Literature Review of Ship Strike Risk to Whales

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Summary

Large whales are at risk of being struck by ships, which at a minimum can lead to injury, but can also cause death. Given that many species of large whales have low populations and are considered of conservation concern, mortality from ship strikes can have devastating consequences for these species. In this literature review, we address three themes in the scientific literature regarding whales and ship strikes: 1) estimates of the frequency that whales are struck by ships; 2) calculations of the risk and lethality of ship strikes to whales; and 3) modeling the risk of ship strikes to whales based on ship tracking data and whale data. Many studies have quantified the number of whales being struck and killed by ships, typically using whale strandings databases from a region. Fin whales are often the most commonly struck whale in the records, although right whales are typically struck often. There is a positive, linear relationship between ship speed and the probability of a whale being struck, and a logistic relationship between ship speed and the probability of a ship strike killing a whale. According to one study, ships traveling at 11.8 knots have a 50% probability of a strike being lethal, increasing to 80% at 15.3 knots. These probability relationships can then be used to model ship strike risk in different regions with appropriate data on ship traffic and whale distribution, typically obtained through automatic identification system (AIS) ship track data and through whale telemetry or aerial surveys. Overlap between whales and ships is estimated by overlaying ship density with whale density, and risk of a lethal collision is then modeled by applying the logistic relationship between ship speed and probability of mortality. At least one study verified this modeling approach by examining spatial patterns from the strandings databases, and found a good match between their ship strike risk model outputs and the strandings of whales down to the species level. Overall, current methodology in assessing ship strike risk is robust, following a few assumptions, and can easily applied to different systems where the appropriate data are available.

1. Introduction

Large cetaceans (henceforth referred to as whales), especially mysticetes, are at risk of being struck by ships, which at a minimum can lead to injury (Laist et al. 2001), but can also cause death (Vanderlaan and Taggart 2007, Conn and Silber 2013). Whales are at risk of ship strikes when they surface to breath, but whales that forage near the surface are also more frequently at risk of ship strikes than whales who forage at depth (Parks et al. 2012). This is particularly apparent in the Canadian context with recent mortality events for North Atlantic right whales (*Eubalaena glacialis*) in the Gulf of St. Lawrence (Davies and Brillant 2019). North Atlantic right whales recently expanded their summer foraging range into the Gulf of St. Lawrence (Simard et al. 2019), directly in the path of busy shipping lanes. North Atlantic right whales are particularly prone to ship strikes because they forage near the surface (Parks et al. 2012). For large whales specifically, ship strikes represent a form of additive mortality that cannot be easily compensated by the low reproductive outputs of whales. Given that many species of large whales have low populations and are considered at risk, mortality from ship strikes can have devastating consequences for these species.

In this literature review, we address three themes in the scientific literature regarding whales and ship strikes: 1) estimates of the frequency that whales are struck by ships; 2) calculations of the risk and lethality of ship strikes to whales; and 3) modeling the risk of ship strikes to whales based on ship tracking data and whale data.

2. Estimates of ship strikes to large whales

Multiple studies have quantified the number of whales struck through time, and the majority of these have done so using national or regional databases of stranded (also known as beach cast) whales. These databases typically include information on the species, location of the stranded whale, and any evidence of cause of death, typically based on a formal necropsy. This general methodology has been used in the North American Pacific Ocean (Douglas et al. 2008, Berman-Kowalewski et al. 2010, Neilson et al. 2012), North American Atlantic Ocean (Laist et al. 2001, Vanderlaan et al. 2009, Van Der Hoop et al. 2013), European Atlantic Ocean, New Zealand waters (Constantine et al. 2015), and Hawaiian waters (Lammers et al. 2013). Two studies also reviewed historic print records of strandings (Peel et al. 2018) and other printed accounts of whale-vessel collisions (Laist et al. 2001).

