) (Laist and Shaw 2006) first appeared in the early- and mid-2000s. These assertions were bolstered by risk reduction analyses (Pace and Silber 2005, Vanderlaan and Taggart 2007) and helped prompt use of speed restrictions in a number of locations (NPS 2003, Tejedor et al. 2007), the most extensive of which occur along the U.S. eastern seaboard. NOAA's vessel speed limits have been the subject of legal (Norris 2008, Firestone 2009), economic (Silber and Bettridge 2012), and risk reduction analyses (Lagueux et al. 2011, Wiley et al. 2011). Estimates of risk reduction to date have been applied to limited areas and times and relied on previously published logistic regression curves. Risk reduction values provided here include the full geographic scope of the vessel speed restrictions over a multi-year period using quantified vessel speeds, new whale strike data, and novel analyses. We believe this to be the most comprehensive assessment to date of the utility of vessel speed restrictions in reducing the threat of vessel collisions with large whales.

Our analysis highlights the importance of accounting for the combined effects of ship speed on (1) the rate at which vessels strike whales, and (2) the probability of mortality given that a whale is struck. In particular, we have shown that vessel speed is positively related to both components. To our knowledge, this is the first time that a use-availability model has been used to analyze the effect of vessel speed on the rate of whale strikes. Although simulation analyses (e.g., by modeling whale and vessel movement) can

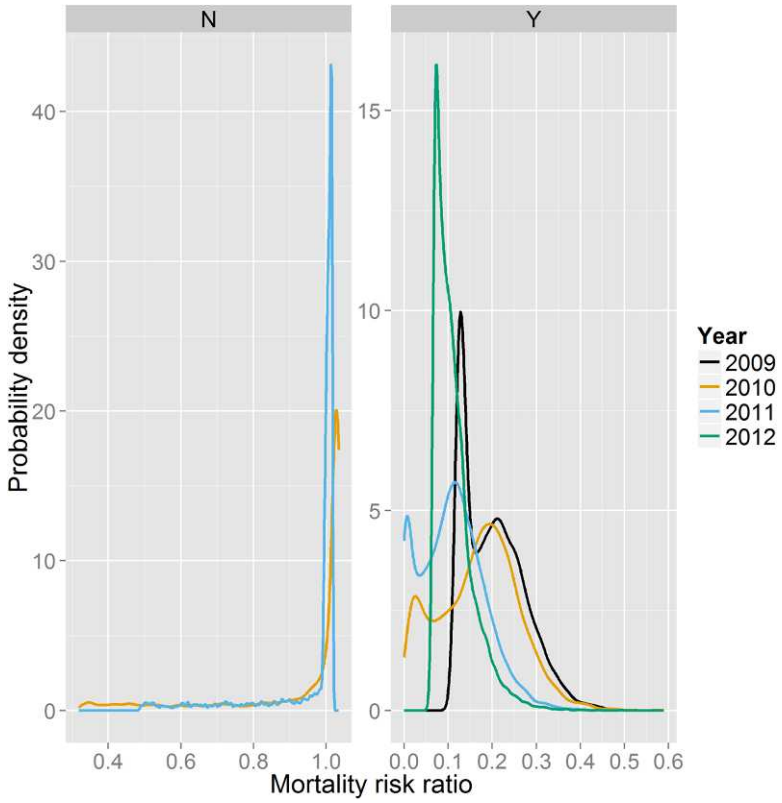

Fig. 5. Posterior predictive densities for comprehensive mortality risk ratio associated with transit speed restrictions in different years and management regimes. The left panel gives results for control periods ('N') while the right panel shows risk ratios when speed restrictions were in effect ('Y'). A ratio less than one indicates reduced risk relative to the control period in 2009.

provide some guidance as to likely functional forms for the relationship between vessel speed and the likelihood of a whale coming into close proximity with a vessel, it is difficult to use these analyses to reliably predict the probability of a collision because of uncertainty about fine scale nature of whale avoidance behavior. For instance, little is known about whale reaction, if any, to approaching vessels, particularly in the near-field. We view our analysis as an improvement in this regard, in that it allows one to explicitly estimate the effect of vessel speed on instantaneous strike rate. The obvious limitation of this approach is the small sample size associated with whale strike speeds, particularly when limited to vessels for which we had reliable control (availability) data. Nevertheless, with just 12 data points there appeared to be ample indication that strike rates increased with vessel speed. By contrast, if one fixes strike rates to be constant and simply uses the mortality curve to account for changes in mortality risk, it is actually possible to arrive at an (erroneous) increase in mortality risk, simply because slower vessel speeds increase transit times (and thus exposure of whales to vessels). This emphasizes the importance of simultaneously accounting for the effects of vessel speed on whale mortality and on strike rates.

