Using ship speed and mass to describe potential collision severity with whales: an application of the Ship Traffic, Energy and Environment Model (STEEM)

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This paper presents an application of the Ship Traffic, Energy, and Environment Model (STEEM) to estimate and visualize the risk and severity of collision between ships and the North Atlantic Right Whales along the U.S. and Canadian Atlantic coast. According to the physics of the interaction between a ship and a whale, for ships larger than 500 tons, speed is more important than the size of a ship in determining a lethal injury to a whale. Reducing ship speed could reduce the ton-force significantly. The visual representation of the risk and potential severity of ship-whale collision along the U.S. and Canadian Atlantic coast shows that the coast between Jacksonville, FL and Savannah, VA, the major shipping lanes of Cape Cod, the mouth of Bay of Fundy, and the area south to Nova Scotia, Canada (Roseway Basin) are the areas with highest risk of severe or lethal injury due to a ship strikes. On the waterway network the distribution of ton-force of ship traffic is rather uniform, and thus, the distribution of whales rather than ton-force determines the distribution of risk of potential severity of injury to whales. We use impact physics from known ship strikes to estimate the probability of injury severity and whale death, showing that these outcomes are correlated with ship-whale collisions at different speeds and masses.

North Atlantic right whales (*Eubalaena glacialis*) are critically endangered throughout their range along the eastern coast of North America (NOAA, 2003). The primary risk right whales face within this area, along with several other species of large whales, is being struck by large vessels transiting between ports along the eastern seaboard (Laist *et al.*, 2001). Approximately 35% of all right whale deaths documented between 1970 and 1989 have been attributed to ship strikes; while data from the period 1991-1998 attribute 47% of right whale deaths to ship strikes. (Knowlton and Kraus, 2001; Laist *et al.*, 2001). Ship strikes are particularly problematic for North Atlantic right whales because the removal of even a single individual from the population threatens their future (NOAA, 2003). The U.S. and Canadian governments are addressing the problem of ship strikes by considering a suite of management options which offer both alternative routes for ship traffic and vessel speed restrictions within certain areas to reduce the risk and severity of interactions between ships and whales (NOAA, 2004; NOAA, 2006).

Successful management depends, in part, upon the ability to predict the risk of an interaction between a ship and a whale under different conditions such that the risk may be mitigated. Further, modeling the criteria which determine a lethal interaction may yield insight into the threat specific vessels impose when they encounter a whale and what measures may be required to reduce this threat. This manuscript addresses directly these modeling criteria as part of larger research objectives to understand ship-strike risk to whales.

Ship-whale collisions are both geospatial and bio-physical in nature; that is, we must consider where these interactions occur in time and space and what forces act on the whale body at the time of impact to understand the nature of the risk. This research utilizes the application of ship speed and mass characteristics to describe the potential severity of risk-based ship collisions with large whales. We begin by determining where ships and whales are likely to interact in time and space and move to describe the specifics of ship-whale interactions. In essence, this work models hypothetical accident locations and details. We employ three models to address this problem: a GIS analysis of ship-whale interactions using our STEEM model (Wang, *et al*., 2006), a pre-mortem momentum prediction model, and a post-mortem force analysis.

Intuitively, ships and whales are likely to interact more frequently in areas where the density of each is high. Moving forward from knowing where ship-whale collisions are likely to occur, we can then look at the specifics of the interaction, e.g., how fast must a ship travel to kill a whale when a collision occurs? The momentum of any object in motion is a product of its mass and velocity; when a ship and whale collide, the impact force is a function of their respective momentums. Standard momentum equations may be manipulated to estimate a range of potential force at the time of impact between the ship and the whale. This model allows determination of the momentum of different sized-ships traveling at different speeds and the force of impact they will have on a whale if a strike occurs. By combining these results with estimates of the probability of a lethal injury to a large whale at various speeds, we can predict the outcome of a ship strike and predict the speed reductions necessary to reduce impact forces such that lethal injury may be averted. These three methods in combination provide insight into the speed restriction management measures which would be required to significantly reduce the likelihood of a lethal interaction between a ship and whale.