One of the most comprehensive studies was by Laist et al. (2001), where they used a combination of historic print records of whale-vessel collisions globally, whale stranding databases from multiple Atlantic regions, and anecdotal evidence from people who experienced a whale-vessel collision globally. They found evidence for 11 species of mysticete being struck by ships, including some rare records for bowhead whales (*Balaena mysticetus*) from the study by George et al. (1994) (see below). Fin whales (*Balaenoptera physalus*) were hit most often. Northern (*E. japonica* and *E. glacialis*) and southern right whales (*E. australis*), humpback whales (*Megaptera novaeangliae*), and gray whales (*Eschrichtius robustus*) were all commonly hit. The earliest record of a ship strike was in 1877 by a steamship in Rhode Island. Collisions were generally rare before 1951, but this could simply be due to a lack of reporting. Stranding databases were much more useful, and effectively showed at least 10% of stranded whales likely died of injuries related to ship strikes. Injuries included propeller slashes or blunt force trauma. They also had a high number of anecdotal responses, showing that 89% of whale collisions occurred with vessel speed ≥ 14 knots, and the remaining 11% at speeds between 10 and 14 knots. The analysis also shows a rapid increase in ship speed between 1950 and 1980, which perhaps suggests increased ship strike risk through time, which leveled off after 1980.

Vanderlaan et al. (2009) quantitatively analyzed the number of reported whales struck per year globally, and showed a three to four-fold increase from the 1970s to the early 2000s worldwide, which corresponds to a tripling of the global ship fleet. Along the U.S. east coast over the same period, there was a three to six-fold increase in ship strikes for all whales, and a two-fold increase for North Atlantic right whales specifically.

Two studies by the same lead author assessed scars on harvested bowhead whales in Alaska (George et al. 1994, 2017). The authors analyzed scarring on whales harvested by Alaska natives between 1990 and 2012. 2% of bowheads had scars related to ship strikes, compared to 12% of bowheads (50% of bowheads > 17 m) with entanglement scars. Since these results are based on whales that were harvested and therefore survived the ship strike, the rates of lethal ship strikes on bowhead whales are completely unknown. Given the remoteness of the coastlines where bowhead whales live, it is unlikely that stranded or floating deceased bowhead whales would be discovered in time for a necropsy, if at all.

3. Calculating the Risk and Lethality of Ship Strikes

Laist et al. (2001) laid the groundwork for more contemporary analyses of the risk and lethality of ship strikes, and this study is described in the previous section. Two studies (Vanderlaan and Taggart 2007, Conn and Silber 2013) built on the database described in Laist et al. (2001). Both of these studies calculated the lethality of ship strikes based on vessel speed, although Conn and Silber (2013) had a larger dataset and effectively updated the relationship presented by Vanderlaan and Taggart (2007) (Figure 1). The probability of a lethal ship strike (P_L) follows the following relationship with ship speed (v), as in Vanderlaan and Taggart (2007):

$$P_L = \frac{1}{1 + exp^{-(-4.89+0.41\,v)}}$$

The relationship from Conn and Silber (2013) follows a slightly different relationship:

$$P_L = \frac{1}{1 + exp^{-(-1.905+0.217\,v)}}$$

The expression developed by Vanderlaan and Taggart (2007) shows that the probability of a lethal ship strike is 50% at a vessel speed of 11.8 knots, 80% at a speed of 15.3 knots, and increases towards an asymptote of 100% above 15.3 knots. The updated relationship calculated in Conn and Silber (2013), which included a few records with slower speeds, has a 50%

probability of ship strike at 9 knots and 80% at 15.4 knots. Most notably, the relationship presented by Vanderlaan and Taggart (2007) goes through zero when speed is at 0 knots, whereas the relationship in Conn and Silber (2013) is still at 13% probability of lethality at 0 knots. For this reason, we prefer the relationship by Vanderlaan and Taggart (2007).