The present analysis does not account for potential reductions in whale mortality attributable to changes in vessel routing regimes. For instance, previous analysis of vessel routing measures designed to lessen vessel occurrence in or near right whale aggregation areas (Lagueux et al. 2011, van der Hoop et al. 2012) suggested that there were substantial decreases in strike rates in at least portions of the range of North Atlantic right whales. In fact, Areas To Be Avoided and modifications to Traffic Separation

Schemes and other routing changes were made in the range of this species during the same period as vessel speed restrictions were introduced (Silber et al. 2012), albeit in targeted localized areas such as the Bay of Fundy, and waters off Georgia, Florida, and New England. We do not currently have data sufficient to account for the effects of management actions based on vessel routing across the entire east coast; however, we note that proportional changes to strike hazards result in an equivalent change to our risk ratio (Eq. 5). For instance, if vessel routing restrictions decreased the strike rate hazard by half, then the risk ratio in Eq. 5 would also be reduced by half. This suggests that our standardized risk ratio likely underestimates the true level of risk reduction accompanying the full suite of implemented management actions. However, we believe the risk ratios we provided here are valuable because it allows us to isolate the effects of a particular management action (in this case, transit speed regulations).

Our finding that vessel strike risk was lowest in the latter two of the four active periods studied is consistent with a measurable increase in vessel trips that comported with the required speed limits in years three and four, particularly as citations and fines were issued at the outset of year three (G. K. Silber, J. D. Adams, S. Bettridge, and B. Sousa, *unpublished manuscript*). This substantial shift in behavior observed across the entire regulated community helps explain, and contributes to, increased risk reduction in the latter two periods of our study.

We note the disparity of records of known vessel strikes by vessel type. Although cargo vessels represent the vast majority of vessels utilizing U.S. east coast ports and are the type most strongly represented in our AIS database, we were only able to obtain a single cargo vessel whale strike record for which strike speed was recorded. In contrast, sovereign vessels account, proportionally, for much higher numbers of recorded vessel strikes than other vessel types (Fig. 2). However, we wish to strongly emphasize that sovereign vessels are much more likely than other vessel types to report a struck whale because they are required to do so by internal protocol, and are obliged by conditions of U.S. Endangered Species Act Section 7 consultations to endeavor to reduce vessel strikes of whales by posting dedicated lookouts, traveling at reduced speeds when traversing active SMAs when and where feasible and when not jeopardizing vital or national security missions, and reporting when a whale strike has occurred. In addition, due to the sheer size of most commercial cargo and passenger vessels (which may be substantially larger than many sovereign vessel classes), these types of vessel operators are rarely aware that a collision with a whale has occurred. Nevertheless, it is important to note that our overall inference about the effect of ship speed on vessel strike rates could be biased if there were a statistical interaction between ship speed and ship type on vessel strike rates (that is, if whales respond to increasing ship speed differently among vessel types). Unfortunately, we do not have data sufficient to test this assumption, but believe it is the safest (and statistically parsimonious) to proceed with the assumption that transit speed affects strike rates similarly regardless of vessel type. A large number of additional reports of transit speed for non-sovereign vessel whale strikes would likely be necessary to relax this assumption.

Indications are that expansion will occur in the commercial maritime transport industry (Corbett 2004, Dalsøren et al. 2007), the cruise industry, offshore energy development, and other maritime sectors, thereby increasing risk of vessel strikes to whales. Conversely, factors such as restrictions on air-borne emissions from large vessels and the recent economic downturn may result in reduced vessel speeds (Khan et al. 2012) or fewer vessel trips (McKenna et al. 2012), which could reduce the likelihood of whale strikes. Nonetheless, the threat is likely to remain a concern as maritime transport and other activities increase and as whale populations grow in some locations. Our analysis suggests that vessel speed restrictions will likely remain a key tool for reducing anthropogenic mortality risk and promoting recovery of endangered large whale species.

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Supplemental Material

Supplement

R code to implement mortality risk analysis for North Atlantic right whales as a function of vessel speed (*Ecological Archives* C004-006-S1).