Methods

GIS Analysis of Ship-Whale Interactions

Figure 1 shows the modified STEEM and its application for quantifying and visualizing the risk and severity of the interaction between ships and whales. The upper part of the model, the ship traffic module, is essentially the same as the module presented in: *Modeling Energy Use and Emissions from North American Shipping: an Application of Ship Traffic, Energy and Environment* (Wang *et al*., 2006). This module is discussed in detail in that paper and its supporting materials. The data sets and the algorithms used in this work are essentially the same as the ones used in that paper. The module outputs needed to evaluate the risk of ship-whale interaction, however, are somewhat different from the outputs needed to estimate air emissions from ships. For example, the mass of a ship and its operational speed are critical attributes to evaluate the potential severity of the interaction between a ship and a whale, while the horsepower of the ship and the number of hours of operations (obtained from dividing distance by operation speed), operation load, etc., are more important to estimate ship fuel use and air emissions. We use the ton-force distribution of each segment to represent the potential severity of the collision between a ship and a whale.

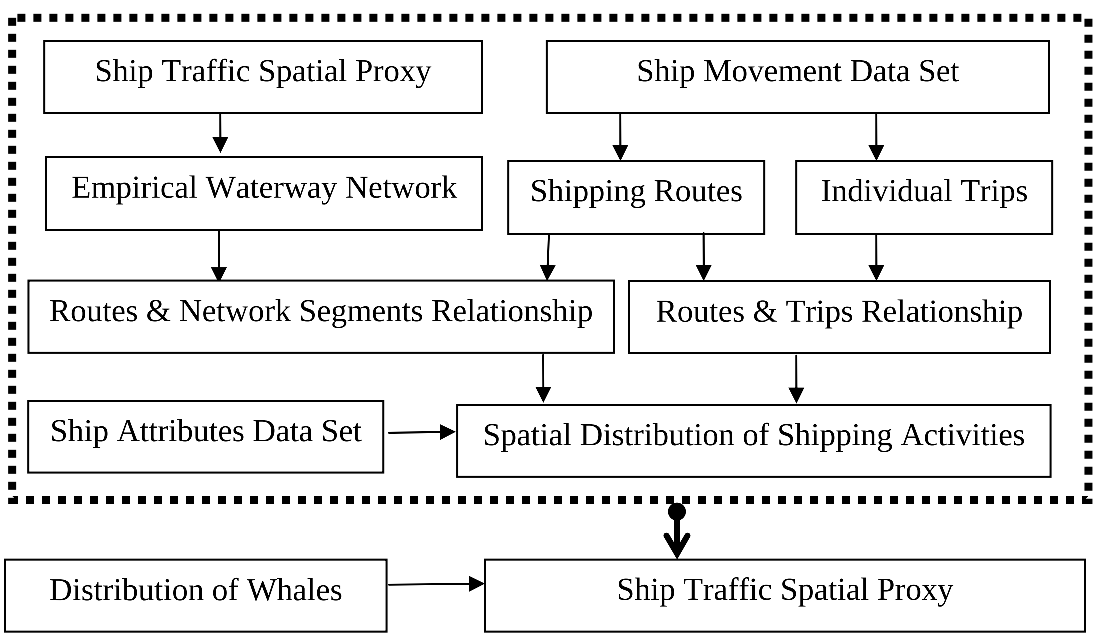

FIGURE 1. Illustration of the Waterway Network Ship Traffic, Energy and Environment Model (STEEM) and its Application to Ship-whale Interactions.

Mass of Ships

Displacement, which is the actual total weight of a ship including the weight of the ship itself, the cargo, fuel, water, people, and stores loaded, is the ideal measurement of the mass of ship. Considering the data we have, however, we use ship deadweight tonnage (DWT) as the surrogate of the mass of ships. DWT represents the cargo, stores, ballast, fresh water, fuel oil, passengers, crew and their effects, which we think is a good proxy for displacement of cargo-carrying commercial ships. Our model thus does not include the weight of the ship itself, nor does it incorporate the impact of load factors of carrying capacity of ships or ships in ballast conditions. Including the former would increase ship momentum, and accounting for less-than-full cargo loads would decrease ship momentum; both refinements may be useful, but are unlikely fundamentally alter our results.

We obtained DWT data for about 76% of the 9,615 unique ships in the U.S. Entrances and Clearances data set (USACE, 2004) by matching these ships to ships in Lloyds Register CD-ROM 2004 (Lloyd's Register, 2004) and Lloyds movement data sets (Lloyd's Marine Intelligence Unit, 2005). We then obtained ship DWT for about 19% of those ships from ship gross tonnage (GT) data based on the relationships in Table 1. We used the average DWT of each ship type in Table 1 for 5% of the 9,615 ships that do not have GT data. Most of these ships are fishing vessels and miscellaneous types of ships.

