OCS Study
BOEM 2021-034

Risk Assessment to Model Encounter Rates Between Large Whales and Sea Turtles and Vessel Traffic from Offshore Wind Energy on the Atlantic OCS

U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

OCS Study
BOEM 2021-034

Risk Assessment to Model Encounter Rates between Large Whales and Sea Turtles and Vessel Traffic from Offshore Wind Energy on the Atlantic OCS

April 2021

Authors:
Mary Jo Barkaszi (CSA)
Mark Fonseca, Ph.D. (CSA)
Tom Foster (DHI)
Amit Malhotra (Geo Horizons)
Kim Olsen (CSA)

Prepared under **Task Order 140M0119F0033**
By
CSA Ocean Sciences Inc.
8502 SW Kansas Avenue
Stuart, Florida 34997

U.S. Department of the Interior
Bureau of Ocean Energy Management
Office of Renewable Energy Programs

DISCLAIMER

REPORT AVAILABILITY

CITATION

Barkaszi MJ, Fonseca M., Foster T, Malhotra A, Olsen, K. 2021. Risk Assessment to Model Encounter Rates Between Large Whales and Vessel Traffic from Offshore Wind Energy on the Atlantic OCS. Sterling (VA): U.S. Department of the Interior, Bureau of Ocean Energy Management. OCS Study BOEM 2021-034. 54 p + Appendices.

ACKNOWLEDGMENTS

We thank Dr. Robert Kenney and Mr. John Calambokidis for their valuable input regarding marine mammal species behavior, technical input to the marine mammal risk matrix, and review of the draft document.

Contents

Contents (Continued)

List of Figures

List of Figures (Continued)

List of Animation Figures

List of Tables

List of Tables (Continued)

List of Abbreviations and Acronyms

AIS	Automatic Identification System
AM	Aggregator Module
BOEM	Bureau of Ocean Energy Management
CSA	CSA Ocean Sciences Inc.
GUI	graphical user interface
IWC	international whaling commission
km	kilometer
kn	knot
m	meter
NARW	North Atlantic right whale
NEPA	National Environmental Policy Act
NMFS	National Marine Fisheries Service
OCS	outer continental shelf
SAG	surface active group
U.S.	United States
UME	unusual mortality event

1 Introduction

With development of offshore wind projects, the Bureau of Ocean Energy Management (BOEM) must evaluate the associated environmental risks. One such risk is the potential impacts of vessel operations on marine species, specifically vessel strikes, which have been identified as a source of injury and mortality in large whales and sea turtles (Chaloupka et al., 2008; Douglas et al., 2008; Foley et al., 2019; Laist et al., 2001; Pace, 2011). Most reports of vessel strikes involve large whales and sea turtles, but collisions with smaller marine mammal species have also been reported (Evans et al., 2011; van Waerebeek et al., 2006). Vessel interactions with small cetaceans and seals are believed to occur less frequently, have not been identified as requiring a higher level of assessment, and subsequently are not included in this model. Vessel strikes happen when encounters between a vessel and an animal occur and the animal or vessel fails to detect one another in time to react and avoid a collision. Variables that contribute to the likelihood of a strike include vessel speed, vessel size and type, the species behavior, and barriers to vessel detection by an animal (e.g., acoustic masking, heavy traffic, biologically focused activity). In some cases, mitigation measures such as the use of lookouts and time/area speed restrictions may be in the place that reduce the risk associated with the vessel operation.

Large whale species most frequently involved in vessel strikes include the fin whale (*Balaenoptera physalus*), North Atlantic right whale (NARW) (*Eubalaena glacialis*), humpback whale (*Megaptera novaeangliae*), minke whale (*Balaenoptera acutorostrata*), sperm whale (*Physeter macrocephalus*), sei whale (*Balaenoptera borealis*), grey whale (*Eschrichtius robustus*), and blue whale (*Balaenoptera musculus*) (Dolman et al., 2006). The international whaling commission (IWC) maintains a ship strike database that helps inform relevant researchers or managers about global ship strike “hot spots” to better prescribe mitigation measures (International Whaling Commission, 2021) and subsequently, several publications have summarized or applied these ship strike statistics to management and mitigation (Cates et al., 2016; Jensen and Silber, 2003; Schoeman et al., 2020). Laist et al. (2001) provided historical and current records of the vessel types and speeds associated with marine mammal collisions. From these records, most severe and lethal marine mammal injuries involved larger ships (≥80 m), but fast-moving, smaller vessels also produced lethal injuries (Laist et al., 2001). Vessel speed also was found to be a significant factor; 89% of the records involved vessels moving at ≥14 knots (Laist et al., 2001). Delphinids such as the common bottlenose dolphin (*Tursiops truncatus*) and common dolphin (*Delphinus delphis*) actively approach vessels to swim within the pressure wave produced by the vessel’s bow. Because of their mobility and directed behavior regarding vessels, these delphinids are at lower risk of possible vessel strike compared to large whale species (Glass et al., 2009; Jensen and Silber, 2003; Laist et al., 2001; van der Hoop et al., 2015).

The U.S. Marine Mammal Stock Assessment Reports (https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-stock-assessments) include an assessment of annual human-caused mortality and serious injury including vessel strikes (Caretta et al., 2020; Hayes et al., 2020; Muto et al., 2020). In 2016, a high number of humpback whale mortalities prompted the National Marine Fisheries Service (NMFS) to declare an Unusual Mortality Event (UME) for Atlantic coast humpback whales (NMFS, 2020). To date, 126 humpback whales have been found dead between Maine and Florida. Of the carcasses that have been examined, approximately 50% have shown signs of human interaction, including vessel strikes. Between 2016 and 2017, the number of vessel strikes for this species was more than six times the 16-year average for the region (NMFS, 2019). Between 2013 and 2017, there were 0.8 annual vessel strikes each of fin whales and sei whales (NMFS, 2019). From 2013 to 2017, 1.0 minke whale per year had reported ship strike mortalities (NMFS, 2019). Minke whale vessel strikes have been documented from New York, Virginia, and Rhode Island (NMFS, 2019). Sea turtle strandings reported to have vessel strike injuries has been reported to be as high as 25 percent in the Chesapeake Bay, Virginia

(Barco et al., 2016). Similarly, Foley et al. (2019) reported that roughly one-third of stranded loggerhead, leatherback, and green sea turtles in Florida had injuries indicative of a vessel strike.

For NARWs, ship strikes pose a substantial risk to the species' recovery, mainly due to their small population size, behavioral characteristics, and habitat preferences, which make them highly susceptible to vessel encounters. From 2013 through 2017, the average reported mortality and serious injury to NARWs due to vessel interaction was 1.3 whales per year (NMFS, 2019). In June 2017, the NMFS initiated an UME for NARWs (NMFS, 2020) due to a significant increase in mortalities. Since 2017, 30 dead NARWs have been reported, 8 of which showed strong evidence of vessel strike injuries (NMFS, 2020). Some carcasses could not be examined or did not have clear cause of death, while other reports are pending (NMFS, 2020). With the potential biological removal threshold for the NARW stock at <1 individual (Hayes, et al., 2020), there is no acceptable injury or mortality for this species, and the majority of offshore wind development is occurring within NARW migration corridors. Two well-documented NARW vessel strikes (incurred by marine mammal research vessels) demonstrated that, even with expert observation, ideal sea state conditions, and vigilant crews, the speed of the vessel combined with sometimes cryptic behavior of whales presents a clear risk for vessel strikes (Wiley et al., 2016). The strike and mortality of rates of NARWs before and after vessel speed restrictions were implemented through seasonal management areas were examined by van der Hoop et al. (2015) and found there was not a direct correlation between decreased mortality and rule implementation. Instead, it emphasized the importance of area-specific protection measures as contributing to the speed rules, and the authors noted the interaction between dynamic spatiotemporal variables (e.g., size of port entrances relative to sizes of seasonal management areas, location of strike versus location of report) often do not fall within a defined regulatory context (van der Hoop et al., 2015). Therefore, while lower vessel speeds can reduce mortality, prediction and implementation of reduced speed zones are a far more complex challenge.

While data from vessel strikes exist, there is no definitive process for quantifying animal-vessel collisions because a large number of strikes likely go unreported (Silber et al., 2010). Predation on carcasses, rapid deterioration, and water currents often results in the animal not washing ashore and thus, not being recorded as a vessel strike mortality. Non-lethal strikes are evident from scarring observed on live animals, but these non-lethal strikes are often not quantified. In some cases, non-lethal strikes have been identified, but the animal subsequently disappears and is presumed dead. Therefore, strike risk may be underestimated compared to strike records; however, there currently are no reliable methods to compare potential strike risk with actual strikes. Development of a risk model may help fill the gap between known and predicted strike numbers. Moreover, current qualitative assessments of strike rates and/or strike probabilities, while powerful, often are restricted to small spatial assessments. Better assessment tools are needed to evaluate the spatial and temporal risks of vessel operations along the Atlantic coast of the United States (U.S.). The CSA Ocean Sciences Inc. (CSA) team, including DHI Water and Environment Inc. and Geo Horizons, has worked with BOEM to develop an assessment tool to evaluate the risks and visualize the results. This model will improve assessment and visualization of vessel strike risk across wind energy areas on the Outer Continental Shelf (OCS) of the Atlantic, but additional interpretation and analysis may be required to quantify the effectiveness of mitigation intended to avert or reduce that risk and assess the potential impacts on individuals (e.g., non-lethal strikes and serious injury or mortality).

1.1 Framework

Several recent models have characterized the risk of vessel strikes to large whales, with the goal of translating these risks into effective management practices (Abrahms et al., 2019; Bezamat et al., 2015; Crum et al., 2019; Redfern et al., 2013; van der Hoop et al., 2015; van der Hoop et al., 2012). The models generally relate vessel movement information to predicted species densities. Although none of the models addressed wind industry-specific vessel strike risk, the framework of these varied approaches is highly applicable to assessing risk of vessel strikes across wind development projects along the U.S. Atlantic coast. In the existing models, vessel movement is treated as a point to point transit which is equivalent to the transits considered in the wind vessel strike risk model. However, vessel activity on the wind farm may be quite different from a standard point-to-point transit with additional time spent within the wind farm area at varied speeds and trajectories. Therefore, the risk framework needed to separate vessel transits between ports and a lease area, and vessel behavior while operating within the wind farm to appropriately assess the risk of both conditions for vessel operation scenarios defined for offshore wind activities.

Due to the difficulties of quantifying overall vessel strike risk and specifically the risk from various types of vessel operations associated with the development of the offshore wind industry on the OCS, there was a need for a desktop predictive assessment tool to quantify the strike risk of large whales and sea turtles over large spatial and temporal scales indicative of current and future offshore wind energy project development. While project-based assessments of vessel traffic and potential vessel strike impacts are required from project developers, no comprehensive assessment of vessel strike risk occurs over all phases of a single project or across multiple projects. Individual project risk to vessel strikes likely is very low, but the outlook for offshore wind development along the U.S. Atlantic coast demands that vessel strike risk be assessed on a more comprehensive basis to inform National Environmental Policy Act (NEPA) decisions and the public.

This study identifies the most sensitive parameters for vessel type, operation, and species conditions that contribute to the potential for vessel strikes in order to produce a robust analytical framework for assessing strike risk associated with offshore wind development. A detailed risk assessment was conducted to establish critical parameters from vessels and species included in the analytical model.

1.2 Scope/Goals of Project

The objective of this study was to characterize the risk of vessel strikes on large whales and sea turtles from different vessel types that operate in support of the current leased and unleased OCS wind energy areas ("wind farms"[1]) in the Atlantic and to develop a model that accounts for geospatial, temporal, and species-specific parameters in the vessel operations area for these wind energy areas.

The study was conducted in four stages. The first stage characterized the baseline conditions for vessel traffic along the Atlantic OCS and within "wind farms", including vessel types, operational parameters, and operational behavior of the vessels during different stages of offshore wind development (e.g., surveys, construction, operations). Additionally, the first stage developed an analytical framework that used existing data to calculate encounter numbers based on species information, including density, behavior, vessel parameters, geographic area, and development stage of offshore wind. The second stage assessed and identified the quantitative parameters used to calculate strike risk and developed an analytical model enumerating potential encounter numbers for large whales and sea turtles within user-driven scenarios. In the third stage, a geographic user interface (GUI) that operates with the model was developed to allow users to create complex scenarios of vessel activity which interacts with animal density distributions. The GUI also provides access to text reports of the expected encounter values generated by the model using the scenario inputs and encounter risk heat maps displayed in a geographic

---

[1] Here, the term "wind farm" is used generically and includes all the destinations that the user will be able to select in the Calculator. This list is composed of data compiled from BOEM data sources (BOEM_Lease_Areas_4_13_2020 and BOEM_Wind_Planning_Areas_4_13_2020) and includes Wind Planning / Wind Energy Areas, Call Areas, Lease Areas and actual wind farm designations within Lease Areas.

context. The potential for an actual strike can be simulated through manipulation of vessel activity and animal behavioral response to vessels. The fourth stage developed the capacity of the GUI to allow aggregation of model results from multiple, user-defined scenarios.

1.3 Terminology

Before proceeding, some important terminology used throughout this document should be introduced. A “strike” is a physical collision between animal and vessel. An “encounter” refers to an event during which a vessel and an animal are in close proximity and within a strike risk zone. Although “encounter” typically is used to describe a vessel-animal interaction not resulting in a strike (e.g., an animal being sighted and passing 100 m from a vessel), in the present context, an encounter describes a precursor situation that could result in a strike unless either the animal, vessel, or both averts. Strike risk increases as encounters increase but decreases with aversion of the animal and/or vessel. The analytical model reports the expected number of animals encountered by a vessel in the user-defined scenario; strike risk is approached by allowing the user to manipulate the effectiveness of aversion by the vessel and animal.

2 Risk Assessment

The risk of an encounter between a vessel and an animal depends on vessel activities and animal behavior and distribution. As data suggest, there is a large volume of vessel activity that does not result in an animal encounter or strike; however, vessel strikes remain a significant contributor of injury and mortality in several large whale species (Carretta et al., 2019; Jensen and Silber, 2003; Muto et al., 2019; NMFS, 2019) and sea turtles (Foley et al., 2019). Estimated vessel strike mortality ranges exceed potential biological removal thresholds for some species, indicating vessel strikes threaten the recovery or continued existence of a population (NMFS, 2019; Rockwood et al., 2018). Simply put, regardless of the relatively low numbers of strikes in relation to the volume of vessel traffic, the current level of vessel strike mortality is a persistent threat, and in the case of NARWs, must be avoided to assist the recovery the of this critically endangered species. Therefore, identifying the probability of vessel/animal encounters provides a mechanism to assess strike risk for species within a given vessel scenario. Overlapping vessel presence and animal densities are a primary driver for potential encounters (Williams and O'Hara, 2010); however, other vessel- and animal-based factors can influence the likelihood of an encounter, and thus strike risk (Crum et al., 2019).

2.1 Approach and Methods

There are multiple contributing activities (e.g., commercial shipping, coastal dredging, fishing, recreation) that can affect a species’ strike risk along the U.S. Atlantic coast, but development of this modeling tool focused on a programmatic scale of offshore wind development and operations. Assessing strike risk from vessels operating in support of offshore wind development is necessary under NEPA requirements and assists in identifying vessel activities that present risk that could be mitigated, under the purview of agencies overseeing wind development. The risk of a vessel strike has several components. This report addresses the first order component of that risk, the probability of a vessel encountering an animal. Subsequent components, including whether that encounter becomes an actual strike (e.g., did the animal or vessel detect one or the other and avert to avoid a strike) or the consequences of that strike (e.g., animal mortality), were not explicitly modeled. However, the GUI provided with this encounter model allows a user to create theoretical scenarios that consider actual strike risk by varying the effectiveness of aversion (by both a vessel and an animal) such that the resulting expected value begins to approximate the number of potential strikes. Through creation of individual scenarios, built on the first order component (i.e., encounters), users may assess the overall likelihood of vessel strikes occurring. The combined predictive model and associated GUI is called the Vessel Risk Calculator (referred to henceforth as the ‘Calculator’).

Importantly, this risk assessment, as a predictor of animal-vessel encounters, required a spatial scale covering the Atlantic OCS (**Figure 1**) and a temporal scale of at least 50 years, given the expected longevity of wind farm operations. **Figure 1** includes all BOEM wind Call Areas and only illustrates the potential areas for development for determining encounter scenarios. As no large-scale commercial wind farms have yet been constructed in the U.S., it was necessary to identify the factors influencing encounter risk for the Calculator using the best available information while maintaining flexibility to adapt to changing vessel and biological data as well as ongoing and future wind development activities.

To build the risk factors for the Calculator, a series of matrices necessary to inform the components of the analytical model (**Section 3.3**) were developed such that each risk factor independently contributed to the overall risk of an encounter. Each risk factor matrix (**Section 2.3**) provides data, using the best available information, that help forecast an encounter and thus begin to determine the vulnerability of an animal to a vessel strike.

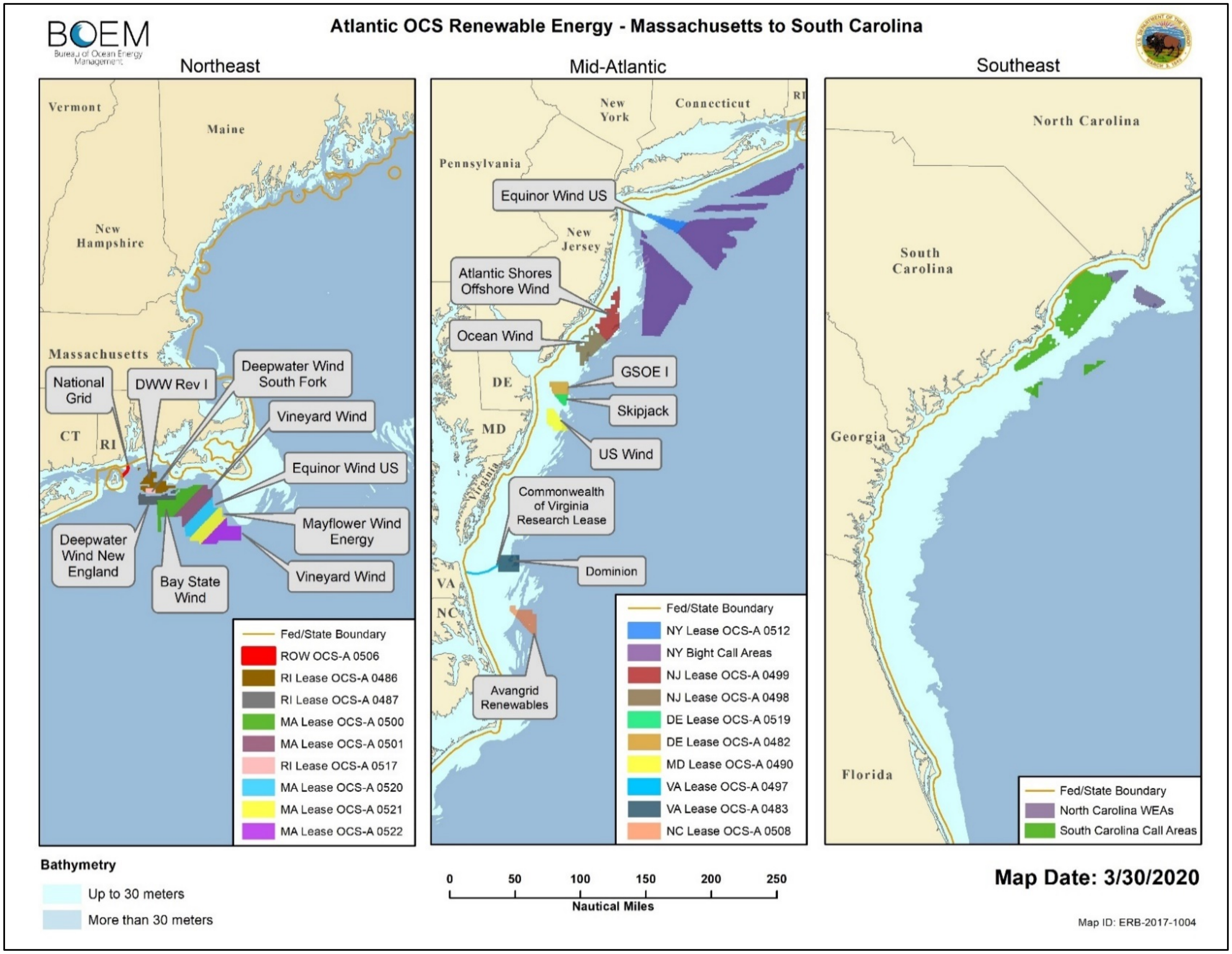


Figure 1. Current Bureau of Ocean Energy Management Atlantic Wind Energy Areas

2.2 Data Sources

Data were derived from published journal articles, government reports (e.g., BOEM, U.S. Navy, NMFS), wind permitting and planning documents (e.g., construction and operations plans), and vessel automatic identification system (AIS) data services. Data utilized in the look up tables for the model are described in **Section 2.3**; individual species look up tables are provided in **Appendix A**; summarized vessel data is provided in **Table 1**.