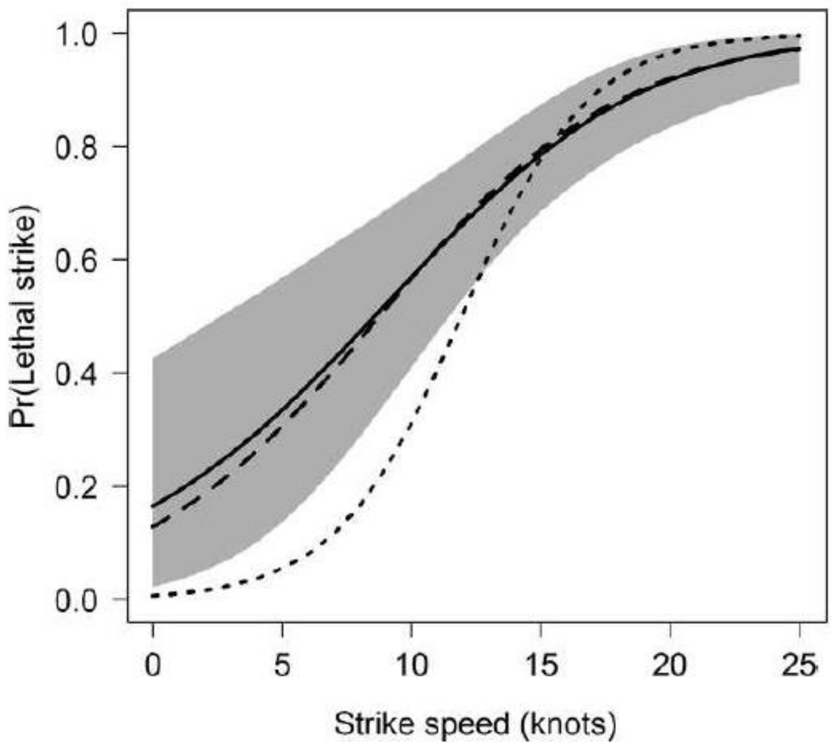

Figure 1. Probability of a lethal whale strike given strike speed. The dashed line gives predictions from a logistic regression, the solid line gives posterior mean estimates from a Bayesian implementation of probit regression, and the dotted line gives logistic regression estimates reported by Vanderlaan and Taggart (2007). The gray area represents a 95% credible interval from the Bayesian analysis. This is Figure 3 from Conn and Silber (2013), including the exact caption, which is used under the Creative Commons Attribution Licence 3.0.

Strike rates in general (i.e. all strikes, not just lethal strikes) tend to increase linearly with vessel speed (Conn and Silber 2013), which is a bit different than the strict cut-off of 14 knots suggested by Laist et al. (2001).

Another study attempted to quantify ship strike risk in the field (Currie et al. 2017). These authors drove their research boat along line transects and quantified their encounter rates with humpback whales. Speed of travel was randomly selected along each transect, with increasing speed every 15 min along the transect. Encounters were coded as close (0-80 m) and far (80-300 m), and as surprise encounters or near misses. The authors found increased close encounters at faster speeds (> 12.5 knots), suggesting that whales are less likely to be able to change their behaviour appropriately to avoid collisions when the ship is traveling faster.

Behavioural Adaptations

Risk calculations do not explicitly account for the behavioural adaptations of whales to simply avoid ships, although it is an assumption of these analyses that despite the behavioural adaptations of whales, the whales are still struck (see last paragraph). Obviously behavioural adaptations alone are not sufficient to mitigate ship strikes. One recent study (Szesciorka et al. 2019) provides an excellent and rare case study of a tagged blue whale (*Balaenoptera musculus*) involved in a near miss with a ship. The whale was tagged with instruments collecting acoustic, depth, kinematic, and location data. The whale encountered a 263-m container ship transiting at 11.3 knots, and came within a closest point of approach (CPA) of 93 m of the ship while the whale was at a depth of 67.5 m. Prior to the CPA, the whale was ascending from a foraging dive down to 278 m. 90 sec before the CPA, the whale slowed its ascent, and 45 sec before the CPA, it switched to a descent. The whale surfaced 3 minutes after the CPA. This example provides evidence that whales can show avoidance behaviour, thus lowering the chance of ship strikes. However, according to the study's authors, this whale had been sighted in the study area many times and likely had a large amount of experience with ships.

4. Modeling Risk of Ship Strikes to Whales

By far the most common type of study related to ship strikes was modeling ship strike risk to different populations of whales (Fonnesbeck et al. 2008, Vanderlaan et al. 2008, 2009, Vanderlaan and Taggart 2009, Williams and O'Hara 2010, Wiley et al. 2011, Van Der Hoop et al. 2012, Conn and Silber 2013, Redfern et al. 2013, 2019, Rockwood et al. 2018, Smith et al. 2020). Some studies also examined the effectiveness of different management measures at reducing ship strikes, such as areas to be avoided (Vanderlaan et al. 2008, Vanderlaan and Taggart 2009, Van Der Hoop et al. 2012), seasonal management areas and vessel slowdowns (Conn and Silber 2013), and transit separation schemes (Vanderlaan et al. 2008).

Most modeling studies followed the same general steps, which involved processing both ship tracking data and whale tracking/sighting data into density spatial grids, and processing ship speed data into a speed spatial grid. The ship density and whale density spatial grids are then combined to estimate the probability of a ship strike. Probability of a ship strike is combined with the ship speed spatial grid, accounting for the relationship between ship speed and lethality of a ship strike, to estimate the probability of a lethal ship strike. The simplest models multiply whale density by ship density to estimate risk of a ship strike, and then multiply this by ship speed (converted using the lethality curve from section 3) to estimate probability of a lethal ship strike (e.g. Redfern et al. 2019).