Speed of Ships

We assume that ships navigate at service speed at sea. We obtained ship speed data for ships in the U.S. Entrances and Clearances data set and the Lloyds movement data set by matching to ships with data contained in the Lloyds Registry CD-ROM 2004. If no speed data were matched in the data sets, we used the average service speed for respective ship types, summarized in Table 2. The speeds we used in this work are close to the average speed used by Lloyds Register in the Baltic Sea study and the average speed used by Entec UK Limited in the study for the European Commission (European Commission, 2002; Lloyd's Register and IMO, 1998).

TABLE 1 Relationship between ship gross tonnage (GT) and dead weight tonnage (DWT)

	GT and DWT[1]		
Ship Type	Number of Samples	Equation (y as DWT, x As GT)	R^2
Container ship	3,462	y = 1.1181x	0.9456
Tanker	10,551	y = 1.8025x	0.9599
General Cargo	11,362	y = 1.3912x	0.9509
Bulk Carrier	9,966	y = 1.8489x	0.9814
Reefer	1,251	y = 1.0394x	0.9172
RO-RO[2]	3,806	y = 0.3971x	0.7042
Passenger	1,779	y = 0.1045x	0.8457
Fishing	5,738	y = 0.6671x	0.8237
Miscellaneous	7,246	y = 1.7429x	0.9336

Notes: 1. Samples are unique GT and DWT pairs in Lloyds Register CD-ROM 2004 *(3)* and Lloyds movement data sets *(4)*; 2. RO-RO is an industry acronym for Roll-on/Roll-off vessel.

TABLE 2 Average cruise speed by ship type

Ship Type	Number of Samples[1]	Average Speed (knots)	Lloyds Register Study (knots)	Entec Study (knots)
Container Ship	2,596	19.9	20	19
Tanker	7,082	13.2	15	14.4
General Cargo	9,308	12.3	14	12
Bulk Carrier	4,464	14.1	14	13.6
Reefer	850	16.4	20	17
RO-RO	2,996	16.9	18	15
Passenger	1,825	22.4	20	21
Fishing	8,199	11.7	13	13.6
Miscellaneous	10,116	12.7	11	12

Notes: 1. Samples are ships with service speed in Lloyds Register CD-ROM *(3)*.

Mapping the Physics of Potential Ship-Whale Interactions

The ton-force of a ship with certain DWT and certain cruise speed were calculated based on equations (1) through (6):

$$P_s = F \times t = m_s \times \Delta v_s = m_s \times (v_2 - v_s) \tag{1}$$

$$P_w = -F \times t = m_w \times \Delta v_w = m_w \times (v_2 - v_w) \qquad (2)$$

Equations (1) and (2) describe the physics of the interaction between a ship and a whale. Where: $\boldsymbol{P_s}$ is the impulse on the ship and $\boldsymbol{P_w}$ is the impulse on the whale; $\boldsymbol{F}$ is the force between the ship and the whale, and $\boldsymbol{t}$ is the time of interaction; $\boldsymbol{m_s}$ is the mass of ship, and $\boldsymbol{m_w}$ is the mass of whale; $\Delta \boldsymbol{v_s}$ is the change of ship speed after interaction, and $\Delta \boldsymbol{v_w}$ is the change of whale speed after interaction; $\boldsymbol{v_s}$ is ship speed before interaction, reported speed in this illustration and $\boldsymbol{v_w}$ is whale speed before interaction.

We assume that an interaction between a ship and whale is inelastic, the ship and the whale travel at opposite directions before the interaction, and ship has a positive momentum while whale has a negative momentum. We also assume that the ship and the whale travel at the same speed $\boldsymbol{v_2}$ after the interaction and $\boldsymbol{v_2}$ has the same direction as $\boldsymbol{v_s}$. These assumptions are conservative, that is, they maximize the impact calculations of a collision. Based on these assumptions, we then derived equations (3), (4), and (5) from equations (1) and (2).

$$m_s \times (v_2 - v_s) = -m_w \times (v_2 - v_w) \qquad (3)$$

$$v_2 = \frac{m_s \times v_s + m_w \times v_w}{m_s + m_w} \qquad (4)$$

$$F = \frac{-m_w \times \Delta v_w}{t} = \frac{-m_w \times \left(\frac{m_s \times v_s + m_w \times v_w}{m_s + m_w} - v_w\right)}{t} \qquad (5)$$

If we further assume that collision time is 2 seconds, and whales swim at -1 knot speed[1], then Equation (5) can be simplified to equation (6).