2.2.1 Literature

Traditional literature searches were performed to include species-specific information, vessel strike studies, risk assessments, and encounter modeling. Most publications accessed were published after 2012.

2.2.2 Vessel Data

Several types of vessel data were needed to build risk factor matrices (**Section 2.3**) and to develop vessel and port information necessary for the GUI. BOEM provided data on offshore wind industry activities that were used to identify the vessel type, number, function, and dimensions expected to operate during wind farm site investigation surveys, construction, operations, and maintenance phases of development. Vessels were categorized according to physical characteristics, including size (length, beam, gross tonnage), average operating speed, and draft. These vessel categories and characteristics were further refined from AIS records gathered from two European wind farms. The AIS data provided a series of vessel positions that also included vessel names, course heading, speed, destination, vessel draft, and estimated time of arrival. From this information, the activity (e.g., speed, number of trips within 24 hours, percentage of time stationary) for each vessel category was summarized during transit to and from or on the wind farm to better characterize the model vessel activities.

Vessel activity (i.e., behavior) is different when in transit between a port and wind farm and when the vessel is working within the wind farm. Therefore, two components, a port-to-wind farm route (transit) component and an on-site (within the wind farm) behavior component, were necessary to build the vessel routes for user-defined scenarios. Common port-to-wind farm routes were built from the U.S. Coast Guard (2016) Atlantic Coast Port Access Route Study (ACPARS); construction and operations plans; a BOEM port study (Whitney et al., 2016); and a BOEM-provided proprietary fishing routes study (unpublished data, provided to CSA, October 2019). Geographic information system (GIS) coverages of the most applicable transit routes between ports and wind leases were built by combining the available data.

Unlike transiting, predicting behavior of vessels while operating in the wind farm (lease) area largely depends on the function of the vessel while in the lease area (e.g., crew transfer, survey, installation, blade delivery). These functions can vary by development phase, operations within each phase, weather, and operational schedules. Because the U.S. currently does not have large-scale wind projects on the OCS, information was gathered from the AIS data feeds from two European wind farms: the Beatrice Wind Farm (Moray Firth, North Sea, Scotland) during its construction between 2017 and 2019, and the Gwynt y Môr Wind Farm (Wales, United Kingdom) during its operation and maintenance between 2016 and 2019. AIS positions in 2-hour increments were obtained from Vessel Finder, Ltd, for all vessels recorded within the geographic boundaries of the wind farms. As with the BOEM provided data, all vessels were categorized according to physical characteristics, including size (length, beam, gross tonnage), average operating speed, and draft. Vessels not likely to be associated with wind farm activities (e.g., yachts, sailing vessels, container ships, cruise ships, oil tankers) were removed from the analysis. Vessels categorized in the AIS data as fishing vessels or cargo ships were assessed on a case by case basis as to whether that vessel was likely associated with wind farm activities or not. Once all vessels were categorized, each vessel category was summarized by the number of records on the wind farm (21,107 two-hour observations from among the seven vessel categories for the Beatrice Wind Farm, and 59,322 two-hour observations from among the seven vessel categories for the Gwynt y Môr Wind Farm and the percentage of time vessels in each category were moving at speeds not exceeding that of the swim speed for the animal species used in the scenario (see **section 2.3.2**) were assumed to be functionally stationary). The average speed of moving vessels also was calculated for each vessel category at each wind farm. A grand mean of the two wind farms was computed for the average speeds of moving vessels and the percentage of time moving for each vessel category. All data manipulation and analysis was performed using SAS software (SAS Institute, Inc., 2016). How this within-wind farm vessel behavior was incorporated into the model is further explained in **Section 4.2**.

2.2.3 Marine Mammal and Sea Turtle Data

In addition to traditional literature, several marine mammal and sea turtle databases/reports were accessed to obtain density, distribution, and swim depth data. All density information for cetaceans was derived from Roberts et al. (2016, 2020) data layers (available at cetsound.noaa.gov). For sea turtles, the U.S. Navy Operating Area (OPAREA) Density Estimates (NODES) (Department of the Navy, 2007a,b) were used as the primary data source and available through the Duke University Ocean Biogeographical Information System (OBIS). Consistent swim depth data were limited in journal publications. The most consistent format was provided in the Navy Undersea Warfare Center’s dive distribution and group size parameter reports (Borcuk et al., 2017; Watwood and Buonantony, 2012). The dive data were supplemented with regional or species-specific depth distribution information, as appropriate.

Swim depth and duration were assigned based on species’ expected activity within one of three east coast regions: Southeast, Mid-Atlantic, or Northeast. Species activity data were broken into three categories based on primary ecological function: foraging, migrating, or calf-care. An additional category, surface active group (SAG), was added for the NARW. Each activity was assigned to a corresponding swim depth bin and mean time within the bin as well as mean swim speed. While highly generalized, this approach enabled consistent treatment across all species. For species with additional information available, subject matter experts were consulted and the information was supplemented with published literature. Subject matter experts, namely Dr. Robert Kenney and Mr. John Calambokidis, served as reviewers and contributors to the species data input to the matrices and the general assumptions made about individual species.

2.3 Matrices

Marine species and vessel data populated the matrices used by the Calculator to identify the correct data for input. The model uses three matrices: a region matrix, a species matrix, and a vessel matrix. The region matrix separates the Atlantic OCS into three sections that correspond to species density and activity changes typical for large whale and sea turtle species. The species matrix uses species density and activity data associated with the month and actual locations input by the user through the GUI. The vessel matrix uses the physical characteristics and behavior of the vessel associated with the phase of wind farm development and the transit selected by the user. The matrices are described further in the following subsections.

2.3.1 Region Matrix

The study area was divided into three regions (Southeast, Mid-Atlantic, and Northeast), primarily based on changes in marine mammal species densities by month. Sea turtle densities generally follow seasonal patterns, and although their densities are more consistent in the south and mid-Atlantic, the patterns are applicable to the regional divisions. Mysticete whale species were used to determine the location of separation boundaries due to their seasonal migrations between low latitude calving grounds and high latitude feeding grounds. Odontocete whale species, while showing some seasonal movements, do not exhibit the same clear changes in densities over large spatial scales. The primary species considered were humpback, NARW, fin, minke, and sei whales. The blue whale was not considered because the species has a relatively uniform density along the entire study area (Roberts et al., 2016). The Southeast, Mid-Atlantic, and Northeast regions were subjectively divided by latitude lines of 25.12°, 35.05°, and 41.07°, respectively (**Figure 2**). These areas serve to determine the primary behavior categories (i.e., foraging, migrating, calf-care, and SAG) expected for each species. While animal behaviors and densities do not change at such clearly demarcated locations, it was necessary to set some physical boundaries to ensure the model will use the most appropriate data available for each region.

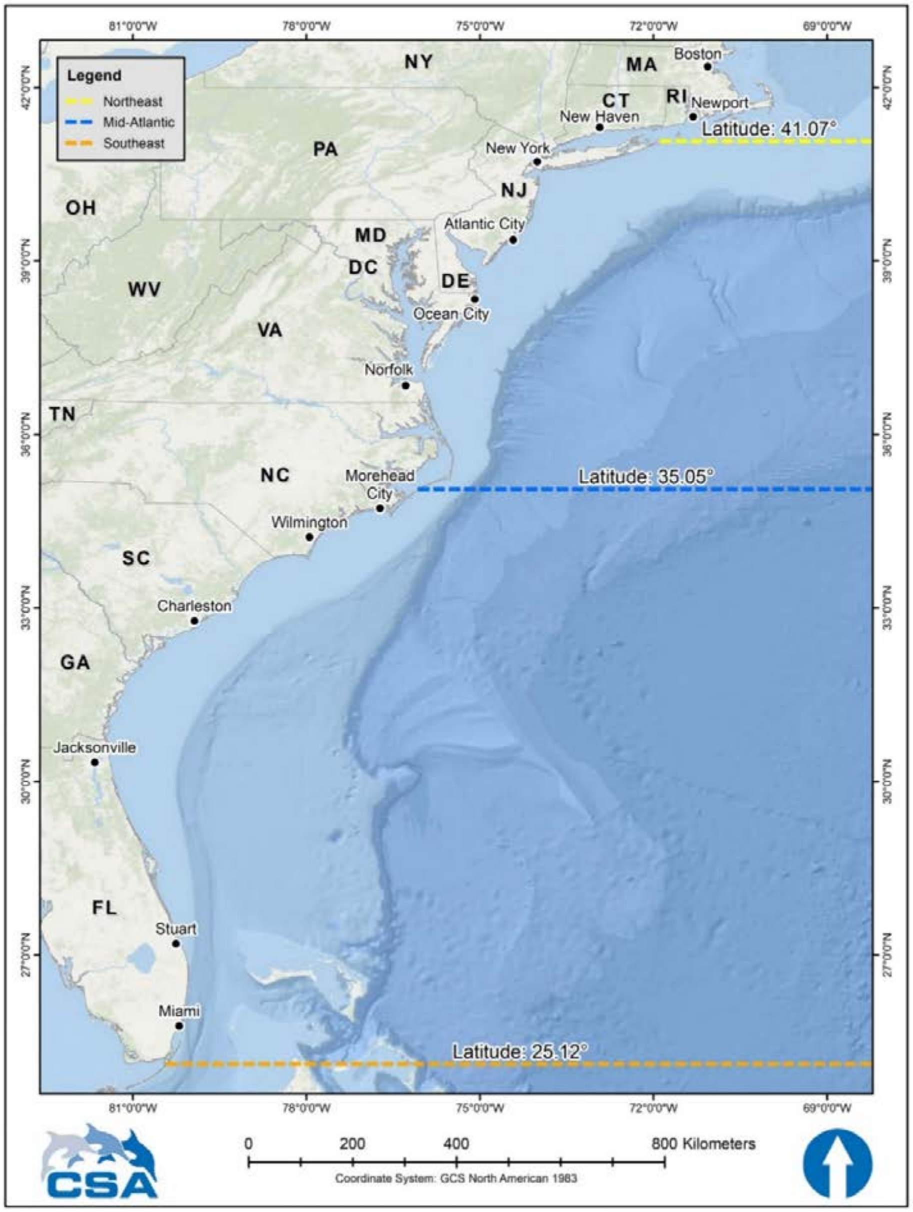


Figure 2. **Risk factor region matrix boundaries**
Boundaries indicate the Southeast, Mid-Atlantic, and Northeast regions, subjectively identified by changes in monthly animal densities. Each area is located to the north of the respective boundary line.

2.3.2 Vessel Matrix

Using the data sources described in **Section 2.2.2**, seven categories of vessels were developed to group vessels based on similar physical characteristics such as size, draft, and average operational speeds (**Table 1**). The data from the identified vessels was compiled and ranges for the width, length, tonnage, and draft categories were determined. In addition, from the AIS data, the percent time moving within the windfarm area and the mean speed traveling versus the time spent stationary was determined. These data provided ranges for each parameter, and the mean of those ranges was used to best characterize that group of vessels and provide a data-driven default for each of the vessel parameters. **Table 1** provides the vessel categories and corresponding mean characteristics used in the model. Vessel speeds in the matrix are default suggestions based on information for each vessel type; however, the user can modify speeds directly using the GUI.

While the vessel type may change throughout the period of wind development in the U.S., the general function and size of a vessel type are unlikely to notably change, and these generalizations are reflected in the matrix. Individual vessels will vary, and the user should be aware that some vessels may not fit well into the vessel categories. Therefore, users should carefully design vessel scenarios and assign vessels into categories that best represent the characteristics of the vessel (**Table 1**). The calculator offers flexibility by allowing the user to design multiple scenarios and specify additional parameters such as trip numbers, vessel speed, and track lines within each vessel category.

Table 1. Vessel category characteristics used in the Vessel Risk Calculator

Category	Activity	General Vessel Types	Example Vessels	Mean Width (m)	Mean Length (m)	Mean Gross Tonnage	Default Transit Speed (kn)	Mean Draft (m)	Percent Time Moving in WFA	Mean Speed when Moving[1] in WFA (kn)
1: Crew Transfer	Crew transfer, service, refueling, guard vessel, multi-purpose support, MMO/biological surveys	High speed transfer/crew vessels	HSC, crew boats, pilot boats	10	25	150	25	2	42	17
2: Tugs	Component feeder, tug support, foundation installation, foundation transport, acoustic monitoring, ESP transport, secondary work, snag, anchor handling support	Limited mobility or companion vessels	Tugs, utility vessels, small dredges, guard vessels, small crane barge	18	68	1,200	14	4	44	7
3: Support Vessels <100 m	Noise mitigation, component feeder, repair vessel, grapnel run	Mooring/anchor and equipment handlers	Anchor, buoy, mooring handlers, small jack ups	12	60	3,500	15	6	26	7
4: Heavy Cargo	Blade transport, WTG transport, boulder clearance/burial, nacelle and tower transport, crew hotel, trenching, foundation transport	Multipurpose offshore vessels	OSVs, support vessels, cargo vessels	20	115	7,650	15	6	38	8
5: Survey	Pre-installation G&G surveys	Survey vessels	Survey vessels	16	63	15,000	30	2	78	7
6: Cable Lay	Cable lay, WTG installation, foundation transport, scour protection installation, rock concrete placement, scour protection repair, WTG commissioning	Cable and similar vessels	Cable lay, pipe lay, floatel, dive support vessels	39	152	22,250	15	7	39	9
7: Construction/ Crane	Dredging, foundation installation, ESP transport	Large, limited-mobility vessels	Crane vessels, drill ships, large dredges (hopper), large jack ups	60	185	40,000	16	6	34	8

[1] Moving at a speed exceeding the following animal speeds in knots, dependent upon the animal species in the scenario: right whale (0.5), humpback whale (1.2), fin whale (1.6), minke whale (1.8), sei whale (1.8), blue whale (1.5), sperm whale (0.9) and turtles (all; 0.6). ESP = electric service platform; G&G = geophysical and geotechnical; HSC = high speed craft; MMO = marine mammal observer; OSV = offshore supply vessel; WFA =wind farm area; WTG = wind turbine generator.

2.3.3 Species Matrix

The species included in the risk analysis model include:

- Fin whale (*Balaenoptera physalus*);
- Minke whale (*Balaenoptera acutorostrata*);
- Sei whale (*Balaenoptera borealis*);
- Humpback whale (*Megaptera novaeangliae*);
- North Atlantic right whale (*Eubalaena glacialis*);
- Blue whale (*Balaenoptera musculus*);
- Sperm whale (*Physeter macrocephalus*);
- Leatherback sea turtle (*Dermochelys coriacea*); and
- Hard-shelled turtles (loggerhead [*Caretta caretta*], green [*Chelonia mydas*], and Kemp's ridley [*Lepidochelys kempii*]).

As described in **Section 2.2.2**, each species has a unique density, activity composition, and swim speed that provides required model information. Physical parameters (e.g., animal's mean length, width) for each species also are provided in the matrix for model access.

A sample species matrix framework (without species-specific data) is provided in **Table 2**, showing how data are incorporated by the model. The monthly species matrices for whales and sea turtles considered in the model are provided in **Appendix A**.

Table 2. Sample matrix format for a species (X) in a given month (Y) within the Northeast region

Species = X Month = Y	Mean Density (animals km^{-2})[a]	Length, Width, Draft (m)[b]	Mean Group Size[b]	% Population Within each Activity Category[b]	Swim Speed (m s^{-1})[c]	% Time in each Depth Bin Based on Activity	Derived Density (km^{2}) at each Depth Bin and Speed
Northeast	#	#,#,#	#	% Foraging	#	0–10 m	#
						10–20 m	#
						>20 m	#
			#	% Migrating	#	0–10 m	#
						10–20 m	#
						>20 m	#
			#	% Calf-care	#	0–10 m	#
						10–20 m	#
						>20 m	#

[a] Data from Roberts et al. (2016).
[b] Data from literature and subject matter expert reviews.
[c] Data from Navy Undersea Warfare Center reports (Borcuk et al., 2017; Watwood and Buonantony, 2012).
represents species-specific data from tables in **Appendix A**.

2.4 Encounter Factors

The encounter factors are the resulting data entered into the corresponding matrices that independently serve to increase or decrease the probability of an encounter between an animal and a vessel. Other vessel strike models and analyses of vessel strikes in the literature account for various encounter factors, sometimes individually and sometimes in combination (e.g., Dolman et al., 2006; Rockwood et al., 2018; Silber and Bettridge, 2010). Taken individually, an encounter factor fundamentally makes the animal more or less accessible to being struck. For this study, encounter factors are considered outside of behavioral aversion from the animal or vessel. In this way, the risk assessment identifies the probability for an animal to be within a three-dimensional strike risk zone (encounter) but does not further calculate if a physical interaction and a strike may occur which is dependent on a number of other unpredictable factors and circumstances. The strike risk zone is identified as a 1 km^2 analysis block containing both the vessel and the animal, with the animal in a depth bin within the mean vessel draft and at a trajectory that, with no aversion, will intersect with the vessel. While the actual strike zone is smaller than 1 km^2 (Silber et al., 2010), the minimum functional information scale (e.g., vessel routes, animal densities) to assess risk in the model would not be applicable (or prudent to use) at finer scales. The mathematical expression of how these encounter factors contribute to the model is detailed in **Section 3.3**.

2.4.1 Vessel and Animal Size

Vessel strikes can occur from all types and sizes of vessels, from large container ships to small personal watercraft (Dolman et al., 2006; Laist et al., 2001). The physical dimensions of the vessel and animal will influence the strike zone in that if a vessel or animal occupies more "space" in the water, there is an increase in the likelihood of an encounter. Vessels that are longer, wider, or have deeper drafts increase the size of the vessel footprint within the water column, thus increasing the likelihood of an encounter. Jensen and Silber (2003) summarized the vessel characteristics of reported whale strikes between 1975 and 2002 and showed that, while all vessel classes are represented, most incidents involve relatively large vessels. However, Jensen and Silber (2003) also cautioned that certain vessel classes likely are over-represented due to reporting requirements (e.g., U.S. Navy, U.S. Coast Guard, whale watching) and an unbiased account of all vessel strikes likely is not attainable. Other vessel strike models have used physical parameters of vessels to assess strike probability (Fonnesbeck et al., 2008; Rockwood et al., 2018; Williams and O'Hara, 2010) as well as strike severity (Silber et al., 2010; Wang et al., 2007). The current risk assessment does not address strike severity, only encounter risk (and strike risk with utilization of aversion options). However, while the gross tonnage of the vessel does not influence the overall risk, it contributes to the vessel's ability to avoid a strike (and to the severity of a strike) and should be considered when selecting aversion effects in the GUI.

Similarly, animals that are longer and wider present a larger "target" in the water for a potential strike. Few studies have addressed the size of the animal as a contributing factor outside the behavioral context associated with those animals (Crum et al., 2019; Martin et al., 2016; Silber et al., 2010). The strike risk will be influenced by the size of the animal by increasing the relative target size within the strike risk zone.