Rockwood et al. (2018) provides one of the most detailed modeling approaches. First, they calculated the critical radius (r_c) within which an encounter between a vessel and a whale is likely to occur, accounting for the width of the vessel, the length of the whale, and the width of the whale's head:

$$r_c = Vessel\,Width + \sqrt{\frac{Total\,Length \times Head\,Width}{\pi}}$$

The encounter rate, λ_e, between one whale and one vessel in each area was calculated as

$$\lambda_e = \frac{2r_c}{S}\int_{v_m} I(v_m, v_b)v_m dv_m$$

where S is the area, v_m is the whale velocity, v_b is the vessel velocity, and $I(v_m, v_b)$ is an increasing function of the velocities as derived from encounter theory. Mortality is then estimated as:

$$Mortality = \lambda_e t P(Strike\,depth)\big(1 - P(Avoidance)\big)P(Mortality|v_b)N_m N_b$$

where t is the total time of vessel transits, *P(Strike depth)* is the probability the whale is within the mean vessel strike depth, $(1-P(Avoidance))$ is the probability of no successful avoidance, $P(Mortality|v_b)$ is the probability of mortality given mean vessel speed, and N_m and N_b are the number of whales and boats, respectively. This methodology was applied to ship strike risk for blue, fin, and humpback whales along the US west coast EEZ, and used AIS data, species distribution modeling, and some dive data for each whale species. This model was much more sophisticated than others, and included variability in swimming depth of whales, ship draft, and speed of ships. These authors also compared their model outputs to stranding records within the region, filtering by strandings with evidence of ship strikes. There was a good match between model outputs and stranding records with evidence of ship strikes, with most strandings near busy ports.

5. Conclusions

The studies reviewed in this report clearly demonstrate that large whales are at significant risk of ship strikes, and that if vessels are traveling fast enough (> 11.8 knots), then the whales are at > 50% risk of a lethal ship strikes (Vanderlaan and Taggart 2007). The studies reviewed in this report also likely underestimate the risk of ship strikes (both lethal and non-lethal) to whales. Most studies used stranding records, which rely on the deceased whale washing up on shore or being towed to shore for an examination, so these records are already missing all whales that sink after death or are undiscovered. The number of whales that can actually undergo a proper necropsy to determine cause of death also tend to be low because the whale has to be recently deceased or the state of decomposition becomes too advanced to properly assess cause of death. These factors are even more important for bowhead whales that live near remote coastlines where dead whales likely go undiscovered. The rates of ship strike scars noted by (George et al. 1994, 2017) do not account for lethal ship strikes, and are not comparable to the levels of ship strikes noted by records from stranding databases. However, these estimates appear to be a unique and rare dataset of whales that are struck by ships and survive.

Next Steps: Bowhead Whale Ship Strike Risk

The impetus behind this literature review was to examine different methodologies for assessing ship strike risk, with the plan to assess ship strike risk to bowhead whales in the Eastern Canada-West Greenland population. Based on the different methods identified in this report, we recommend the following steps for modeling ship strike risk to bowhead whales:

1. Using the satellite telemetry data for this population of bowhead whales, calculate the relative monthly density of bowhead whales in a spatial grid with 10 x 10 km cell size or smaller between August and October.
2. Using satellite AIS data, calculate monthly (August to October) ship density in the same cell size used for the bowhead density calculation. Can do this for each year of satellite AIS data from 2011 to 2018 (or 2019 if it is available), although we recommend focusing on 2015 and after based on the poor quality of AIS data before 2015.
3. Calculate average ship speed (after removing stopped vessels (speed ≤ 1 knot)) in each month of each year used in step 2, using the same cell size.
4. Convert ship speed to probability of lethal strike by applying the equation from Vanderlaan and Taggart (2007).
5. Calculate the probability of encounter by multiplying whale density by ship density in each month of each year available for the ship density data. Note that we assume that estimates of whale density will remain static between years. A follow-up analysis should likely include variation in whale density between years, but we are unsure if the sample size from satellite telemetry is high enough to include yearly variation at this point.
6. Calculate the probability of lethal ship strikes by multiplying the probability of encounter by the probability of lethal strike for each month of each year.

Following these steps will provide us with estimates of encounters between ships and bowhead whales through time, as well as the risk of lethal ship strikes through time.

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