[1] See http://www.sefsc.noaa.gov/UserFiles/Reefteam4/mitigating_right_whale.htm

$$F = \frac{-m_w \times (\frac{m_s \times v_s - m_w}{m_s + m_w} + 1)}{2} \qquad (6)$$

We understand that the greater the ***F*** between a ship and whale during an interaction the severer the damage the whale will get. We also note that decreasing impact time (t) below 2 seconds greatly increases impact forces; we assumed a 2-second time of impact based on informal discussions with other ship-strike researchers, acknowledging limited data on the range of this value. Note that ***F*** is negative because we assume ships have positive momentum. We modeled this scenario for ships of various sizes traveling at various speeds to determine the force of impact for specific sized ships traveling at specific speeds. This model may be further adapted to account for alternative scenarios of ship and whale size, speed, and direction.

Using the algorithm described in the *"Ship Energy Use and Emissions STEEM"* Paper and its algorithm, we obtained the number of trips in the historical ship movement data set spatially associated with the segments of the waterway network. Each trip in the historical ship movement data set was made by a specific ship that can be identified in the ship attributes data sets we built. Using this ship data and a typical adult right whale's mass of 45 metric tons[2,3], the ton-force collision potential was calculated for each trip in the movement data sets. The spatial distribution of ship traffic intensity and ton-force of ship traffic is visualized in Figure 2 using ArcGIS tools.

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[2] See http://www.rightwhaleweb.org/biology.html
[3] See http://www.whalecenter.org/species.htm

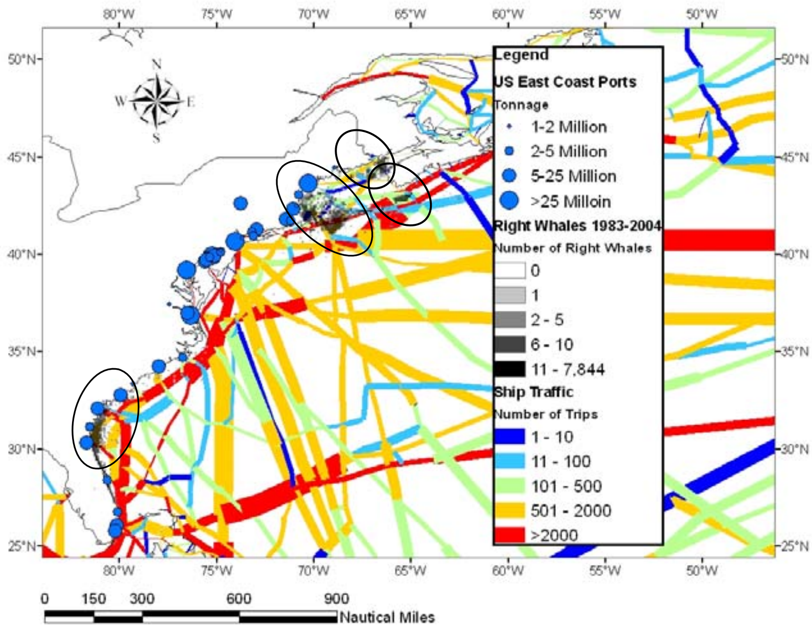

FIGURE 2 Illustration of the risk of interaction between ships and whales.

Figure 2 shows number of trips on the shipping lanes of the waterway network for the U.S. and Canadian Atlantic coast overlaid with the distribution of whales observed in the past 22 years. Note the two shipping activities data sets we used, the U.S. Entrances and Clearances data set and the Lloyds Movement data set, include nearly all ship traffic along the Atlantic coast. The Right Whale Consortium granted our research group permission to use their long-term dataset containing data on right whales collected during surveys and also observed opportunistically. Intuitively, the risk of interactions between ships and whales is greater where heavier ship traffic coincides with greater whale observations.