2.4.2 Vessel Speed

Vessel speed has been widely assessed in vessel strike literature (Berman-Kowaleski et al., 2010; Conn and Silber, 2013; Dolman et al., 2006; Gende et al., 2011; Jensen and Silber, 2003; Martin et al., 2016; Redfern et al., 2013; Silber and Bettridge, 2010; Wang et al., 2007) and has significant influence on the probability and severity of a strike in real-world circumstances. In addition to reduced response time for the vessel, studies suggest increased vessel speed is a causative factor in an animals' inability to avoid collision (Dolman et al., 2006; Laist et al., 2001; Rockwood et al., 2018; Silber and Bettridge, 2010). Vessel speed has less effect on strike risk over a fixed distance with fixed target density when there are no behavioral components considered (Yin et al., 2019). Vessel speed has a significant effect on strike risk only when behavioral components are considered, thus the ability for the user to input animal or vessel aversion is an important variable that can provide insights to the encounter risk based on vessel speeds. The key mathematical relationship between vessel speed and *encounter* risk is that the expected number of animal encounters (and hence opportunities for a strike to occur) decreases exponentially with increasing vessel velocity through only that single 1 km^2 block (i.e., the vessel is spending less time within a block, hence, less time for an encounter to occur). However, as noted by virtually every author that has addressed the subject: slow moving vessels provide more time for the animals and vessel operators to avert the collision (e.g., Crum et al., 2019; Martin et al., 2016; Vanderlaan and Taggart, 2007), such that *strike* risk (rather than encounter risk) will increase with increasing vessel speed. The two findings are entirely consistent. It must be recognized that the aversion probabilities of both ship and animal should reflect the speed of the vessel, with an increasing chance of overall aversion the lower the vessel speed. It is noted that user-defined aversion for vessel and animal is included as an option in the Calculator.

2.4.3 Animal Density and Activity

Higher animal (and vessel) densities increase strike risk (Rockwood et al., 2018; Williams and O'Hara, 2010; Yin et al., 2019) and those densities vary spatially and temporally for each species and vessel type. The species density data used to provide risk model input (Roberts, 2018; Roberts et al., 2016) (unpublished data) were developed using long-term transect survey data linked to ocean habitat information as well as remotely sensed sea surface temperatures and chlorophyll concentrations during the survey periods. The density models (Roberts et al., 2016) estimated abundance for areas that have not been surveyed and provided the spatially registered data needed for the scale of this project. Roberts (2020) further updated model results for NARW by implementing three major changes: increasing spatial resolution, generating monthly estimates on three time periods of survey data, and dividing the study area into five discrete regions. These changes are designed to produce estimates that better reflect the most current, regionally specific data, and to provide better coastal resolution. While local animal densities are highly dynamic and currently in flux due to climate factors influencing ocean conditions (Charif et al., 2020; Davies et al., 2019; Gowan et al., 2019; O'Neil et al., 2019; Tulloch et al., 2019); the Roberts et al. (2016); and Roberts (2018, 2020) data are the best available data accessible in a single published database at the required spatial extent and resolution for the Calculator. As data are updated (e.g., Roberts, 2018) (unpublished data), they can be incorporated into the matrices and model.

Within any population, location, and season, there will be different percentages of animals engaged in a variety of activities whose frequency of occurrence ranged from 0 to 100%. Animal activity categories (foraging, migrating, calf-care, and SAG) dictate the mean group size, swim speed, and time within specified depth bins, which are used as encounter factors in the model. For example, whales in calf-care activity typically spend more time in the shallower depth bins than whales engaged in foraging activity, thus increasing the strike risk for the portion of the population expected to be engaged in calf-care.

Group Size

Higher mean group sizes within 1 km^2 will increase the probability of an encounter; however, over the course of a transit, the probability would be countered by areas without animals because of aggregation. The aggregation condition that presents the greatest strike risk is the SAG behavior demonstrated by NARWs. Rather than aggregating densities where a percentage of the population is likely to be in a SAG, the effective size of the whales was increased in the corresponding percentage of the population density to account for the aggregation condition.

Swim Speed

Increased animal swim speeds, when within the strike risk range, will decrease strike risk by decreasing the amount of time an animal is within the predicted strike risk zone (**Section 3.3**). Animal swim speeds have been used in other vessel strike models without the inherent behavioral aspects of a whale’s speed in relation to a vessel (Crum et al., 2019; Martin et al., 2016; Silber et al., 2010). However, swim speeds are highly contextual and depend on animal activity, life stage, disturbance, and other factors that make assignment of a consistent swim speed a challenge. Swim speeds have been reported in topical studies (Baumgartner and Mate, 2003; Blix and Folkow, 1995; Hain et al., 2013; Henderson et al., 2018; Lagerquist et al., 2008; Noad and Cato, 2007), but the only comprehensive list of mean swim speeds for multiple species is provided in Navy Undersea Warfare Center reports (Borcuk et al., 2017; Watwood and Buonantony, 2012).

Dive Depth

Animals that spend a large portion of time at the surface or in shallow depth bins experience higher risk for vessel strike. Animal dive depths influence the spatial risk of the vessel and animal occupying the same space, and evidence suggests animals at or near the surface have to initiate an avoidance dive (typical aversion behavior) to at least 250 to 500 m before intersection with a vessel to successfully be out of the strike risk zone (McKenna et al., 2015; Silber et al., 2010).

2.5 Aversion

Although aversion is not well understood, aversion (by the animal or vessel) typically occurs, if at all, within 1 km of a vessel (Gende et al., 2019; McKenna et al., 2015; Nowacek et al., 2004; Richardson et al., 1995; Szesciorka et al., 2019; Wiley et al., 2016). Responsiveness to vessels by large whales may extend much farther and is highly contextual, with species, speed, sound, bathymetry (McKenna et al., 2015), and behavior of animals and vessels contributing to the success or failure of the aversion (Gende et al., 2019; McKenna et al., 2015; Nowacek et al., 2004; Szesciorka et al., 2019; Wiley et al., 2016). Therefore, it is not practical to assign vessel or animal aversion consistently across spatial, temporal, species, or operational variability within the model. As such, the default assumption is no aversion; however, recognizing its importance to strike risk and assessing the potential outcomes of mitigation effectiveness or behavioral responses to vessels, vessel and animal aversion can be modified within the GUI. By modifying vessel and animal aversion, the predicted value for vessel encounters provided by the model transforms into possible strikes.

3 Model for Predicting the Expected Number of Animals Encountered (Strikes)

In the analytical model, “strike” represents when an animal and a vessel are expected to intersect. With aversion of the vessel and animal set at 0 (default), the vessel and animal must come in contact when they intersect. However, because the analytical solution does not contain the aversion coefficient, whether the vessel and animal would, in a real-life situation, actually come in contact cannot be determined. Hence, here a “strike” is the forecasted intersection of a vessel and an animal. However, the analytical model only predicts the number of animals expected to be encountered in 1 km^2 (i.e., number of strikes); as pointed out in **Section 2.5**, vessel and animal aversion can be modified within the GUI, completing the consideration as to whether the vessel and animal actually come in contact (i.e., an actual strike).

At its simplest form, the overall methodology adopted by the study addresses the problem by separating the analysis into two components:

1. Development of an encounter probability model that predicts the number of encounters along a generic 1-km vessel transit path, considering the variability of key parameters such as the number of vessel transits, animal density, etc.
2. Development of a totaling process that integrates the predicted number of animals encountered along a vessel route into the user-defined scenarios that consider strike risk probability in broad temporal and spatial scales.

The mathematical framework underpinning the model, which is composed of the analytical solutions used to explicitly determine the expected number of animals at risk for encounter per kilometer sailed, is based on a given set of location- and time-specific vessel and animal input data entered into the GUI. The model predicts an expected number of encounters along a vessel route that equates to the risk posed by a specific vessel activity scenario (i.e., unique vessel compliment, routes, trips, seasons, and species). The differences between strikes and strike risk are detailed in **Sections 3.2** and **3.3**.

3.1 Approach and Methods

The modeling framework developed and presented herein for determining encounters is process-based, meaning encounter probability is separated into key underlying processes, or encounter factors, that become possible to quantify when considered on an individual basis. While a process-based approach provides a basis for modeling complex phenomena, it also means the overall accuracy of the model entirely depends on the accuracy represented by the individual underlying processes. Even when considered independently, the underlying processes often are highly complex. Assumptions must be made to meaningfully deconstruct a real-world phenomenon into key underlying processes and to incorporate expert knowledge and available data into a mathematical description of those processes for use in the model.

There were two possible approaches to model animal-vessel encounters:

- ***Agent-based (animal and vessel behavior) approach*** – In recent years, agent-based approaches have become increasingly refined and accepted. While not without notable limitations and a reliance on substantial assumptions and data, agent-based models are powerful tools for addressing strike risk that avoid some of the overarching mathematical assumptions required to solve the problem analytically. However, due to their level of detail and data requirements, agent-based models tend to be better suited to detailed project assessments rather than the large-scale assessment required for the current study.
- ***Analytical-based approach*** – An analytical solution, sometimes referred to as a closed form solution, involves framing the problem in a well understood series of mathematical expressions, from which it is possible to determine a single, exact solution. Fundamentally, the risk of a vessel encounter with a marine animal is a subset of the well understood "trapping problem" (**Section 3.6.1**) (Gallos and Argyrakis, 2001), which lends itself to an analytical solution. While the analytical solution requires significant assumptions and simplifications, it provides a consistent framework applicable for large areas and a framework that can be applied based on available (and evolving) secondary data sources.

After considering the limitations of data availability and aversion efficiency at a seaboard scale, the analytical approach was utilized. However, by adding the ability to input aversion as a simple percentage rather than incorporating an animal movement (agent-based) model that is not within the scalability of the project's scope, the model becomes a pseudo agent-based model. The pseudo agent-based model thus simplifies to an analytical solution when aversion is simplified to an aversion probability rather than an aversion behavior. A full description of the pseudo agent-based model is described in **Appendix B**.

3.2 Assumptions

The model framework assumes that a vessel route can be split into individual segments of arbitrary length (e.g., 1 km), where an encounter along a given route segment is statistically independent of all other segments. This means events occurring along one segment of the route do not affect events that occur in preceding or subsequent segments. Three notable implications arise from this assumption:

1. Long-term aversive behavior by the vessel or animal cannot be represented explicitly. From this mathematical perspective, this means that when a vessel strike occurs, nearby animals do not change their behavior whatsoever. Furthermore, the vessel cannot change its behavior in response

to strikes along successive route segments. Due to the importance of aversion, however, the Calculator allows the user to assign an aversion coefficient into the equation through the GUI.

2. Animals are sampled with replacement, meaning that when a vessel strike occurs, the overall number of animals that could be encountered in the future does not decrease (i.e., vessel strikes resulting from assessed traffic patterns are not modifying the overall population density).
3. The distribution of animals is considered uniform within any single density block; therefore, aggregations of animals that may be co-dependent on behavior are not captured in the model. The only exception to this rule is the adjustment for SAGs in North Atlantic right whales as described in **Section 2.4.3**.

These assumptions are required for an analytical solution.

An illustration of how individual vessel routes can be discretized is provided in **Figure 3**. Vessel-animal interactions are modeled from the reference point of the vessel by splitting the vessel route into many small segments of equal length. The mathematical relationships describe vessel-animal collisions along each segment in a two-dimensional domain (1 km × 1 km) centered on the individual vessel route.

Encounter counts are calculated within the 1 km^2 blocks by the analytical framework presented here, then totaled along the entire vessel route (vessel route total) by the totaling process developed by CSA (in the GUI, the animals encountered on a vessel route are summed). Thus, the totaling process relies on the analytical model for data on vessel speed, animal density, animal behavior, etc., for every kilometer as the vessel proceeds along a given transit route. All parameters are considered constant for the 1 km^2 block under consideration (i.e., the Calculator resolution is 1 km^2). Specifically, certain parameters will vary along a vessel route depending on the region, actual location, season, and other environmental factors. This variability in parameters along a transit route is accounted for by the totaling process by using information about the specific vessel and animal characteristics based on region, actual location, time of the year, etc. However, for the purpose of the mathematical formulation, the parameters that vary over broader spatial and temporal scales are locally constant within the 1 km^2 block under consideration.

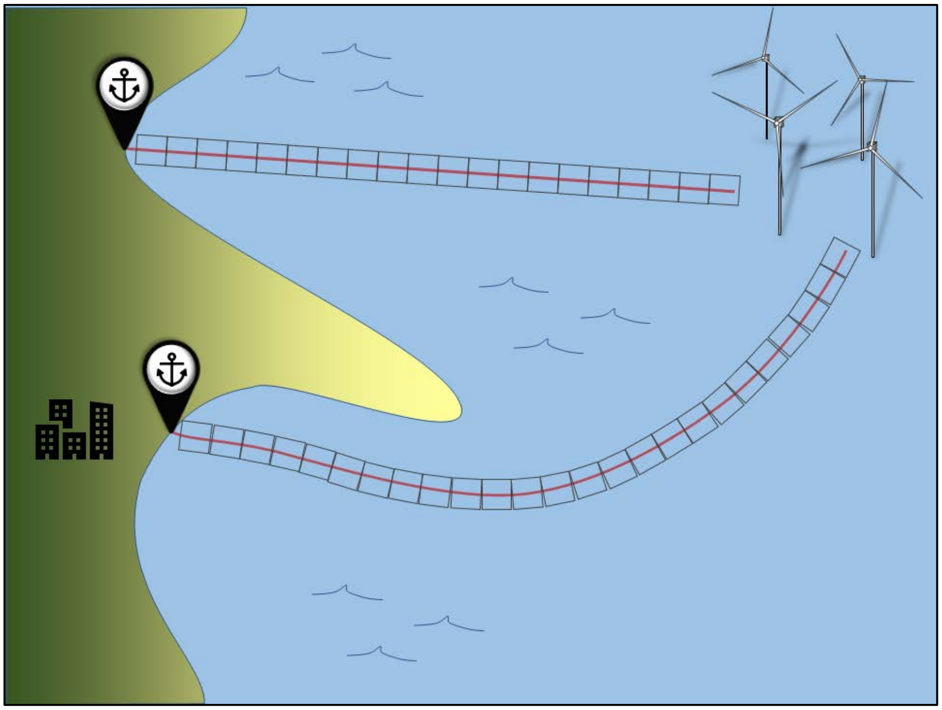


Figure 3. Plan view illustration of the division of a vessel route (red line) into individual segments of equal length (black squares)

Figure 4 provides a close-up illustration of the mathematical domain for an individual segment of the vessel route. Within this domain, for a given 1-km vessel transit through the 1 km^2 block, the following assumptions are made:

- The vessel is represented as a rectangular prism with defined length overall and width (beam) that sails in a straight line through the center of the domain. Errors resulting from ignoring the exact shape of the bow/stern are assumed to be negligible.
- Velocity, draft, and heading of the vessel remain fixed for the 1-km sailing distance across the block.
- Vessel aversion capabilities are represented statistically and remain fixed for the 1-km sailing distance.
- Only one species of animal is represented at a time.
- All animals, regardless of species, are represented as rectangular prisms with an assumed negligible effect arising from differences between the assumed rectangle and the actual animal shape.
- All animals of a given species are assumed to have identical physical characteristics that remain fixed across the block, including velocity, heading, length, and width (beam).
- Animal density (the number of animals of a given species in the domain) remains constant, and animals are assumed to be uniformly distributed throughout the block.
- Complex animal behavioral characteristics (e.g., diving behavior, aversion capabilities) are represented statistically and remain fixed across the block.
- For all animal behavioral characteristics, animal actions (e.g., animal dive profiles) are assumed independent across the population. Consequently, probabilities expressed as a percent of time act mathematically as equivalent to percent of the population.
- Assessment is restricted to first encounter only (i.e., an animal swimming deeper than the vessel draft at first encounter cannot surface as it transits the vessel beam).
- All physical relationships are symmetrical along the x-axis, which is always defined as parallel to the ship heading (shown as the dashed red line in **Figure 4**). As such, animals are assumed to always move in the positive y-direction (i.e., from the bottom to the top of the domain shown in **Figure 4**).
- Domain boundary effects are ignored. This includes the slight angle between the square domain between route segments and the distribution of animals within route segments, which could change as animals swim from one route segment to another.

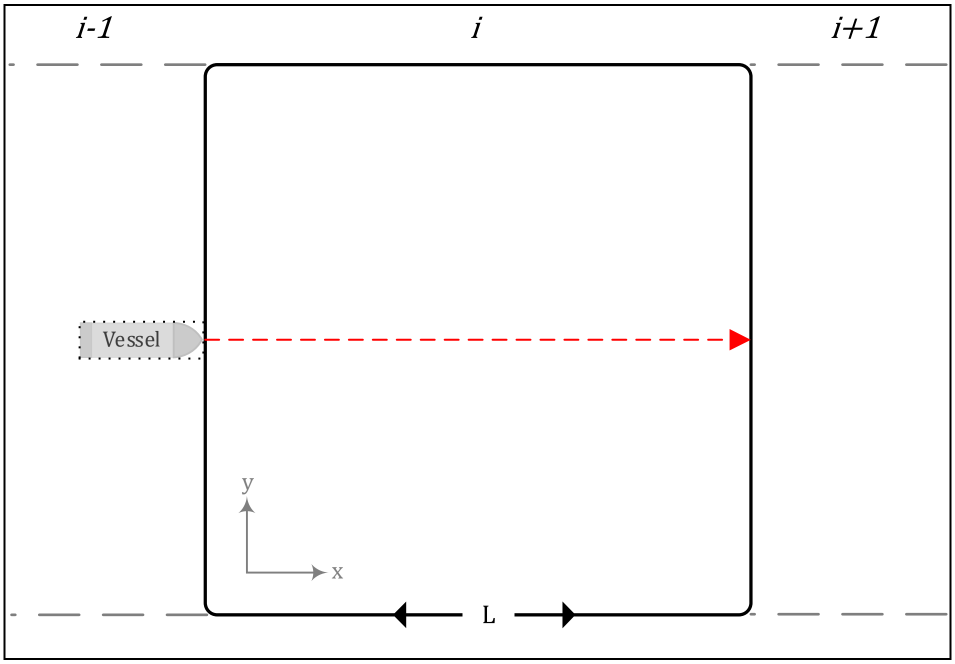


Figure 4. **Plan view diagram of the $L \times L$ square domain (shown in black) centered about a single (i^{th}) segment of the vessel route**

The vessel (shown in gray) sails in the x-direction at a constant velocity along the entire length (L) of the segment (shown as the dashed red line). The square domain is always oriented such that the x-axis is aligned with the vessel heading. The vessel is considered to have entered a new segment when its bow leaves the previous segment. This snapshot depicts the instant the vessel transitions from the $(i-1)^{th}$ segment to the i^{th} segment.

Although these assumptions may seem restrictive, it is critical to recognize that the versatility of the modeling framework lies in the ability to vary the characteristics (including those defined statistically) of the vessel and animal species under consideration between individual route segments in the totaling process. In this manner, spatially and temporally varying data (e.g., animal population density, meteorological conditions, animal foraging, migration, parenting behavior) can be incorporated to provide increased resolution along a full vessel transit. Some data are explicitly represented in the underlying mathematics (e.g., animal population density), and more complex data (e.g., meteorological conditions, nuanced animal behavior) can be interpreted by experts to meaningfully assign vessel and animal characteristics to different route segments. For example, groups of animals can be represented by increasing the size of the single animal to reflect the area of water that an animal cluster would swim through.

3.3 Vessel Strike Risk Criteria

For a vessel strike to occur, three criteria must be satisfied:

1. An encounter must occur. This requires the vessel and animal occupy the same spatial coordinates within the areal domain (i.e., their trajectories must intersect in space and time).
2. The animal must be swimming at a depth equal to or less than the draft of the vessel during the encounter period.
3. During the encounter, neither the vessel nor the animal successfully averts the collision.

Figure 5 depicts the beginning of an encounter between a vessel and animal as the vessel traverses through a 1-km route segment. The encounter begins once the animal and vessel occupy one or more identical coordinates in two-dimensional space at a single point in time. This is depicted at time t_3 in **Figure 5**. **Figure 6** illustrates this geometrically, showing the intersection of a vessel and animal trajectory through space and time. In this example, the encounter begins when the starboard bow of the vessel intersects with the front left of the animal at time t_e.

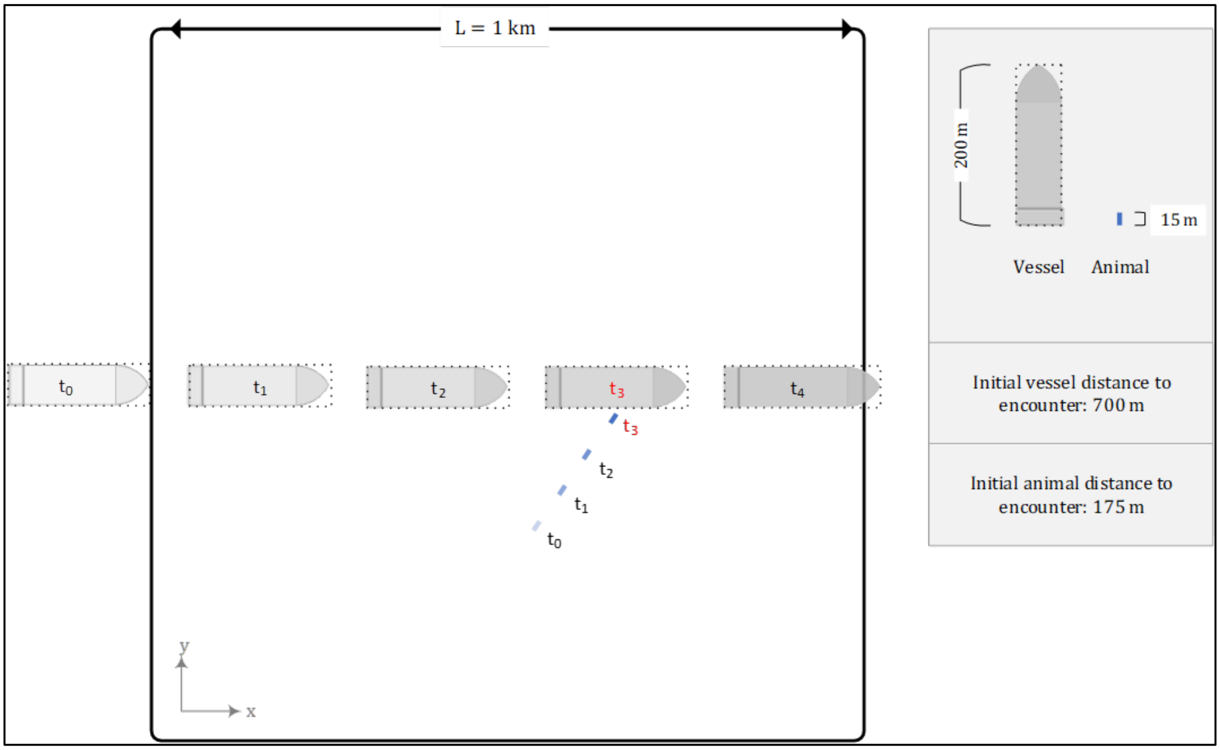


Figure 5. **Illustration of an example vessel-animal encounter within a route segment**
Drawing is approximately to scale. The route segment length is 1 kilometer, signified as L. In this example, the vessel sails at a rate approximately four times faster than the animal swims. The vessel and animal lengths are 200 meters and 15 meters, respectively. The dotted black rectangle around the vessel signifies the vessel is mathematically represented as a rectangle. The vessel and animal are shown at their initial locations, labeled t_0. As time progresses, the vessel and animal are shown at their respective locations, labeled with the corresponding timestep (t_1, t_2, etc.). An encounter occurs at time t_3, shown in red.

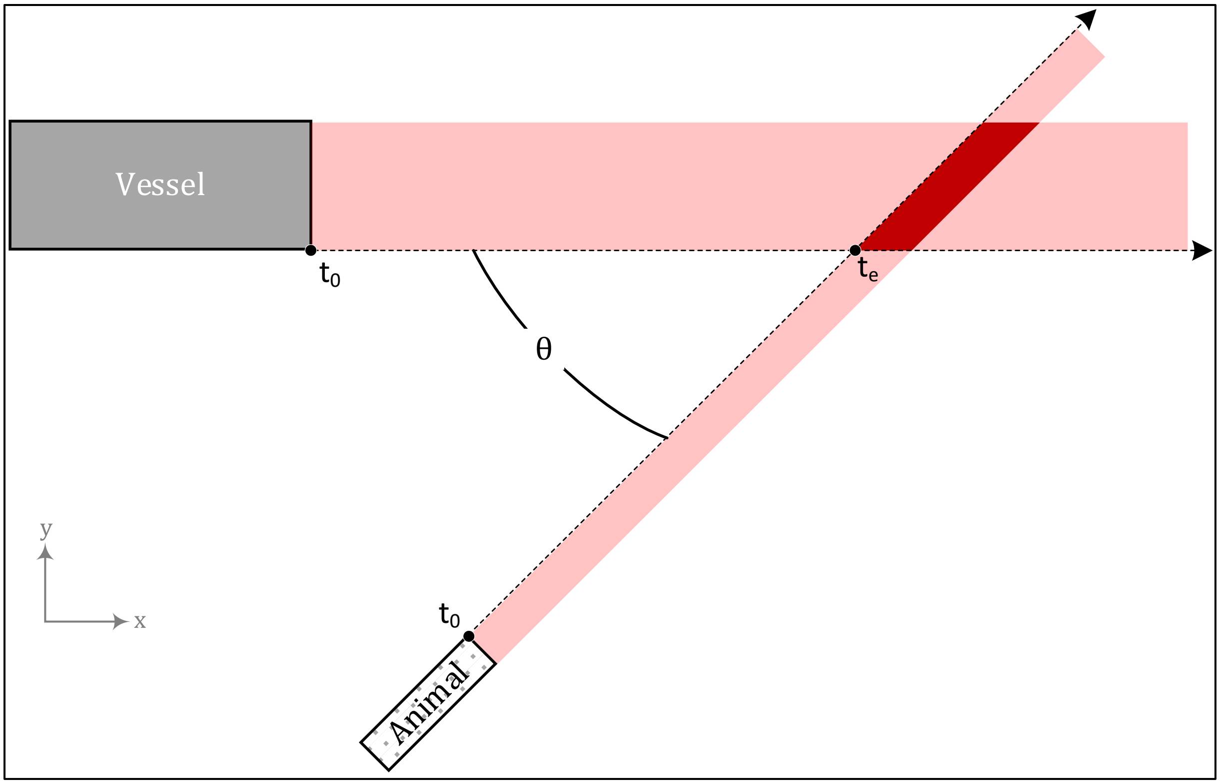


Figure 6. **Illustration of the trajectories**
Graphical illustration of a vessel and an animal intersecting in two-dimensional space. Trajectories for a vessel (gray rectangle) and an animal (white rectangle) are shown as translucent red rectangles. The vessel travels at a fixed velocity directly along the x-axis. The animal travels at a fixed velocity, along a fixed heading $\boldsymbol{\theta}$ degrees counterclockwise from the vessel heading. The initial positions of the animal and vessel are signified with small black circles, labeled $\boldsymbol{t_0}$. At time $\boldsymbol{t_e}$, the vessel encounters the animal. The duration of the encounter is equal to the amount of time the animal and vessel spend traveling through the intersection area (dark red parallelogram).

Important features of the third dimension of the system (e.g., animal swim depth, vessel draft) are represented probabilistically. If a species spends a certain percentage of time swimming at a depth at or above the depth of the vessel draft, assuming independence between animals, then that same percentage of animals can be assumed to be swimming within that depth range during a given encounter (this concerns the second criterion for a strike to occur).

Overall, strike risk is conceptualized as being directly proportional to the expected number of animal encounters a given vessel will accrue while sailing to its destination. The mathematics underlying these estimates are detailed in the following sections. The equations are derived solely from geometric relationships that result from the simplifying assumptions discussed earlier.

3.4 Mathematical Description

Although strikes *per se* are not the output of the Calculator, understanding the mathematical basis for a strike can help users conceive their scenarios. The expected number of strikes along the vessel transit is computed by the totaling process as the sum of the expected strikes from each of the N individual route segments. This can be written as:

$$E[strikes] = \sum_{i=1}^{N} E_i[strikes] \,, \tag{1}$$

where $E[strikes]$ is the expected number of vessel strikes along the route, and $E_i[strikes]$ is the expected number of vessel strikes within the i^{th} segment of the vessel route. The expected number of vessel strikes along the i^{th} route segment is

$$E_i[strikes] = E_i[encounters]P_i(depth)\big(1 - P_i(avert)\big), \tag{2}$$

where E_i $[encounters]$ is the expected number of animal encounters within the i^{th} route segment. P_i $(depth)$ is the probability that the animal is swimming at a depth equal to or less than the vessel draft during the encounter:

$$P_i(depth) = \ P(swim\ depth \leq vessel\ draft) \tag{3}$$

P_i $(avert)$ is the probability of the vessel or animal averting the collision entirely. A further explanation on the implementation of aversion is provided in **Section 3.5.4**.

The expected number of animal encounters along the i^{th} route segment is:

$$E_i[encounters] = \mu_i A_i, \tag{4}$$

where μ_i is the average animal population density inside the domain while the vessel sails through. Animal population density has units of $\frac{\boldsymbol{\#\ Animals}}{\boldsymbol{L^2}}$, where L is the vessel route length (1 km). A_i is the total encounter area and is defined as the region of the domain where an animal would have to originate for its trajectory to intersect with the vessel. **Figure 7** depicts a vessel sailing through the domain, with several possible animal trajectories. The initial position of the vessel and animals are labeled t_0, and the markers for the vessel and animals become increasingly opaque as time progresses. If an encounter occurs, the time markers for the animal and vessel are labeled in red.

The key realization is there is a defined region within the domain where animal trajectories must originate in order to intersect with a transiting vessel. This region always is a parallelogram (due to the established assumptions in **Section 3.2**) and is outlined by the dashed dark gray lines in **Figure 7**. The area enclosed by the parallelogram represents the total encounter area (A_i) for the given route segment.

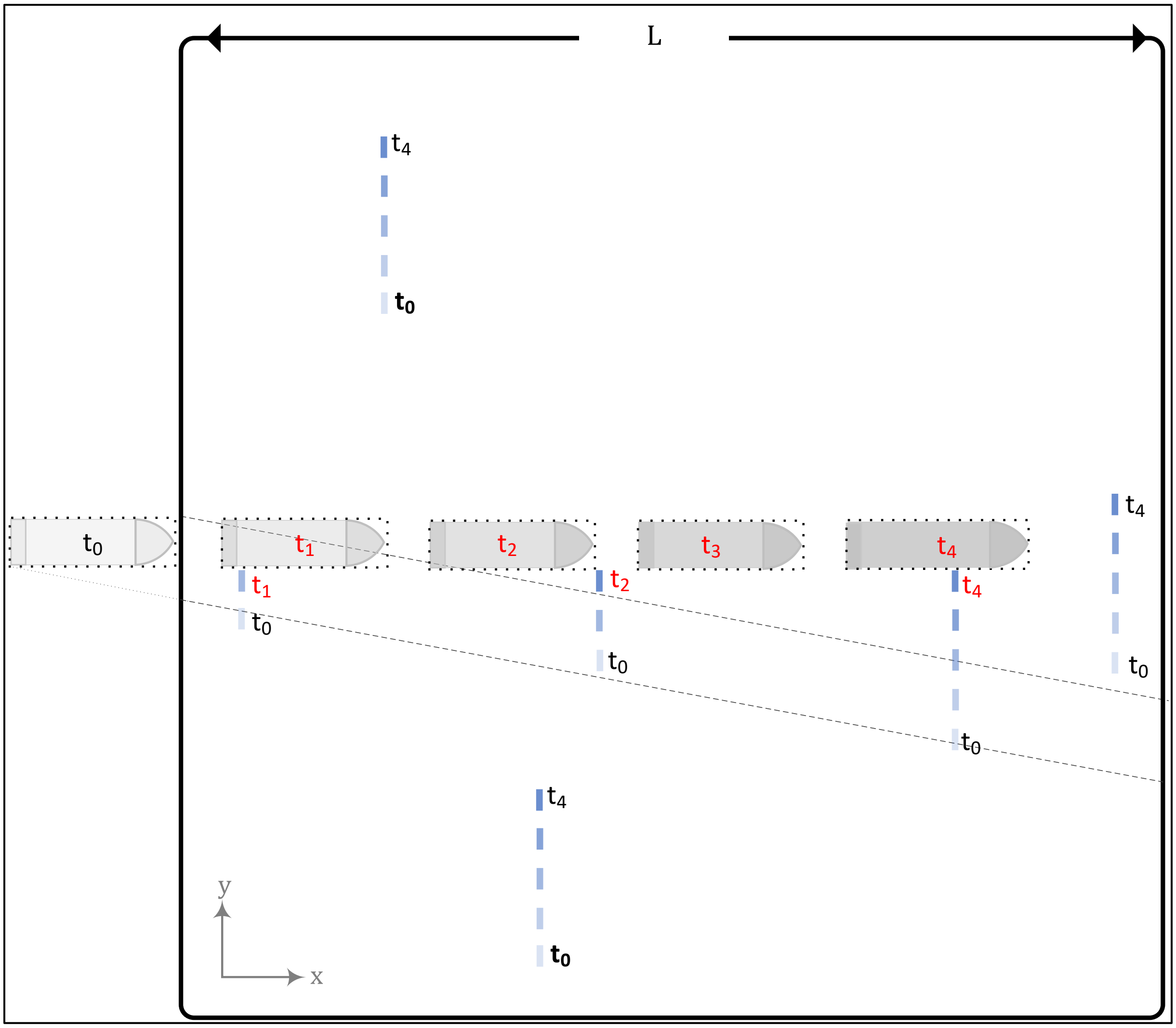


Figure 7. **Depiction of a vessel sailing through a route segment, with several possible animal trajectories shown**

The initial position of the vessel and animals are labeled $\boldsymbol{t_0}$, and the markers for the vessel and animals become increasingly opaque as time progresses. Animals are swimming along the same heading of 90° relative to the vessel. If an encounter occurs, the time markers for the animal and vessel are labeled in red. The dashed dark gray lines enclose the region where animal trajectories must originate in order to intersect with the vessel.

Consider a vessel of length l_v and beam b_v, whose starboard bow originates at the point $\begin{pmatrix} x_v(t_0) \\ y_v(t_0) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}$ within the route segment domain and travels along a route segment of length L at a fixed velocity $\boldsymbol{v_v} = \begin{pmatrix} v_v^x \\ 0 \end{pmatrix}$. The coordinate system of the domain is oriented such that the x-axis is parallel to the direction of the vessel heading; as such, there never is a y-component to the vessel velocity. The position of the starboard bow of the vessel at time t is:

$$\boldsymbol{x_v}(t) = \begin{pmatrix} x_v(t) \\ 0 \end{pmatrix} = \begin{pmatrix} v_v^x t \\ 0 \end{pmatrix} \tag{5}$$

Similarly, consider an animal of length l_A and beam b_A, whose front left corner originates at the point $\begin{pmatrix} x_A(t_0) \\ y_A(t_0) \end{pmatrix}$, that swims at a fixed velocity $\boldsymbol{v_A} = \begin{pmatrix} v_A^x \\ v_A^y \end{pmatrix}$ along a heading θ degrees counterclockwise from the x-axis (which also is relative to the vessel heading). The position of the front left of the animal at time t is:

$$\boldsymbol{x_A}(t) = \begin{pmatrix} x_A(t) \\ y_A(t) \end{pmatrix} = \begin{pmatrix} x_A(t_0) + v_A^x t \\ y_A(t_0) + v_A^y t \end{pmatrix}. \tag{6}$$

An intersection (i.e., encounter) between the starboard bow of the vessel and the front left of the animal requires that they occupy the same point in space at a given point in time:

$$\boldsymbol{x_v}(t) = \boldsymbol{x_A}(t) \rightarrow \begin{pmatrix} v_v^x t \\ 0 \end{pmatrix} = \begin{pmatrix} x_A(t_0)+v_A^x t \\ y_A(t_0)+v_A^y t \end{pmatrix}, \tag{7}$$

which yields the following linear system of equations to be solved:

$$\begin{pmatrix} v_v^x t - x_A(t_0) - v_A^x t \\ -y_A(t_0) - v_A^y t \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}. \tag{8}$$

Because the vessel and animal velocities are known, the only unknown variable that needs to be solved for is the initial coordinate of the animal $\begin{pmatrix} x_A(t_0) \\ y_A(t_0) \end{pmatrix}$.

This basic relationship must be satisfied for an encounter to occur between any two points on the vessel and animal transit lines. The total encounter area A_i is defined as the set of all possible initial animal positions that lead to in intersection between one or more points on the animal and vessel transit lines. A geometric representation of all possible solutions to this linear system (i.e., the encounter area A_i) is provided in **Figure 8**. A_i is shown in two parts, as red parallelograms. The region enclosed by the light red parallelogram (that abuts the bow of the vessel in **Figure 8**) corresponds to the initial position of animal trajectories that result in an encounter with the bow of the vessel ($\boldsymbol{v_A^y}$ in **Figure 8**). The region enclosed by the dark red parallelogram beneath corresponds to initial positions that result in an initial encounter with the starboard side of the vessel. For example, the left front of an animal originating at the white dot labeled $\left(x_A(t_0), y_A(t_0)\right)$ would encounter the starboard bow of the vessel at the time of encounter.

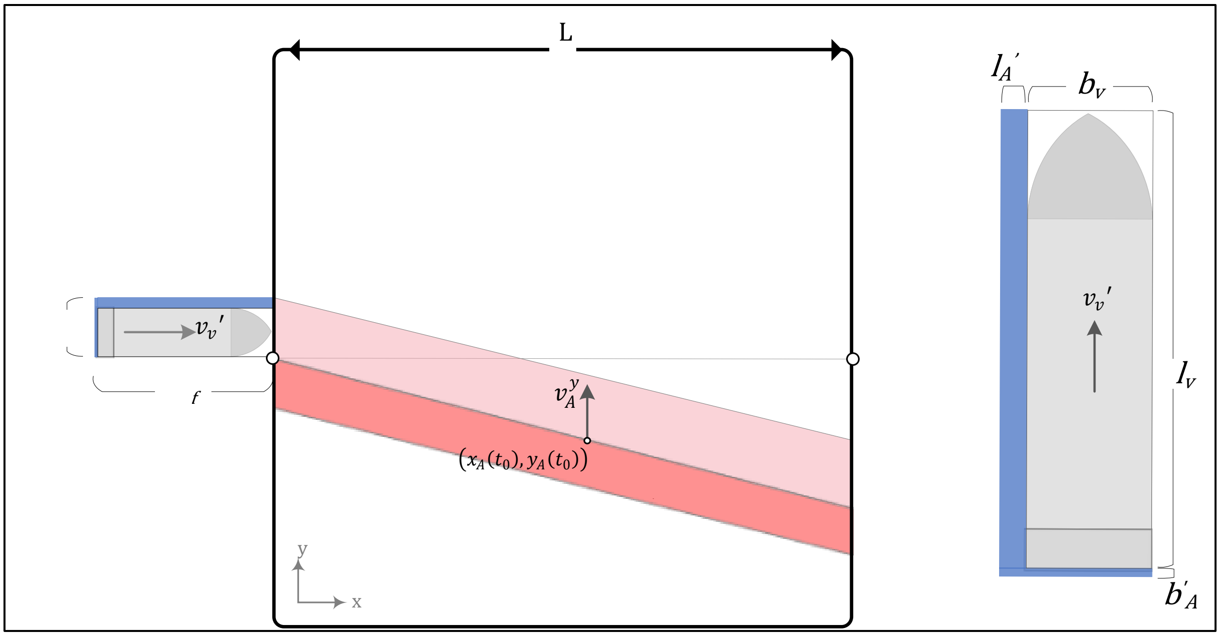


Figure 8. (Left) Diagram illustrating the mathematical framework used to estimate the total encounter area A_i, which is shown in two parts as light red and dark red parallelograms corresponding to the initial encounter off the bow, then from the starboard side of the vessel, respectively

The region enclosed by the light red parallelogram (that abuts the bow of the vessel) corresponds to the available initial positions of animal trajectories that result in an initial encounter with the bow of the vessel. The region enclosed by the dark red parallelogram corresponds to initial positions that result in an initial encounter with the starboard side of the vessel. For example, the left front of an animal originating at the white dot labeled $(\boldsymbol{x_A(t_0)}, \boldsymbol{y_A(t_0)})$ would encounter the starboard bow of the vessel at the time of encounter. At the white dot, the y-component $\boldsymbol{v_A^y}$of the velocity vector $\boldsymbol{v_A}$ of all animals in the domain is shown. The vessel sails in the positive x-direction at its relative velocity $\boldsymbol{v_v}'$ to the animal. The physical dimensions of the animal are consolidated into the corresponding dimensions of the ship, which is shown at its initial position, with the starboard bow at the origin $(\boldsymbol{0}, \boldsymbol{0})$. The effective length $\boldsymbol{l_{eff}}$ and beam $\boldsymbol{b_{eff}}$ are determined based on the total length of the animal exposed to the vessel perpendicular to its heading $\boldsymbol{b_A}'$ (y-direction) and parallel to its heading $\boldsymbol{l_A}'$ (x-direction). (Right) Expanded view of how the vessel dimensions are modified to include the animal dimensions.