We identified areas with high risk of ship-whale interaction. These areas include the coast between Jacksonville, FL and Savannah, GA, the shipping major of Cape Cod, the mouth of Bay of Fundy, and the area south to Nova Scotia, Canada (Roseway Basin). Although North Atlantic right whale distribution is relatively well understood within these feeding and calving grounds, there is little information available along the right whale migration route between these critical habitat areas (Knowlton *et* al., 2002). We understand that better representation of whale distribution is needed to improve the evaluation of the risk of ship-whale interaction in migratory corridors which may prove equally important in mitigating ship strikes. Our ongoing research is focused on improving understanding of whale activity in migratory corridors, discussed elsewhere (Firestone, et al, 2006).

Figures 3(a) – 3(d) show the spatial distribution of ton-force between ships and whales overlaid with the spatial distribution of whales. Figure 3(a) shows very few vessels are small or slow enough to produce less than 9 metric tons of force should they hit a whale. Figure 3(b) shows that few ships are small or slow enough to produce between 9 and 16 metric tons of force should they hit a whale. Conversely, Figure 3(d) shows that shipping lanes with potential whale-ship impact forces greater than 24 metric tons are concentrated in and near whale habitat or migratory regions. Figure 3(c) shows that nearly all shipping lanes in the East Coast are used by vessels that could produce whale-ship impact forces between 16 and 24 metric tons. Importantly, these figures collectively show that more than 75% of commercial ships in East Coast shipping lanes could cause greater than 16 metric tons impact force if they struck an adult whale.

Results

Figure 4 illustrates the results of our pre-mortem momentum predictions. The isopleths plot the mass of the ship in metric tons on the y-axis and the relative ship speed in knots on the x-axis to reveal the potential impact force in metric tons. As an illustration of this model, a ship of 500 metric tons traveling at a relative speed of 15 knots has a potential impact force of 15-20 metric tons; if it reduces its relative speed to 10 knots, it has a potential