Although not depicted in **Figure 8**, **Equation 9** explicitly implies that an intersection of the x-coordinates depends on the relative velocities of the vessel and the animal in the x-direction. The relative velocity of the vessel with respect to the animal along the x-direction is:

$$v_v' = v_v^x - v_A^x \,. \qquad 9$$

Similarly, an intersection of the y-coordinates depends on the relative velocities of the vessel and animal in the y-direction. However, because the vessel trajectory has no y-component, there is no reason to introduce a new variable to describe relative motion along this dimension.

The hypothetical animal in **Figure 8** is shown as a single infinitesimally small point that represents the position of the left front of the animal. The dimensions of the animal are consolidated into the corresponding dimensions of the ship. While this may seem counterintuitive, it is important to recognize that this is a transformation of reference frame (change of variables), which allows for simplification of the mathematics and has no effect on the adequacy of the system's underlying physics. The vessel dimensions, therefore, are represented in terms of effective length l_{eff} and beam b_{eff}, determined by the total length of the animal exposed to the vessel perpendicular to its heading (y-direction) and parallel to its heading (x-direction):

$$\begin{aligned} l_{eff} &= l_v + b_A \cos(\theta_r) + \ l_A \sin(\theta_r) \\ b_{eff} &= b_v + l_A \cos(\theta_r) + \ b_A \sin(\theta_r) \end{aligned} \tag{10}$$

$$\theta_r = 90° - \theta \tag{11}$$

where θ_r is the angle complementary to the relative heading between the vessel and the animal.

The geometric framework shown in **Figure 8** can be used to derive an expression for A_i in terms of the size of the domain L, the effective length l_{eff} and beam b_{eff} of the vessel, the angle between the animal and vessel headings θ, and the velocities of the vessel $\boldsymbol{v_v}$ and animal $\boldsymbol{v_A}$.

Figure 9 illustrates the simple geometric relationships used to derive A_i. This problem reduces to computing the height h and width w of the (combined) red parallelogram using trigonometry.

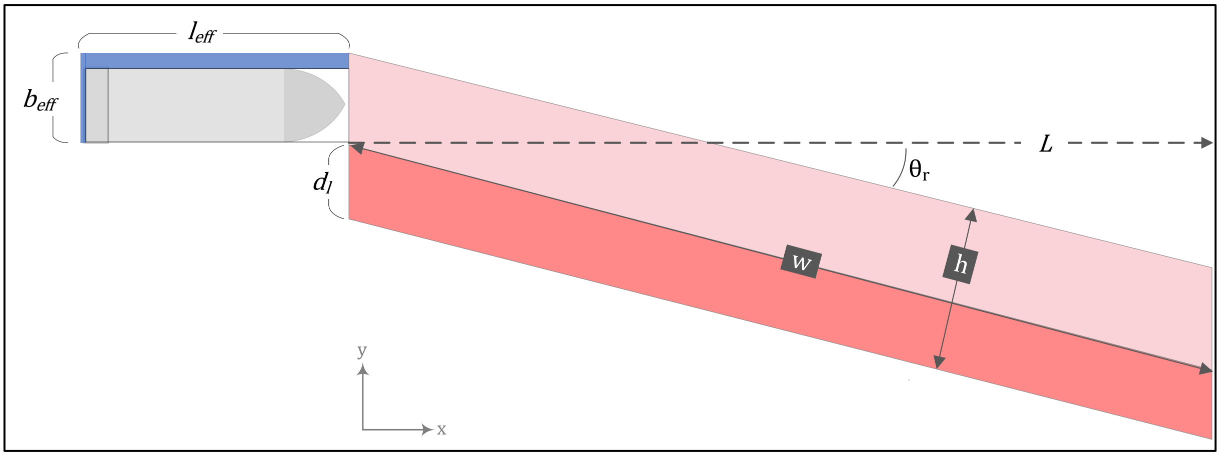


Figure 9. Diagram of the geometric relationships used to calculate the total encounter area A_i, as the combined area of the light red and dark red parallelograms corresponding to the initial encounter off the bow, then from the starboard side of the vessel, respectively

The total area of the parallelograms is equal to the product of the lengths of the line segments labeled $\boldsymbol{h}$ and $\boldsymbol{w}$. $\boldsymbol{d_l}$ is the distance the animal swims in the y-direction in the time it takes the vessel to sail its own length. $\boldsymbol{d_b}$ is the distance the vessel sails in the time it takes the animal to swim the distance of the vessel beam (in the y-direction).

$$A_i = wh \, . \tag{12}$$

$$w = \frac{L}{cos(\theta_r)}, \tag{13}$$

with L being the length of a route segment, and θ_r is computed as in **Equation 11**.

$$h = (d_l + b_{eff}) \cos(\theta_r). \tag{14}$$

Here, d_l is the distance the animal swims in the y-direction in the time t_l it takes the vessel to sail its own length (at its relative velocity $v_v{}'$):

$$t_l = \frac{l_{eff}}{v_v{}'} \quad \rightarrow \quad d_l = v_A^y t_l = \frac{v_A^y}{v_v{}'} l_{eff}\,. \tag{15}$$

Substituting back into **Equation 12** and reducing yields:

$$A_i = L\left(\frac{v_A^y}{v_v'} l_{eff} + b_{eff}\right) = L\left(\frac{v_A \cos(\theta_r)}{v_v - v_A \sin(\theta_r)} l_{eff} + b_{eff}\right), \tag{16}$$

As the difference between the vessel velocity $\boldsymbol{v_s}$ and the x-component of the animal velocity $\boldsymbol{v_A^x}$ decreases, **Equation 16** tends to infinity. In these cases, encounters occur over such large timescales that many of the established assumptions become invalid.

When the relative velocity reaches a critical threshold (determined by calibration; **Section 3.6.1**), the expression for total encounter area A_i becomes:

$$A_i = l_{eff} v_A^y t_{max}. \tag{17}$$

Here, t_{max} is the maximum amount of time the animal trajectory can be assumed to be constant. Truncating the total encounter area expression prevents assumptions regarding encounters that occur on relatively short timescales (generally seconds to several minutes) from overwhelming the estimates of expected animal encounters.

3.5 Model Implementation

The general mathematical framework presented in the previous section is highly versatile in its adaptability to the temporal and spatial resolution of available data. This section documents additional simplifications made to the mathematical framework to efficiently accommodate (often limited) available data into the model, considering the Calculator must be applicable across the U.S. Atlantic coast.

3.5.1 Route Segment Length

The route segment length L was chosen to be a fixed 1 km, which provides a suitable timescale over which the established assumptions regarding vessel-animal encounters are valid and a suitable spatiotemporal resolution at which to vary estimates for the following encounter factors (**Section 2.4**) between route segments:

- Mean animal density μ_i
    - Roberts et al. (2016) habitat density maps

- Animal swim speed, length, width, swim depth probabilities, and aversion probabilities
    - Data regarding seasonal migration routes, seasonal foraging, and reproductive behavior
    - Swim depth probabilities and aversion probabilities that can be adjusted to reflect water depth
    - Specific expert knowledge regarding the physical and behavioral traits of individual animals or groups of animals within a species

- Vessel speed, draft, length, beam, and aversion probabilities
    - Historical AIS data for calibration of the model to observation data
    - Projected vessel routes and fleet characteristics to facilitate operational decision making, including route optimization to minimize vessel-animal encounter probability

3.5.2 Relative Heading of Animal

Animal swim directions are highly complex, and there is a lack of information to determine the relative heading in degrees between the vessel and animal (θ) for any specific vessel route. **Figure 10** shows the relationship between θ and encounter risk depends on the relative velocities of the animal and vessel. The influence of the relative heading on encounter risk diminishes greatly as the relative velocities of the vessel and animal increase. For the most common transit speeds, ratios on the order of 5:1 to 10:1 can be expected. As such, maximum encounter rates will occur with a relative heading (θ) close to 90°.

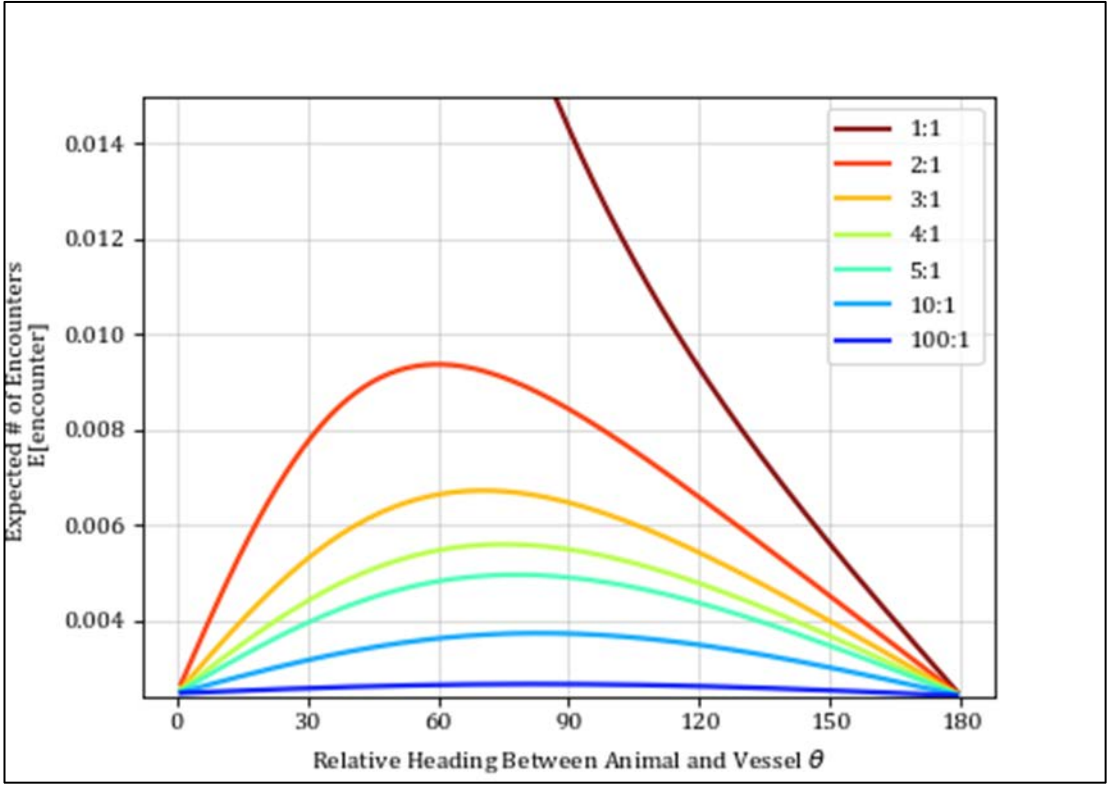


Figure 10. Relationship of the relative heading between animal and vessel heading (θ) in degrees, the ratio of vessel and animal velocities, and expected encounters on a 28-kilometer transit

Each line in the plot corresponds to a ratio of vessel speed to animal speed, indicated in the legend. Vessel speed was specified at 15 kn, and animal speed was adjusted to reflect each ratio. For example, in the 2:1 case (red), the animal is swimming at 7.5 kn. All parameters were selected to remain consistent with the results presented in **Section 5**.

Consequently, in the absence of appropriate data, the relative heading between the vessel and animal has been assumed to be 90°. Substituting L = 1 km and θ = 90° into **Equation 16** yields:

$$\begin{gathered} A_i = 1\left(\frac{v_A}{v_v} l_{eff} + b_{eff}\right), \\ l_{eff} = l_v + b_A \\ b_{eff} = b_v + l_A \end{gathered} \tag{18}$$

Where all distances are expressed in kilometers, velocities in kilometers per hour, and angles in degrees counterclockwise from the x-axis (values are converted to knots in the Calculator).

3.5.3 Animal Dive Profile

Available data regarding animal swim depth probabilities are limited to a seasonal temporal resolution, with the best data assigning probabilities to the animal being within certain binned ranges of swim depth, rather than providing full dive profiles. Therefore, a binning method was used to incorporate the data into an estimate of **Equation 3**. As vessels supporting wind farm development activities will not have drafts >20m, only two depth bin ranges were considered.

$$P_i(depth) = \begin{cases} P_1 \; if & 0m < D_v \le \; 10m \\ P_1 + P_2 \; if & 10m < D_v < 20m \end{cases} \tag{19}$$

Here, D_v is the vessel draft, P_1 is the probability (percentage of overall time) the animal is swimming between 0 and 10 m depth, and P_2 is the probability the animal is swimming between 10 and 20 m depth. Although this assumption is conservative (e.g., a 3-m draft vessel will have the same encounter probability as a 9-m draft vessel, if all other factors are the same), it is a necessary assumption driven by data limitations.

3.5.4 Aversion

Although aversion is by default set to zero in the Calculator (although this may be adjusted in the GUI), it is worth understanding where the influence of aversion, if it could be reliably forecast, falls in the analytical model framework. The probability of the animal or vessel or both averting a collision is *P(avert)*. Given sparse information on aversion, it is easier to estimate aversion probabilities separately for the animal and vessel. **Equation 2** can be expressed as:

$$E_i[strikes] = E_i[encounters]P_i(depth)\big(1 - P_i(avert_v)\big)\big(1 - P_i(avert_A)\big), \tag{20}$$

Where $P_i(avert_v)$ is the probability of the vessel successfully averting collision, and $P_i(avert_A)$ is the probability of the animal successfully averting collision. However, separating aversion probabilities as **Equation 20** means there is no covariance (i.e., joint variability) between the two probabilities. This means that during an encounter, the likelihood of the outcome of an aversion maneuver by the vessel (i.e., success or failure) is assumed to be entirely unrelated to the likelihood of the outcome of an aversion maneuver by the animal, and vice versa. This is because the animal can perceive and thus react in response to the presence of a vessel and the vessel can perceive and react in response to the presence of an animal; however, the evasive maneuvers of each are not correlated with one another. The probability of the animal or vessel averting (and averting in a manner that successfully avoids a strike) are inherently independent, which makes standardizing the probability of aversion highly impractical, as very little is known about how the true nature of these interactions. Therefore, assuming that the probability of successful aversion for the vessel and the animal are mutually independent makes the problem of quantifying aversion significantly more tractable, as empirical data can be used to directly estimate the probability of aversion for the vessel and the probability of aversion for the animal.

3.6 Strike Risk Discussion

This section analyzes the equations derived in the previous section to assess the implied relationships between vessel speed, vessel size, and encounter probability. These relationships are presented and discussed in terms of encounter risk instead of strike risk, which means *P(depth)* and *P(avert)* are assumed to always be zero.

3.6.1 Effect of Vessel Speed

A modest body of literature has addressed the relationship between vessel speed and encounter probability, using theoretical (Crum et al., 2019; Currie et al., 2017; Hazel et al., 2007; Laist et al., 2001; Leaper, 2019; Martin et al., 2016; Neilson et al., 2012; Nowacek et al., 2004; Rockwood et al., 2018; Vanderlaan and Taggart, 2007; Ventikos and Rakas, 2015) and empirical (Hain et al., 2013; McKenna et al., 2015; Nowacek et al., 2004; Parks et al., 2011; Parks et al., 2012) approaches, the results of which are in general agreement with the salient conclusions of this assessment, specifically, without aversion (vessel or animal) vessel speed has little effect on the encounter rate and is a mathematical reflection of vessel and animal density combined with the time the vessel spends within the km^2 assessment block; however, speed becomes a significant factor in the strike risk when aversion is considered. Thus the model user must have an expected aversion rate in relation to vessel speed when building their encounter scenarios. This is described in more detail in **Section 4.1.1**. The relationship between vessel speed, animal speed, and expected encounters is illustrated in **Figure 11**. The left plot shows the expected number of encounters as a function of vessel speed. The right plot shows the expected number of encounters as a function of the ratio of vessel speed to animal speed. Two animals with contrasting swimming speeds were evaluated, one based on a dolphin species (fast swimming, shown as the dashed gray line) and the other on a manatee (slow swimming, shown as a black line). Parameters used in these calculations are documented in **Table 3**. Results show the expected number of encounters consolidate to a single line when plotted against the speed ratio.

The results of Martin et al. (2016) and Vanderlaan and Taggart (2007) are directly comparable to this work. In particular, **Figure 11** can be compared to Figure 2 of Martin et al. (2016), which shows a very similar relationship between encounter rate and vessel speed. Figure 4 of Vanderlaan and Taggart (2007) shows this same relationship; however, it is expressed in terms of encounter probability instead of expected number of encounters. The parameters used to generate the plots in **Figure 11** were selected to match those used in Martin et al. (2016) as closely as possible. This included simulating a 28-km vessel route where all parameters remained constant between segments (i.e., the results for the number of encounters along a 1-km segment were multiplied by 28).

The key relationship illustrated by **Figure 11** is that the expected number of encounters (and opportunities for a strike to occur) decreases exponentially with increasing vessel velocity. However, as noted by most authors who have addressed the subject, although decreased vessel speeds increase the potential number of encounters, slow-moving vessels provide more time for animals and vessel operators to avoid strikes (e.g., Crum et al., 2019; Martin et al., 2016; Vanderlaan and Taggart, 2007), conversely, the strike risk (rather than simply encounter risk) will tend to increase with increasing vessel speed. The two findings are entirely consistent so long as aversion is considered. Aversion for the vessel and animal can be defined by the model user (**Section 3.4.4**).

The ratio of animal and vessel speeds should be considered when characterizing encounter numbers. The right plot in **Figure 11** shows this relationship for two different animal speeds. The curves are identical in form, and as the ratio of vessel to animal speed $(\frac{v_v}{v_A})$ approaches zero, the expected number of encounters increases exponentially. Intuitively, this is because the vessel is spending increasingly more time within the route segment, increasing the number of passing animals it could encounter. Because of this, when $0 < (\frac{v_v}{v_A}) < 1$, the truncated expression for the total encounter area (A_i) should be used (**Equation 17**). The actual cutoff ratio applied must be determined based on sensitivity testing in the totaling process; however, for the purposes of this assessment, 0.5 is a reasonable value based on the approximate inflection point of the curve on the interval $0 < (\frac{v_v}{v_A}) < 1$. The mean swim speed for large whales based on the Navy Undersea Warfare Center dive data (Borcuk et al., 2017; Watwood and Buonantony, 2012) is 2.7 kn, with ranges from 0.26 kn for NARWs to 3.6 kn for sei and minke whales. Sea turtle swim speeds have been estimated at 1 to 1.5 kn while in transit (Arendt et al., 2012).

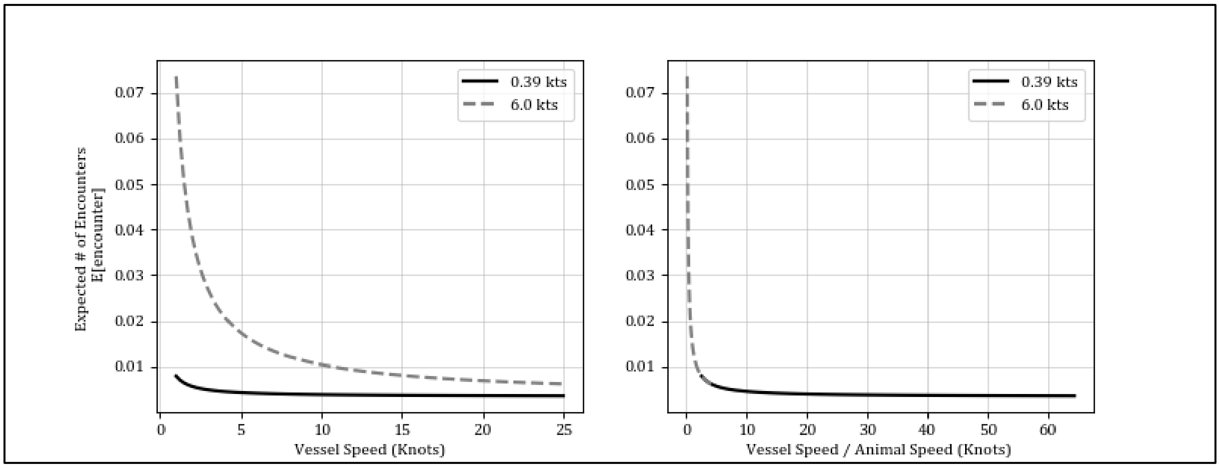


Figure 11. Relationship among vessel speed, animal speed, and expected encounters. (Left) The expected number of encounters as a function of vessel speed. (Right) The expected number of encounters as a function of the ratio between vessel speed and animal speed.

Two animal speeds were evaluated, one based on a dolphin (shown as the dashed gray line) and the other based on a manatee (shown as a black line). (Right) The expected number of encounters as a function of the ratio of vessel speed to animal speed. This plot can be compared to Figure 2 of Martin et al. (2016), which shows similar results. The parameters used to generate these plots (**Table 3**) were chosen to match those used in Martin et al. (2016) as closely as possible.

Table 3. List of constant parameters used to generate the expected number of encounters in Figure 11. Relationship among vessel speed, animal speed, and expected encounters. (Left) The expected number of encounters as a function of vessel speed. (Right) The expected number of encounters as a function of the ratio between vessel speed and animal speed.

Parameter	**μ_i (Animals km^{-2})**	**N (# of 1 km segments sailed)**	**l_v (vessel length [m])**	**b_v (vessel beam [m])**	**l_a (animal length [m])**	**b_a (animal beam [m])**
Value	0.003	28	140	29	12	3

l_v = length of vessel; b_v = beam (width) of vessel; l_a = length of animal; b_a = beam (width) of animal.

From a mathematical standpoint, the modeling approaches developed for this study, Martin et al. (2016) and Conn and Silber, 2013; are slight variations on a well-studied problem in mathematics and physics literature, referred to as the "trapping problem" (Athreya et al., 2019; Gallos and Argyrakis, 2001). In the trapping problem, particles move randomly throughout a bounded space filled with randomly located "traps". The traps can be mobile or immobile. If a particle encounters a trap, the particle disappears forever. The trap remains after destroying a particle and thus can destroy an infinite number of particles. Aversion probability in this context is the probability of a particle not disappearing when it encounters a trap. The quantity of interest in the trapping problem typically is a "survival probability" for a particle in terms of the expected number of steps through space that a randomly sampled particle may expect to endure. There are many practical motivations for studying systems like these, such as modeling the probability of finding a taxi cab in a large city (Gallos and Argyrakis, 2001), determining optimal strategies for following fugitives through wilderness areas (Yin et al., 2019), or evaluating wildlife management strategies along remote roadways (Vanderlaan and Taggart, 2007).

For this study, the particles in the trapping problem are analogous to marine animals and the traps correspond to vessels. There are two general cases for this problem that have major implications on the relationship between vessel speed and encounter probability:

1. ***Fixed Distance Case –*** The vessel travels directly to its destination and stops sailing once the destination is reached. The amount of time required to reach the destination is velocity dependent. This case is particularly applicable to commercial vessels sailing to and from a single destination (e.g., between a port and an offshore wind farm) along well-defined routes.

2. ***Fixed Time Case –*** The vessel sails to no particular destination in a fixed amount of time. This case is most applicable to recreational watercraft (or in the present case, service vessels moving around the wind farms), which may sail an arbitrary route for a fixed amount of time.

For the fixed distance case, the optimal strategy to minimize animal encounters is to sail the route as fast as possible. This is analogous to crossing a busy highway on foot. Because this mathematical framework does not permit explicit aversion behavior (e.g., stopping to look both ways and subsequently modifying behavior), the safest strategy is to proceed as fast as possible across the highway. However, the optimal strategy would be different if aversion behavior was considered.

For the fixed time case, the optimal strategy is to sail as slow as possible to minimize the total number of animals that could be encountered. In other words, in a given amount of time, a fast-sailing vessel with no destination will have more possibilities to encounter an animal (i.e., sail more route segments) than a slow-sailing vessel.

Both cases (fixed destination and fixed time) were explored by Martin et al. (2016) and Vanderlaan and Taggart (2007). The primary differences between the approach taken in this assessment and that of similar work (e.g., Crum et al., 2019; Martin et al., 2016; Vanderlaan and Taggart, 2007) is that the vessel and animal were modeled (more realistically) as rectangular prisms instead of circles/spheres, and the animals moved through space under different assumptions. However, the assumptions regarding vessel motion were very similar (vessel travels in a straight line through route segments of a certain length and area). Vanderlaan and Taggart (2007) and Martin et al. (2016) used a circular encounter region (as opposed to the rectangular domain used here), and assumed the animals moved under Brownian random motion with step length and direction governed by probability distributions (whereas this analysis used animal movement and dive behavior from published literature). These differences are responsible for differences in the results derived in this work versus that of Vanderlaan and Taggart (2007) and Martin et al. (2016). Conn and Silber (2013) showed that, mathematically, increased vessel speed did not correlate to increased encounter rates; however, using a use-availability model they showed a clear, positive correlation to vessel speed and encounter risk. as described above, the analytical solution will increase strike risk with *lower* vessel speeds simply because transit times are longer and thus the potential exposure of whales to vessels is greater. Conn and Silber (2013) noted that although simulated whale and vessel movement can provide 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 simulations to reliably predict the probability of a collision because of uncertainty about fine scale nature of whale avoidance behavior. In the case of sea turtles, vessel speed may be inconsequential to strike risk at anything but the slowest speeds given the lowered maneuverability and aversion uncertainty in that group of species. Thus, with the current model, the user must define an aversion coefficient if vessel speed is to be assessed in any meaningful way. More appropriately, our model provides the user with an important comparative assessment tool of *where* and *when* speed restrictions might be best implemented rather than predicting the efficacy of such restrictions.

The effects of vessel dimensions on encounter risk were analyzed by varying the vessel length and beam while fixing all other parameters. Vessel beam was defined as a function of vessel length. Three scenarios were considered, where the vessel length to beam ratio was 4:1, 5:1, and 6:1, which covers a typical range of vessel dimensions. Vessels were assumed to travel at 15 kn, and animals (dolphins) were assumed to travel at 6 kn. To remain consistent with the results from **Figure 11**, animal density was assumed to be 0.003 animals per square kilometer, and the vessel sailed 28 route segments (28 km total), with no change in parameters between route segments. Results are shown in **Figure 12**. When considered in context with **Equation 16**, the results are rather intuitive. Increasing the length and beam of the vessel increases the total area over which an encounter can occur. For a given vessel length, a vessel with a smaller length-to-beam (l_v/b_v) ratio has a greater area, and thus more opportunities for an encounter than a vessel with a larger length-to-beam ratio, if all other factors are held constant.

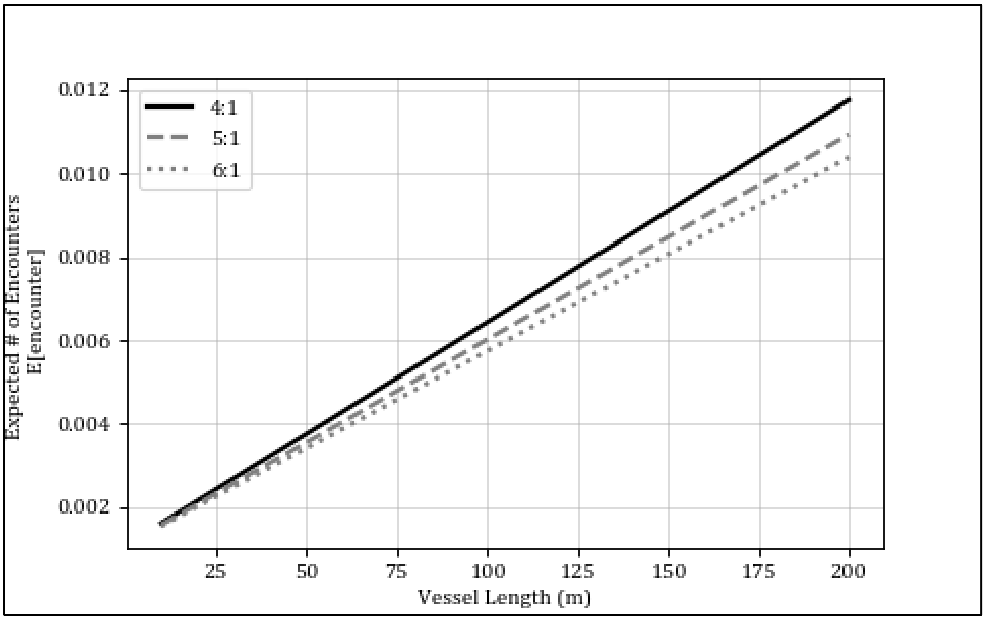


Figure 12. Relationship between vessel dimensions and the number of expected encounters
Vessel beam was defined as a function of vessel length. Three scenarios were considered, where the vessel length-to-beam ratio was 4:1, 5:1, and 6:1. These scenarios are shown as the black solid line, the gray dashed line, and the gray dotted line, respectively. Vessels were assumed to travel at 15 kn, and animals (dolphins) were assumed to travel at 6 kn. To remain consistent with the results from **Figure 11**, animal density was assumed to be 0.003 animal per square kilometer, and the vessel sailed 28 route segments (28 km total), with no change in parameters between route segments.

3.6.2 Effect of Vessel Dimensions

The effects of vessel dimensions on encounter risk were analyzed by varying the vessel length and beam while holding all other parameters fixed. Vessel beam was defined as a function of vessel length. Three scenarios were considered, where the vessel length to beam ratio was 4:1, 5:1, and 6:1, which covers a typical range of relative vessel dimensions. Vessels were assumed to travel at 15 knots, and animals (dolphins) were assumed to travel at 6 knots. To remain consistent with the results from **Figure 11**, the animal density was assumed to be 0.003 $Animals/km^2$, and the vessel sailed $N = 28$ route segments (28 km), with no change in parameters between route segments. Results are shown in **Figure 12**. When considered in context with **Equation 16**, these results are rather intuitive. Increasing the length and beam of the vessel increase the total area over which an encounter can occur. For a given vessel length, a vessel with a smaller length-to-beam (l_v/b_v) ratio has a greater has greater area, and thus more opportunities for encounter than a vessel with a larger length-to-beam ratio all other factors held constant.

3.6.3 Sensitivity Analysis

The results presented in **Section 3.6.1** and **Section 3.6.2** were tailored (by judicious choice of input parameters) specifically for comparison to the results of relevant peer-reviewed literature. This section provides a similar analysis, with focus on analysis of encounter risk between large whales and vessel traffic from offshore wind energy on the Atlantic Outer Continental Shelf. The analysis presented here considers a range of parameter combinations that reflect the vessel and animal characteristics that are expected to arise most commonly in practice at this particular site. A sensitivity analysis is used to evaluate how uncertainty (or variation) in model input parameters affects the model output. From a mathematical standpoint, a model sensitivity is fundamentally a derivative, a fractional representation of how much a function (e.g., model) changes in proportion to a small change in one or more of its independent variables (i.e., input parameters). For linear models, the derivative (i.e., sensitivity) with respect to the given linear variable(s) is always the same, regardless of the value of any other independent variables. For non-linear models (like the model developed in this work), the derivatives are always dependent on the values of other variables in the equation(s). As such, when performing a sensitivity analysis on non-linear components of a model, it is important to develop a priori a set of model scenarios (i.e., parameter combinations) that best reflect the conditions of the real-world system that is being analyzed.

3.6.4 Validation Using Agent-based Model

The scope of this work initially included development of an agent-based numerical model to evaluate encounter probability. While it was subsequently decided that insufficient data are available to calibrate an agent-based model for such large-scale application, the generalized model framework was already developed and used as partial verification of the analytical solution. While validation of a model using another model is undesirable, actual validation data are not available at the same scale as the Calculator (i.e., 1-km sailed distance), such that validation of the analytical model relies on validation of the totaling process against the strike data that are available for the larger OCS region. Validating the analytical model against an independent model provides an opportunity to mitigate risk in the underlying implementation of the analytical solution. An overview of the agent-based numerical model is documented in **Appendix B**.

The agent-based numerical model was developed within the same mathematical framework provided by **Equation 1**. The key difference is that all the terms in the equation were estimated simultaneously. The numerical model takes a pseudo agent-based modeling approach, which means the vessel route still was divided into 1-km segments, but an agent-based model was used inside each segment to estimate encounter probability, as opposed to the analytical solution, which estimated the number of expected encounters in each segment. Within a given route segment, the vessel and animal were treated as agents with their own unique set of equations that defined their behavior. Many of the same assumptions that govern the derivation of the analytical solutions also apply to the numerical model. However, the numerical model provides a framework for deviating from these assumptions when there are data and sufficient understanding of the nature of the phenomena being represented. This primarily concerns the simulation of animal aversion behavior, which might include representing (to the extent possible) the complexities posed by a calf-cow interaction or other seasonal behaviors. Similarly, details regarding human behavior and more detailed vessel physics can be incorporated into vessel aversion behavior, which depends on complex interactions between vessel observers, the vessel captain, and the vessel's maneuverability.

The analytical model was verified using simplified cases of the numerical model. The expected number of animal encounters along a 1-km route segment was computed using both models. Four cases were evaluated, differentiated by the relative speeds or sizes of the vessel and animal. For all cases, animal density was assumed to be 0.003 animals per square kilometer, and the relative heading of the animal and vessel was assumed to be 90°, which is the most conservative choice as it returns the highest likelihood of encounter.

For each case, the numerical model was run 10,000 times over a 1-km route segment, and the total number of expected encounters were computed as the fraction of those simulations that led to an encounter. The analytical solution was evaluated once for each case. Results are shown in **Figure 13**, and the parameters used in the model runs are summarized in **Table 4**.

Results generally were in good agreement between the two models. In all cases, the numerical model estimates were approximately 3 to 5% lower than those of the analytical model, making the analytical model a more conservative approach to forecasting expected encounters. This was due to differences in assumptions related to the shape of the vessel and animal.

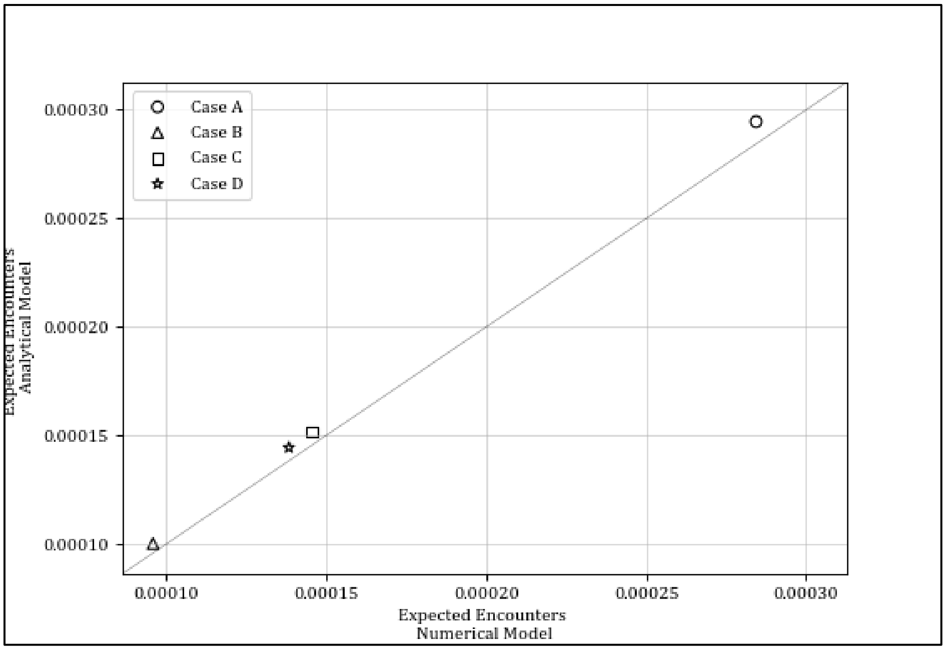


Figure 13. Comparison between the analytical and numerical models
Expected number of encounters along a 1-km route segment. Four cases were evaluated, differentiated by the relative speeds or sizes of the vessel and animal. For all cases, animal density was assumed to be 0.003 animals per square kilometer, and the relative heading of the animal and vessel was **90°**. Parameters corresponding to the four cases are summarized in **Table 4**. A 1:1 trendline is plotted for comparison.

Table 4. Summary of parameters used to compare the analytical and numerical (agent-based) models. These parameters were used to generate the results shown in Figure 11.

Parameter	v_v (kn)	v_A (kn)	l_v (m)	b_v (m)	l_a (m)	b_a (m)
Case A	15	6	140	29	12	3
Case B	15	6	60	5	4	1
Case C	15	1	140	29	12	3
Case D	20	1	140	29	12	3

v_v = velocity of vessel; v_a = velocity of animal; l_v = length of vessel; b_v = beam (width) of vessel; l_a = length of animal; b_a = beam (width) of animal.

4 Graphical User Interface

A GUI for displaying vessel routes and expected numbers of encounters in a heat map format based on various user inputs was developed in conjunction with the underlying analytical model to enable user input and scenario-building and to render the user-defined scenarios. The GUI displays the number of vessel encounters with large whales and sea turtles and employs a basic totaling process that integrates the encounter counts along the vessel route, considering various parameters such as vessel speed and animal density. To facilitate use by BOEM personnel and agency software licensing, BOEM elected to have the GUI developed in Python 2.7, using ArcGIS version 10.5 or higher as the software backbone for creating data visualizations. Details of the inputs and outputs are described in **Appendix C**.

The GUI was developed as an ArcMap add-in due to ease of use within the ArcGIS platform. However, updates may be required based on the frequency and nature of license updates in response to new releases of ArcMap versions over time.

The overall methodology for GUI development was to separate vessel encounter computations into two components (**Figure 14**):

- Vessel encounters during a transit (round trip) to and from a wind farm area; and
- Vessel encounters within a wind farm area.

Transit speed between the port and the wind farm area is assumed constant with the model defaulting to a normal operating speed for the selected vessel that can be adjusted by the user. The constant speed assumption removes the complexity (and inaccuracy) of adjusting the aversion coefficients as a function of speed along a single track line (**Section 3.6.1**). Within a wind farm area, vessel behavior is more complex and can often not be predicted simply based on its task. Consequently, the vessel behavior (by vessel category) within the wind farm is represented by the percent time the vessel was at operating speed; there is no spatial representation of a vessel's behavior in a wind farm area given the boundless combinations of movement patterns. Consequently, only one value for encounter risk is returned for a wind farm area. The speed at which any vessel is considered to be zero was determined by satisfying the ratio of vessel speed (v_v) in a wind farm (separately for wind farm vessel activity under both construction status and operations and maintenance status) to animal swim speed (v_a) at unity. This means that the speed at which a vessel is considered to be functionally stationary is equal to the swim speed of the animal species used in the scenario. The cutoff speeds in knots at which a vessel operating in wind farm is considered stationary are: right whale (0.5), humpback whale (1.2), fin whale (1.6), minke whale (1.8), sei whale (1.8), blue whale (1.5), sperm whale (0.9) and turtles (all; 0.6) (**Section 2.2.3**).