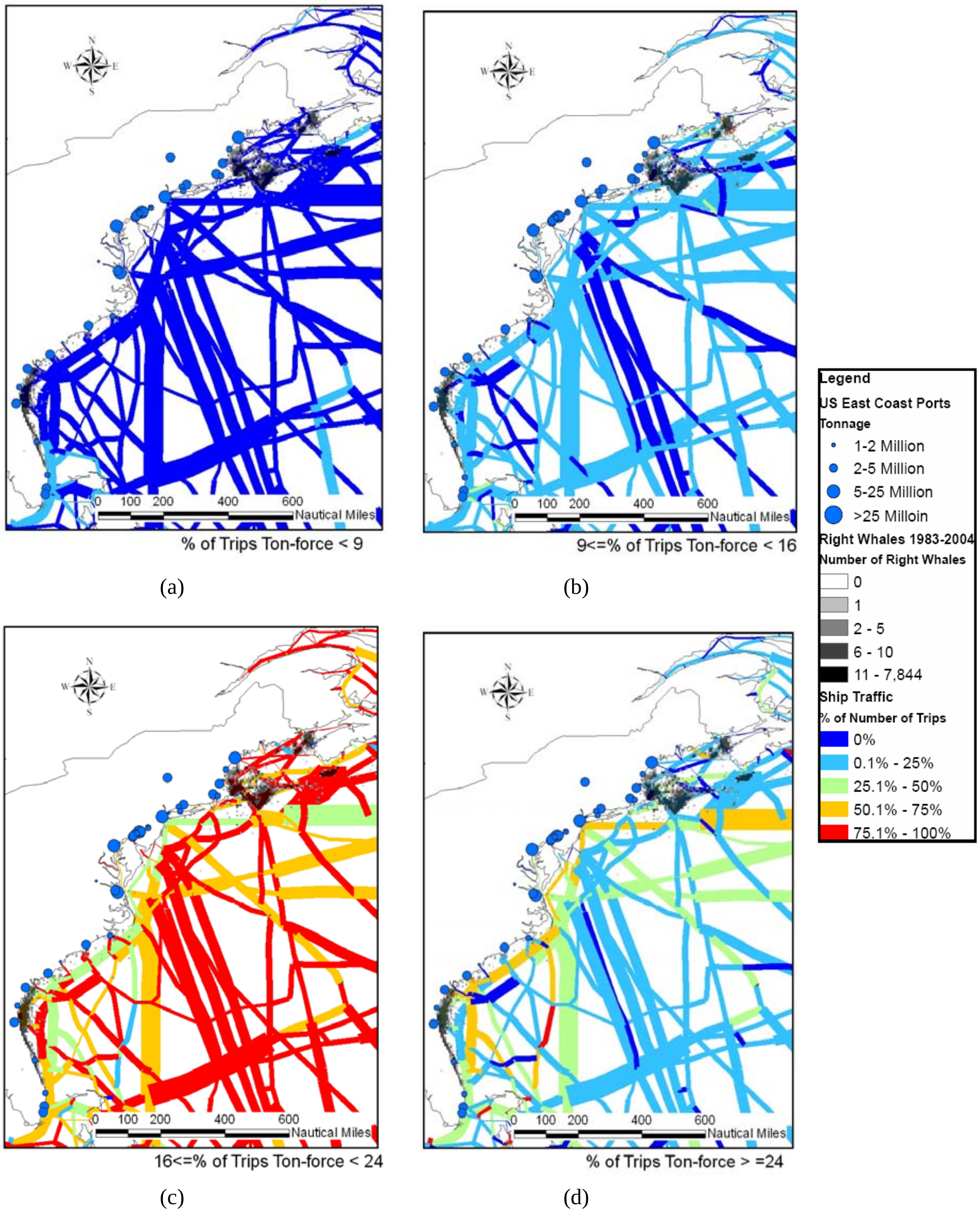

FIGURE 3 Distribution of ton-force of interaction between ships and whales. Frame (a) illustrates the percent of traffic that could produce whale-ship impact forces less than 9 metric tons; frame (b) illustrates the percentage of traffic on each shipping segment that could produce whale-ship impact forces between 9 and 16; frame (c) illustrates the percentage of traffic on each segment that could produce whale-ship impact forces between 16 and 24 metric tons; frame (d) illustrates the percent of traffic that could produce whale-ship impact forces greater than 24 metric tons.

impact force of 10-15 metric tons. The figure reveals that below a certain ship size (500 tons), ship mass becomes as or more important than speed. Above 500 tons, changes in the mass of the ship affect the potential impact force less and speed becomes the dominant factor in determining momentum. Therefore, speed represents the most important variable to reduce momentum and potential impact force for commercial cargo ships. Moreover, since vessels cannot realistically change their respective mass, speed reduction also represents the most feasible way for vessels to reduce their potential impact force in a ship strike of a whale.

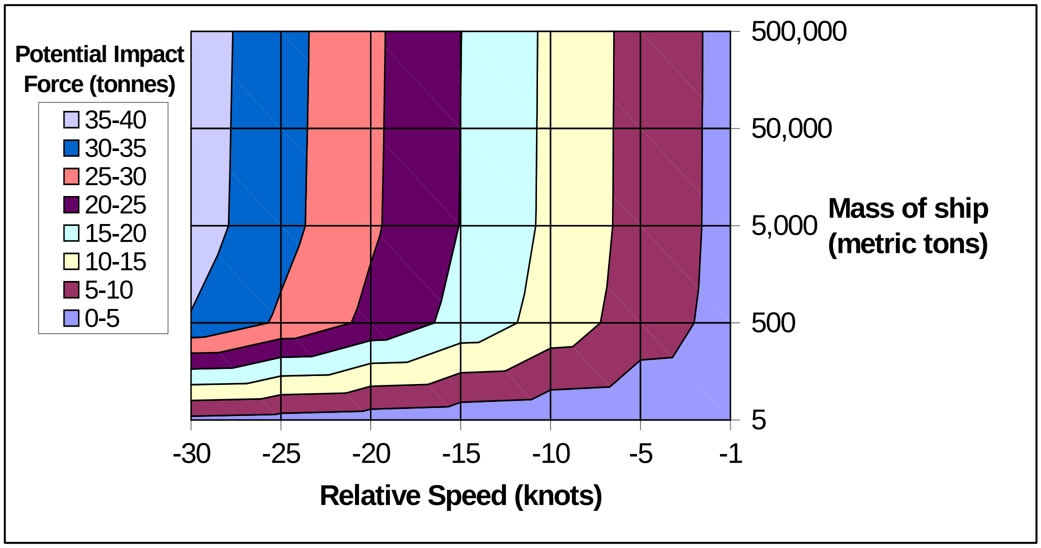

Figure 4: Isopleths of Ship Speed and Mass. Negative speed values represent directional assumptions in the development of collision equations, discussed above.