Upon opening the GUI, the user will select the desired tool, a monthly transit route calculation or a daily wind farm area (in transit to and from the wind farm or within the wind farm) of the vessel being considered (**Figure 14**).

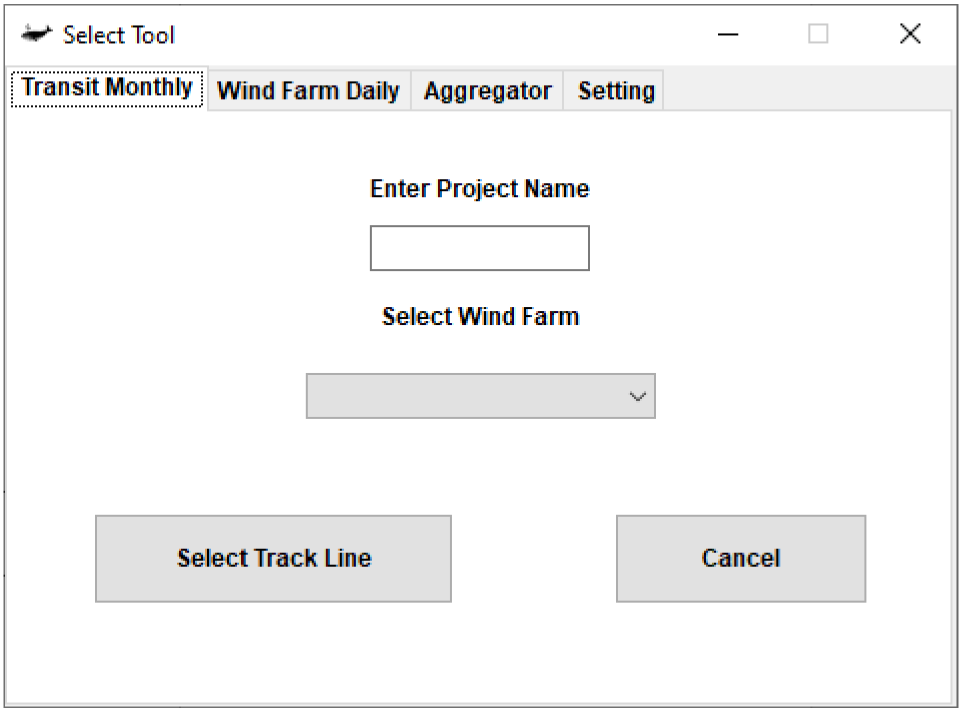


Figure 14. **Screen capture of graphical user interface, prompting the user to select a Monthly Transit to a wind farm area or a Daily Wind Farm calculation**

4.1 Vessel Transit Encounters

4.1.1 GUI Inputs

Once the wind farm destination is selected, the vessel transit total integrates probabilities calculated by the model for each 1-km route segment into a combined total number of encounters along the entire vessel round-trip transit route. To facilitate this task, the GUI provides options to select pre-defined vessel routes from major ports along well-defined shipping routes on the U.S. Atlantic coast (**Figure 15**).

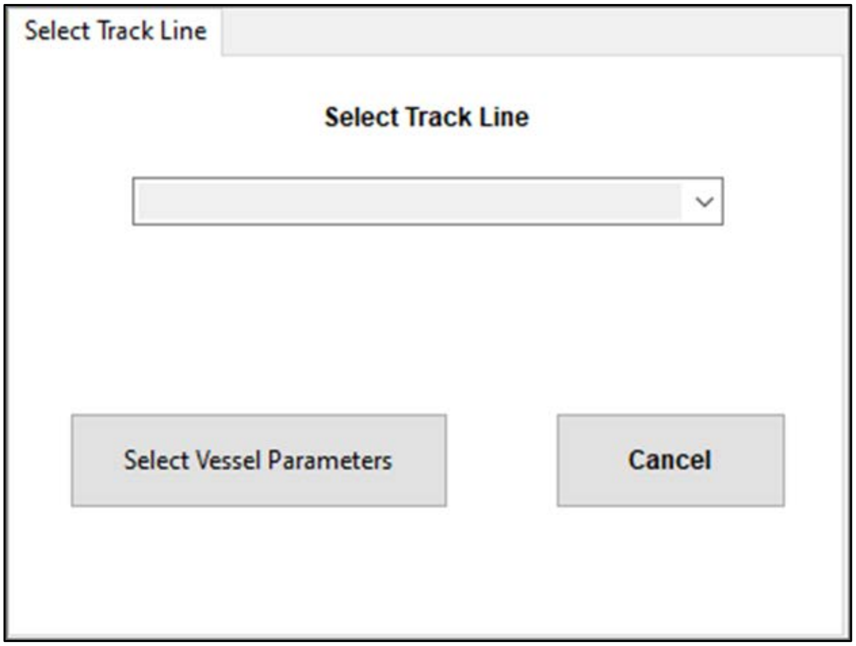


Figure 15. Screen capture of graphical user interface used to select vessel route options in the risk model

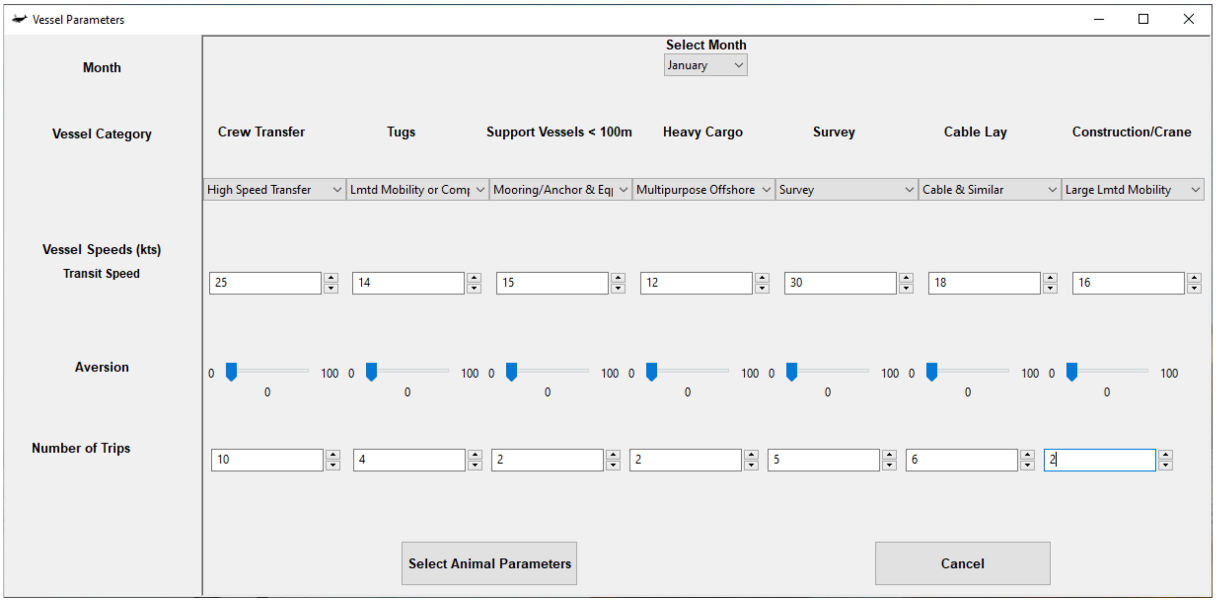
After choosing a pre-defined route, the user can select various parameters, as defined below (**Figure 16**):

- ***Project Name*** – The name of the project helps tie the runs together with similar parameters for a final aggregation of runs based on months, species, routes, etc.
- ***Time Period*** – A month is the default unit of time for the vessel transit due to the availability of animal species density data.
- ***Vessel Categories*** – An option to select all vessel categories (**Section 2.3.2**) for a single run on a selected route gives the user flexibility and reduces the number of runs to be conducted. The user can increase the number of replicate trips for the scenario and apply an aversion option for the vessel and animal.
- ***Vessel Speed*** – Vessel speed for all vessel categories defaults to the inputs in **Table 1** (**Section 2.3.2**) and can be manipulated by creating different scenarios.
- ***Aversion*** – The user can make assumptions as to the ability and efficacy of the vessel to successfully avert a strike. The user will consider placement of observers on the vessel and the size and maneuverability of the vessel. Note that vessel aversion relates only to the vessel taking action to avoid a detected animal and does not relate to any behavioral aversion on the part of the animal that is encountered. Animal aversion is addressed in the next set of GUI inputs.
- ***Number of Trips*** – The user will identify how many round-trip transits are expected from each vessel type within a single month. This essentially becomes a multiplier for the vessel scenario.

The GUI then computes the total encounter counts for a transit (round trip) as the number of animals encountered and is re-written here from **Equation 2**, replacing ‘strikes’ with ‘encounters’ for clarity and replacing depth with the number of trips taken:

$$E[encounter] = \sum_{i=1}^{n} E_i[encounter]\,(N_i)(1 - P_i(avert_v)) \qquad 21$$

Where, $E[encounter]$ is the total expected number of encounters from all vessels on the user-selected route during the month, $E_i[encounter]$ is the expected number of encounters for the vessel I on the user-selected route, n is the number of vessel categories, $P_i(avert_v)$ is the probability of the vessel sucessfully averting collision, and N_i is the number of trips taken by vessel i.



Month

Select Month

January

Vessel Category	Crew Transfer	Tugs	Support Vessels < 100m	Heavy Cargo	Survey	Cable Lay	Construction/Crane
	High Speed Transfer	Lmtd Mobility or Com	Mooring/Anchor & Eq	Multipurpose Offshore	Survey	Cable & Similar	Large Lmtd Mobility
Vessel Speeds (kts) Transit Speed	25	14	15	12	30	18	16
Aversion	0	0	0	0	0	0	0
Number of Trips	10	4	2	2	5	6	2

Figure 16. Screen capture of the graphical user interface vessel parameters and their number of trips in the vessel transit total

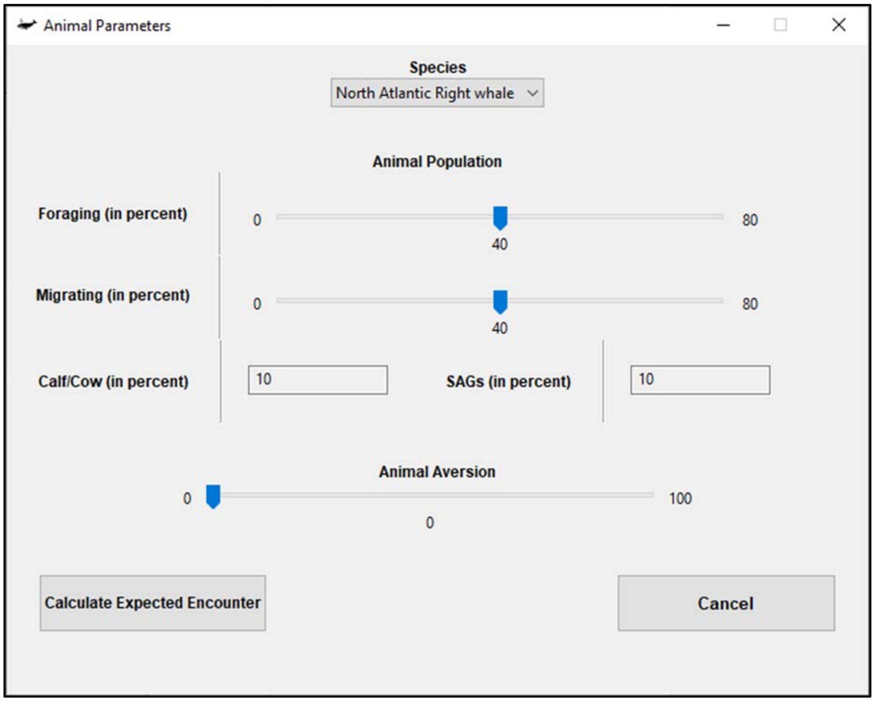
This shows the vessel transit total process setup for creating a transit scenario with vessel selection parameters, the month of operation, the vessel category, the vessel's area of operation, number of trips (multiplier), and vessel aversion coefficient selection.

- ***Species*** – The user then transitions to marine species selection (**Figure 17**). Each scenario (run) is for a single species and dictates the animal activities (foraging, migrating, calf-care, SAG), speed, and density, which are critical parameters for encounter probability. The user can select the species of interest in the GUI, and default activity parameters are selected but can be adjusted according to the scenario. To account for variable animal activities within the population based on season and region, ***P(depth)***, as defined in **Section 3.5.3**, is calculated by:

$$P_i(depth) = \begin{cases} P_1 = (f_1 + m_1 + c_1) & 0m < D_v \leq 10m \\ P_2 = (f_2 + m_2 + c_2) & 10m < D_v < 20m \end{cases} \tag{22}$$

Where, P_1 is the probability the animal is swimming between 0 and 10 m depth; P_2 is the probability the animal is swimming between 10 and 20 m depth; f_1 and f_2 are the percentages of the population engaged in foraging activity between 0 and 10 m depth and 10 and 20 m depth, respectively; m_1 and m_2 are the percentages of the population engaged in migration activity between 0 and 10 m depth and 10 and 20 m depth, respectively; and c_1 and c_2 are the, percentages of the population engaged in calf-care activity between 0 and 10 m depth and 10 and 20 m depth, respectively.

The user may also apply animal aversion as part of their scenario (**Figure 17**). As described in **Section 3.6.1**, it is imperative that the user adjust aversion if vessel speed changes are to be assessed. As noted, the model is primarily designed to assess where and when speed restrictions should be applied, or to assess comparative risk in transit routes or transit densities over the course of wind area development. However, with the understanding that vessel speed is a component of information that a user may want to explore, the model provides that option by allowing the user to increase the percent aversion as vessel speeds are decreased. Notably, if vessel speeds are increased *without* a corresponding decrease in aversion, vessel strike risk will necessarily *increase* at slower speeds. The challenge in this is that strike probability is really only available for vessel speed in regard to mortality, not encounter risk; however, these analyses provide a good basis for successful aversion assessment. We recommend that the user reference available species-specific aversion literature to make aversion decisions and consider species activity, daily variations in activity, and species-specific behavior when considering adding aversion (Calambokidis et al., 2019). For example, in the case of North Atlantic right whales, we recommend applying the logistic regression analysis in Conn and Silber (2013), modified from Vanderlaan and Taggart (2007), as the basis for choosing the percent aversion (e.g., 5 kt vessel speed would correspond to ~70% aversion; 10 kts to ~50% aversion; 20 kts ~10% aversion). This is a simplistic method of dealing with vessel speed and aversion and should not be used a predictive indicator of the actual number of strikes, but rather, used to compare scenarios in the model with a measure of vessel speed assessment.



Species: North Atlantic Right whale

Foraging (in percent): 40

Migrating (in percent): 40

Calf/Cow (in percent): 10

SAGs (in percent): 10

Animal Aversion: 0

Figure 17. Screen capture of graphical user interface animal parameters available in the graphical user interface of the strike risk model
This shows the Calculator setup for creating the animal species, the percent time foraging or migrating, and the percent of animals existing as calf/cow pairs along an animal aversion coefficient selection.

4.1.2 GUI Outputs

Based on inputs selected by the user through the GUI, the Calculator provides a text file of the expected encounter values for each 1-km segment along the route for that species in that month. The report also provides a cumulative value for the number of encounters along the whole route for the number of trips selected by the user for that species in that month. Finally, the Calculator produces an encounter count-based heat map corresponding to the report, showing each midpoint of every kilometer along the route as color-ramped encounter count (**Figure 18**). It is important to note that to obtain just the expected number of encounters in the round-trip transit, the aversion factors for both vessels and animal must be set to zero. Consequently, setting aversion to 0 can be taken to simply mean the expected maximum number of encounters but also, the most conservative estimate (maximum) of strikes wherein with 0 aversion, every encounter becomes a strike.

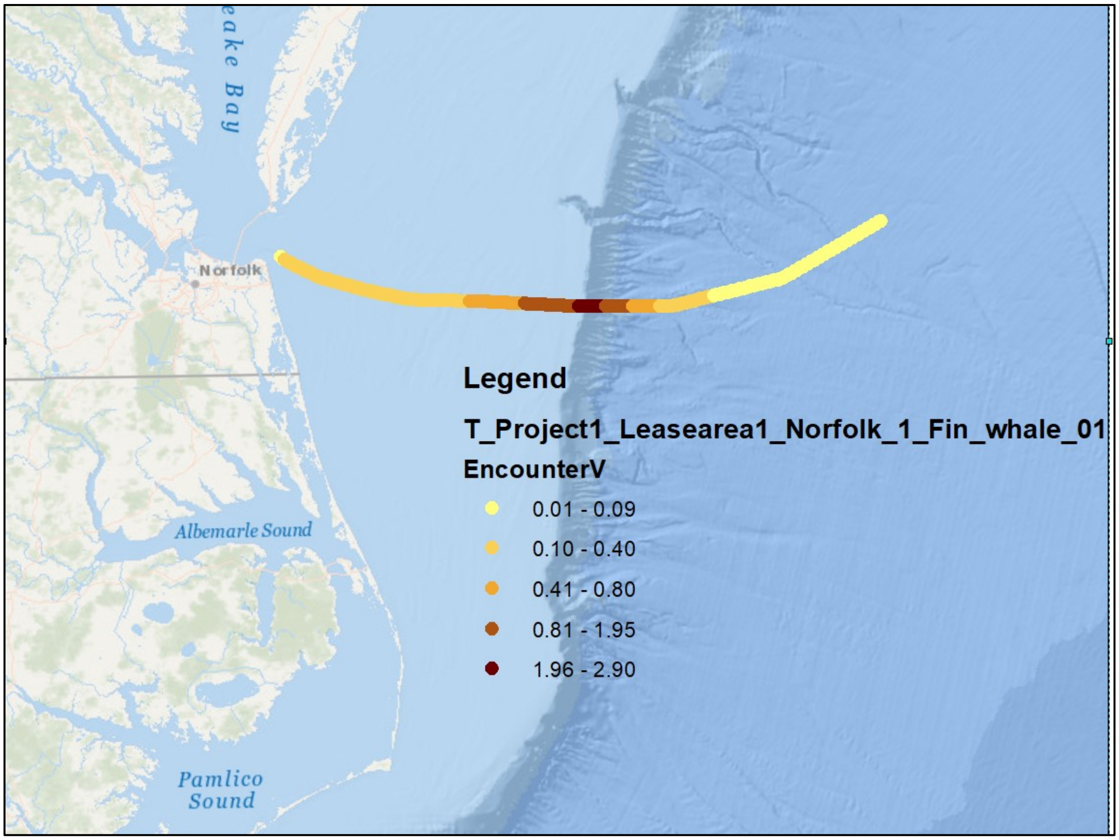


Figure 18. **Screen capture of a graphical user interface used vessel route**
This graphic shows an example of the number of expected animal encounters as a heat map along a hypothetical vessel route off the coast of Virginia.

4.2 Within Wind Farm Vessel Encounter Probability

4.2.1 GUI Inputs

The wind farm portion of the GUI integrates probabilities calculated by the model for each 1-km block within a wind farm area into a combined probability for the entire wind farm over a 24-hour period. Vessels are assumed to travel at an average speed in the wind farm or be stationary within the wind farm during that 24-hour period. Combined encounter probabilities of vessels traveling at average speeds and while stationary are the Calculator’s output for wind farm encounter probability.

This analysis does not rely on pre-selected or user-defined routes within the wind farms; instead, vessels are assumed to be capable of moving everywhere in the wind farm at an average speed. The 24-hour time period is split into vessels at speed and vessels stationary (**Table 5**), based on examination of European vessel AIS data within wind farms (**Sections 2.2.2** and **2.2.3**).