Of course, sensitivity to time of impact and corresponding impact physics will affect the value of forces significantly, although it will not affect the general insights in Figure 4 that, under a given time-of-impact assumption, ship speed and size determine the forces of a ship-whale collision. We illustrate the general sensitivity of impact forces on different times of impact, whale sizes, and ships' speed and size in Figure 5. Figure 5a indicates that improved understanding in the nature of the impact between whales and ships, and corresponding necropsy information could recalibrate the force estimates in Figure 4. In a fully elastic collision the time of impact may be shorter than two seconds, which produces greater forces on the whale. Figure 5b further illustrates how forces are proportional to impact time, and reveals the conservative nature of our time-of-impact assumption at 2-seconds by showing that our force estimates could be within a factor of two unless very high impact or very low impact physics are involved.

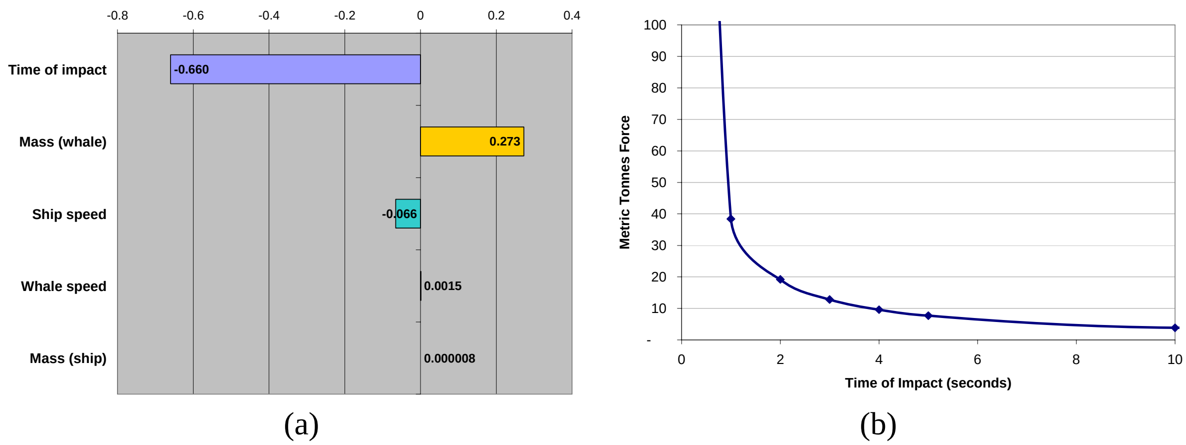

Figure 2. a) Sensitivity analysis of impact force assumptions showing that time of impact with a ship and whale size most significantly determine force of collision on whales; b)

This analysis is most useful when discussed in the light of post-mortem analyses of whale deaths from a ton-force perspective. Figure 5 uses those entries from two datasets documenting historical ship strikes of large whales (Jensen and Silber, 2003; Kraus *et al.*, 2005) that include speed and mass to derive post-mortem estimates of the relationship between ton-force and the probability of death of a whale hit by a ship. Where entries in the dataset omitted information on ship's mass, we used length and type of vessel to estimate DWT. The datasets also included information on whether the collision result in *no or minor injury*, *severe injury* or *death*. We assumed that a severe injury was ultimately lethal, and thus created the dummy variable DEATH =1 if the collision result in severe injury or death, and 0 otherwise. We used the force of impact equation derived above to calculate the impact force on individual right whales and created the variable IMPACT. We then employed logistic regression, regressing DEATH against IMPACT and generated predicted probabilities. The results of that regression are set forth in Table 3. Despite the small number of observations, the variable IMPACT is highly significant (p=.002) and the data fits the model well.

Table 3. Logistic Regression of Large Whale Death from Vessel Collisions

		Number of Observations:	43
		Pseudo R^2:	0.4013
Variable	Coefficient	Std. Error	P Value
IMPACT	0.332	0.107	0.002
CONSTANT	-6.79	2.17	0.002

We plotted the impact force in metric tons against the predicted probability of death. Figure 5 shows that below 9 tons-force, the impact force of a collision is likely to result in no or only minor injury. Whale-ship strikes with 9-15 tons-force most often produce a severe injury (that may ultimately contribute to premature death). For whale-ship collisions resulting in 15-23 tons-force, the model predicts the injury is likely to be either severe or the collision will result in death; above 23 tons-force, death is predicted for all whale strikes.

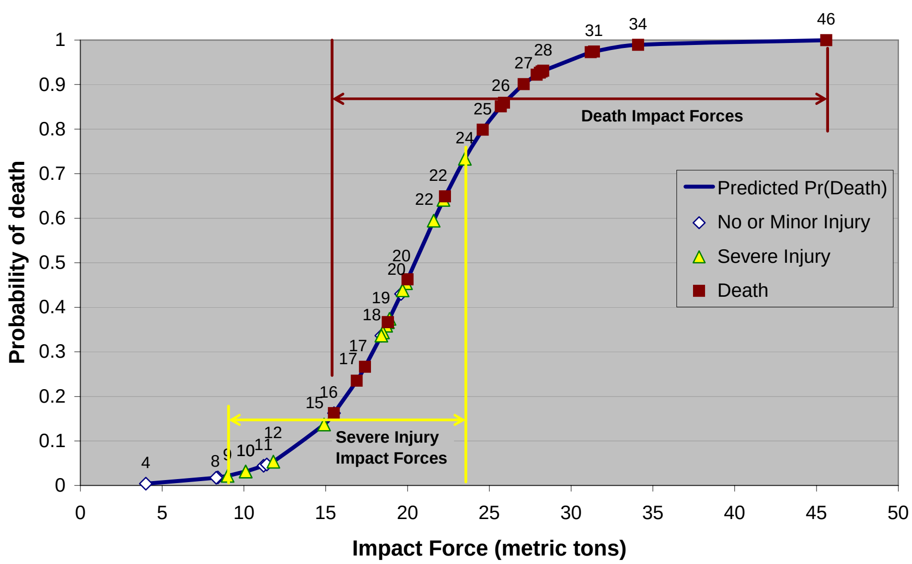

Figure 5: Illustration of the Relationship between Ton-Force and Probability of Ship Strike Death, Vessel Speed is noted on the Logistic Curve.

DISCUSSION

The distribution of ship traffic relative to the distribution of whales (Lyons, *et al*., 2006) and collision impact potential determines the risk distribution of potential severity of injury of whales. According to impact and momentum physics, speed is more important than ship size in determining a lethal injury for ships larger than 500 tons, essentially for all commercial cargo ships. Lowering ship speed could reduce impact force potential significantly. This work estimates whale-ship impact forces along the eastern coast of North America and applies historic whale-strike data that demonstrates these forces are harmful to North Atlantic right whales (Figure 5). Specifically, Figure 5 illustrates respective impact forces associated with known whale strikes, demonstrating that impact forces approaching 25 metric tons have an 80% probability of causing a lethal injury while impact forces less than or equal to 12 metric tons have less than a 5% probability of causing a lethal injury. Referring to Figure 4 for larger commercial ships (> 5,000 DWT), these forces would correspond to speeds of ~18 knots or greater that are highly likely to be lethal and speeds of ~10 knots that appear to be non-lethal, respectively.

Visual representation of potential severity of ship-whale collision along the U.S. and Canadian Atlantic coast shows that coastal waters between Jacksonville, FL and Savannah, VA, the shipping major of Cape Cod, the mouth of Bay of Fundy, and Roseway Basin are areas with high risk of interactions between ships and whales. Essentially, the momentum-impact potential of ship traffic in waters that are also North Atlantic Right Whale habitat is rather uniform; therefore, the distribution of whales determines the risk distribution of the potential impact severity from ship strikes.

Within U.S. jurisdiction, these areas also have been identified as high risk areas by government regulators and are currently being considered for speed and re-routing measures

(US Coast Guard, 2006; NOAA, 2006). Our results suggest that to mitigate the risk of ship strikes, policy makers are correctly focused on areas where North Atlantic right whales congregate and migrate, as we have suggested in comments on the U.S. Coast Guard's (2006) Port Access Route Study and on NOAA's (2006) Proposed Rule to Implement Speed Restrictions to Reduce the Threat of Collisions with North Atlantic right whales (Firestone and Corbett, 2006; Firestone, Corbett, and Lyons, 2006). Moreover, our results connect speed reductions to fewer lethal collisions by direct estimation of the impact force mitigation that may result, which complements the indirect statistical analyses of ship speed and whale injury or death.

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