Table 5. Vessel speeds by vessel type and percent time stationary based on animal swim speeds, while operating in the wind farm area during construction and survey stages of wind farm development

Vessel Speeds and Percent Time Stationary During Construction By Vessel Type				Vessel Speeds and Percent Time Stationary During Surveys By Vessel Type			
Species	**Vessel Type**	**Average Vessel Speed**	**Percent time vessel is effectively stationary** [1]	**Species**	**Vessel Type**	**Average Vessel Speed**	**Percent time vessel is effectively stationary**
Fin whale	1	14.7	44.7	Fin whale	1	16.1	59.1
Fin whale	2	5.3	38.9	Fin whale	2	6.1	28.3
Fin whale	3	4.5	23.8	Fin whale	3	5.7	77.8
Fin whale	4	6.7	67.4	Fin whale	4	7.0	40.4
Fin whale	5	6.3	3.0	Fin whale	5	6.8	21.0
Fin whale	6	8.0	63.5	Fin whale	6	7.7	47.6
Fin whale	7	6.0	78.0	Fin whale	7	8.2	47.0
NARW[2]	1	11.1	25.0	NARW	1	11.7	42.4
NARW	2	4.0	10.2	NARW	2	5.2	12.0
NARW	3	3.9	10.2	NARW	3	5.3	76.6
NARW	4	4.6	48.0	NARW	4	5.7	25.2
NARW	5	6.2	0.2	NARW	5	6.2	14.0
NARW	6	5.7	42.7	NARW	6	7.0	45.2
NARW	7	5.3	73.5	NARW	7	7.6	40.5
Humpback whale	1	13.7	40.4	Humpback whale	1	15.1	56.4
Humpback whale	2	4.9	30.8	Humpback whale	2	5.8	23.5
Humpback whale	3	4.3	19.3	Humpback whale	3	5.5	77.4
Humpback whale	4	6.2	63.8	Humpback whale	4	6.7	36.8
Humpback whale	5	6.2	1.2	Humpback whale	5	6.6	19.2
Humpback whale	6	7.7	62.3	Humpback whale	6	7.6	46.1
Humpback whale	7	5.9	77.3	Humpback whale	7	8.0	45.6
Minke whale	1	15.1	46.5	Minke whale	1	16.3	59.8
Minke whale	2	5.5	41.4	Minke whale	2	6.2	30.7
Minke whale	3	4.6	27.2	Minke whale	3	5.7	79.0
Minke whale	4	7.0	69.3	Minke whale	4	7.1	41.3
Minke whale	5	6.3	3.3	Minke whale	5	6.8	21.0
Minke whale	6	8.2	64.0	Minke whale	6	7.7	47.6
Minke whale	7	6.0	78.1	Minke whale	7	8.2	47.4
Sei whale	1	15.1	46.5	Sei whale	1	16.3	59.8
Sei whale	2	5.5	41.4	Sei whale	2	6.2	30.7
Sei whale	3	4.6	27.2	Sei whale	3	5.7	79.0
Sei whale	4	7.0	69.3	Sei whale	4	7.1	41.3
Sei whale	5	6.3	3.3	Sei whale	5	6.8	21.0
Sei whale	6	8.2	64.0	Sei whale	6	7.7	47.6

Table 5. Vessel speeds by vessel type and percent time stationary based on animal swim speeds, while operating in the wind farm area during construction and survey stages of wind farm development (Continued)

Vessel Speeds and Percent Time Stationary During Construction By Vessel Type				Vessel Speeds and Percent Time Stationary During Surveys By Vessel Type			
Species	**Vessel Type**	**Average Vessel Speed**	**Percent time vessel is effectively stationary [1]**	**Species**	**Vessel Type**	**Average Vessel Speed**	**Percent time vessel is effectively stationary**
Sei whale	7	6.0	78.1	Sei whale	7	8.2	47.4
Sperm whale	1	12.7	35.0	Sperm whale	1	14.0	52.5
Sperm whale	2	4.5	21.7	Sperm whale	2	5.5	19.0
Sperm whale	3	4.1	13.4	Sperm whale	3	5.4	77.3
Sperm whale	4	5.5	58.3	Sperm whale	4	6.3	32.5
Sperm whale	5	6.2	1.0	Sperm whale	5	6.5	18.0
Sperm whale	6	6.8	57.7	Sperm whale	6	7.5	46.0
Sperm whale	7	5.8	76.5	Sperm whale	7	7.9	43.8
Blue whale	1	14.4	43.6	Blue whale	1	15.9	58.6
Blue whale	2	5.3	37.9	Blue whale	2	6.0	27.0
Blue whale	3	4.4	22.2	Blue whale	3	5.7	77.8
Blue whale	4	6.6	66.5	Blue whale	4	6.9	39.4
Blue whale	5	6.3	2.5	Blue whale	5	6.6	19.5
Blue whale	6	8.0	63.5	Blue whale	6	7.7	46.2
Blue whale	7	5.9	77.8	Blue whale	7	8.1	46.8
Turtle	1	11.5	27.7	Turtle	1	12.4	46.0
Turtle	2	4.1	13.0	Turtle	2	5.3	14.3
Turtle	3	4.0	11.2	Turtle	3	5.3	76.7
Turtle	4	5.1	54.2	Turtle	4	5.9	27.7
Turtle	5	6.2	0.7	Turtle	5	6.3	15.2
Turtle	6	6.1	48.6	Turtle	6	7.4	45.9
Turtle	7	5.3	74.3	Turtle	7	7.7	41.2

[1] The percent time that a vessel is effectively stationary while in the wind farm is equal to all speeds less than the mean swim speed of the animal.

[2] North Atlantic right whale.

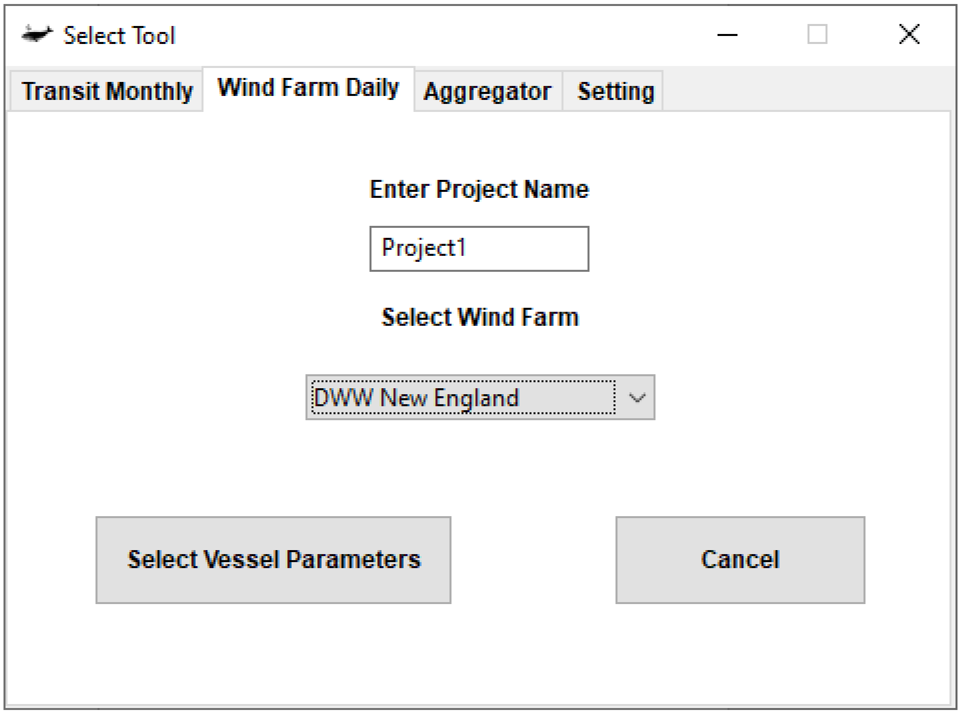
The combined encounter probability for a wind farm area for a 24-hour period is calculated as:

$$E[encounter] = \sum_{i=1}^{n} E_i[encounter]\,(V_{si\ avg})(24)(1 - T_{si})\big(1 - P_i(avert_v)\big) + E_{io}[encounter](T_{si})\big(1 - P_i(avert_v)\big) \tag{23}$$

Where, $E[encounter]$ is the total expected encounters from all vessels moving within the wind farm for a 24-hour period, $E_i[encounter]$ is the expected value of the encounter for the i^{th} vessel moving at average speed in the wind farm, $E_{io}[encounter]$ is the expected value of the encounter for the i^{th} vessel in the wind farm, $V_{si\ avg}$ is the average speed of the i^{th} vessel in wind farm, n is the number of vessel categories,

$P_i(avert_v)$ is the probability of the vessel sucessfully averting collision, and T_{si} is the percent of time vessel i was stationary during the 24-hour period.

Entry into the wind farm portion of the GUI is similar to the vessel transit portion, where the project name is entered, the wind farm is selected, and the transition into the GUI where vessel parameters are selected is prompted (**Figure 19**).



Enter Project Name: Project1

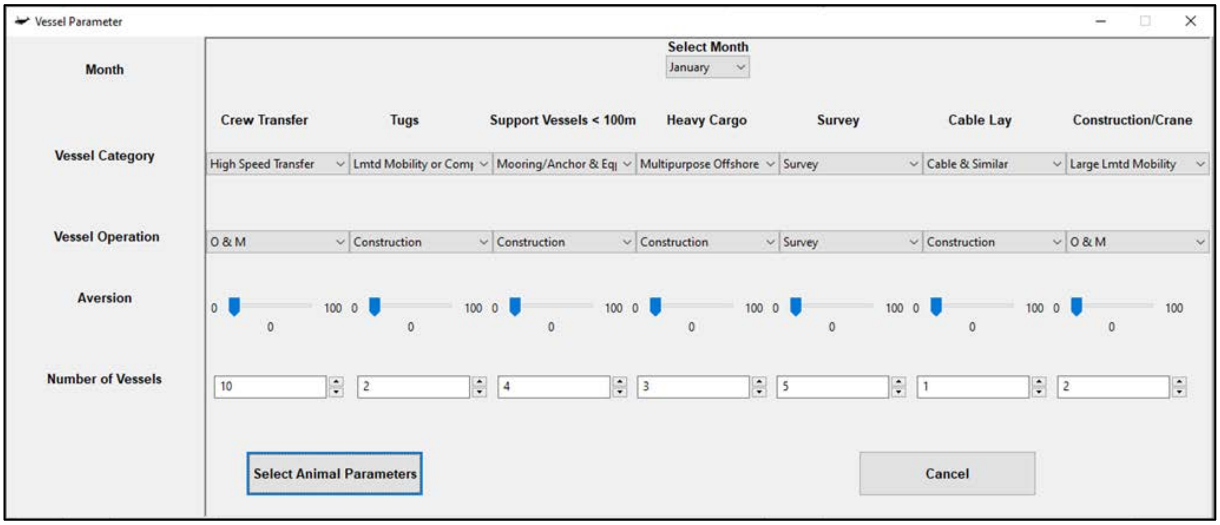
Select Wind Farm: DWW New England

Figure 19. Screen capture of graphical user interface entry into the wind farm portion of the graphical user interface

The wind farm total process has various parameters, as defined below (**Figure 20**):

- ***Wind Farm*** – The user selects a wind farm to calculate a combined probability from various vessels active in that wind farm for a 24-hour period. Vessels could be stationary or moving at average speeds, as defined in **Section 2.3.2**, based on operation of the vessel;
- ***Vessel Categories*** – Option to select all vessel categories (**Section 2.3.2**) for a single run, which provides flexibility and reduces the number of runs conducted; and

- ***Vessel Operation*** – Instead of speed selection as in the vessel transit portion of the GUI, the wind farm portion of the GUI employs vessel operations to determine vessel speeds. Each vessel operation has a corresponding average speed in the wind farm and the percentage of time the vessel is stationary.

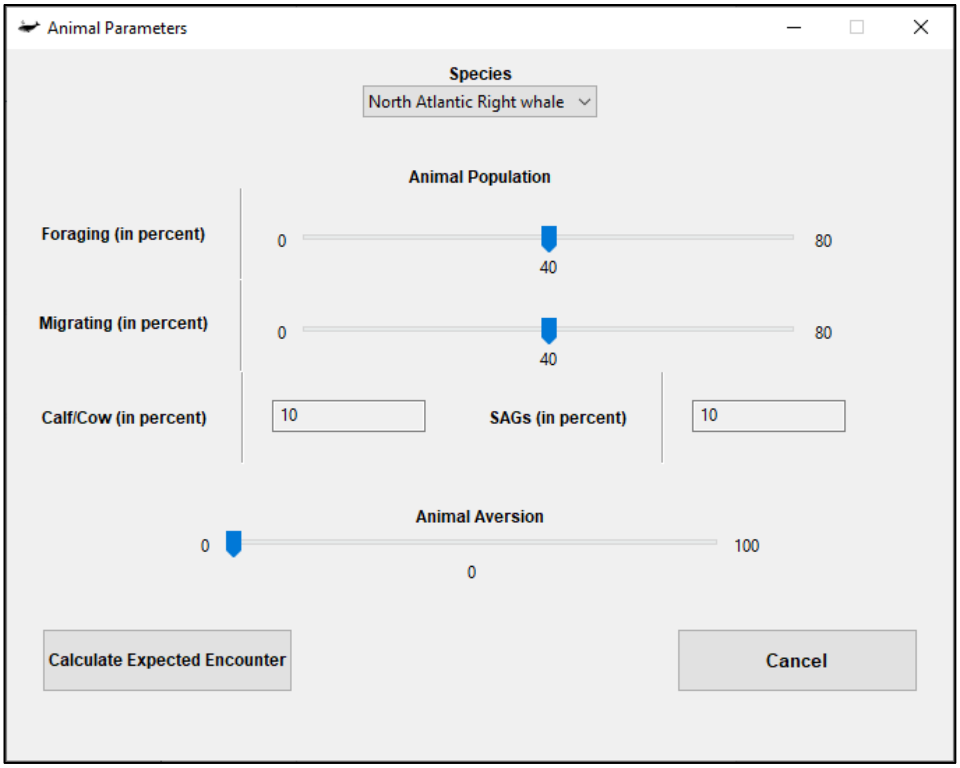


Month: January

	Crew Transfer	Tugs	Support Vessels < 100m	Heavy Cargo	Survey	Cable Lay	Construction/Crane
Vessel Category	High Speed Transfer	Lmtd Mobility or Com	Mooring/Anchor & Eq	Multipurpose Offshore	Survey	Cable & Similar	Large Lmtd Mobility
Vessel Operation	O & M	Construction	Construction	Construction	Survey	Construction	O & M
Aversion (0–100)	0	0	0	0	0	0	0
Number of Vessels	10	2	4	3	5	1	2

Figure 20. Screen capture of graphical user interface wind farm total process graphical user interface
This shows the wind farm total process setup for creating a wind farm scenario with vessel selection parameters, the month of operation, the vessel category, the vessel's area of operation, number of trips (multiplier), and vessel aversion coefficient selection.

The animal parameters in the wind farm portion of the GUI are the same as the vessel transit portion of the GUI. Each run is for a single species and dictates the animal activities (foraging, migrating, calf-care, SAG), speed, and density, which are critical parameters for encounter probability (**Figure 21**).



Species: North Atlantic Right whale

Foraging (in percent): 40

Migrating (in percent): 40

Calf/Cow (in percent): 10

SAGs (in percent): 10

Animal Aversion: 0

Figure 21. **Screen capture of graphical user interface animal parameters**
This shows the Calculator setup for creating the animal species, the percent time foraging or migrating, and the percent of animals existing as calf/cow pairs, along with an animal aversion coefficient selection option.

4.2.2 GUI Outputs

Based on inputs selected by the user through the wind farm portion of the GUI, the Calculator provides a text file showing the expected number of encounters with animals for all vessels in the wind farm over a 24-hour period. As with transits, to obtain just the expected number of encounters while in the wind farm, the aversion factors for both vessels and animal must be set to zero. Consequently, setting aversion to 0 can be taken to simply mean the maximum expected number of encounters but also, the most conservative estimate (maximum) of strikes wherein with 0 aversion, every encounter becomes a strike.

5 Calculator Application

The Calculator provides a risk assessment framework that applies the best available science to user-defined scenarios consistent and applicable across the U.S. Atlantic OCS. The risk assessment is based on predicted animal-vessel encounters aggregated either along a vessel route or within a wind farm over a user-defined period of time. The user-created scenarios of vessel activities provide the ability to explore different "what-if" scenarios to address planning issues and assess potential cumulative risk to animals from development of offshore wind across the OCS. The Calculator is designed to allow for updates in the baseline information about animal densities and behavior as new science becomes available. An important component of new information will be the inclusion of aversion behavior, which currently is not fully understood. Because the success or failure of aversion determines whether a strike occurs during an encounter, this behavior is a user input through the GUI based on the user's discretion and understanding of predicted aversion by the animal or vessel.

In addition, an Aggregator Module (AM) is included in the calculator that has the functionality to aggregate model runs from user-selected scenarios compiled under a project. The AM lets users select the zone (Transit or Wind Farm) where the AM will run (**Figure 22**) and can aggregate three different scenarios (**Figure 23**).

- **Month**: For Month, the AM will sum the potential risk value from each month selected (months 1 through 12) for a specified project for all species for all scenarios to provide a total risk value for the month selected;
- **Species**: For species, the AM will sum the potential risk values for all scenarios for each species by month or by year or both, so one could have a monthly or annual risk value for a single species (e.g., right whales). **Note**: if users need just an annual risk value the month dropdown should be left blank.
- **Total**: For total, the AM will sum all potential risk values for all species for all scenarios across all months to provide one overall risk value for the time period for which scenarios were run.

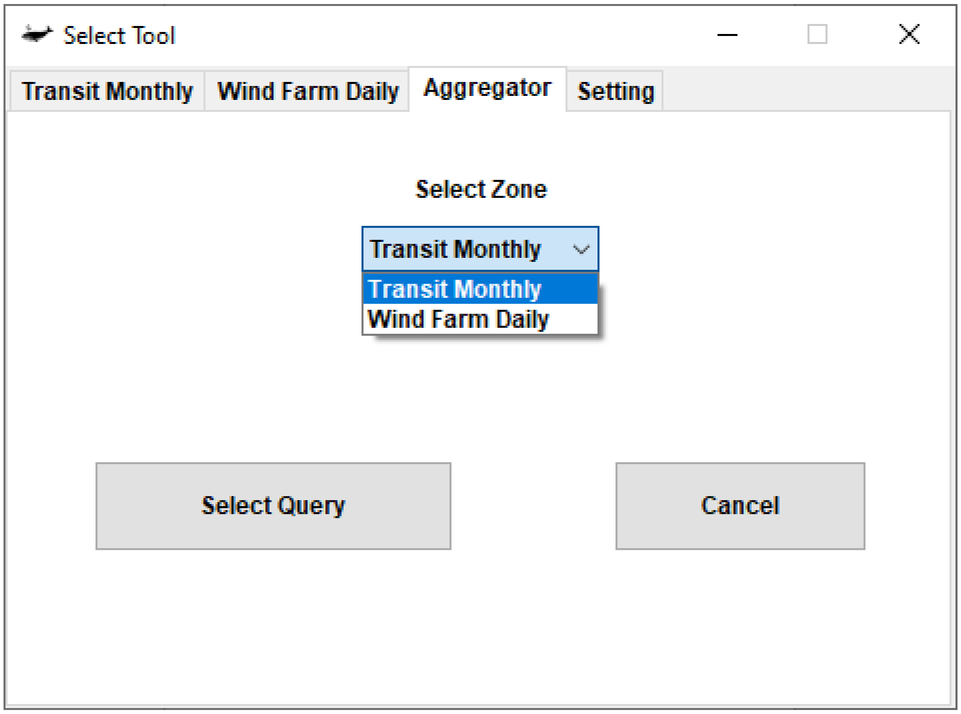
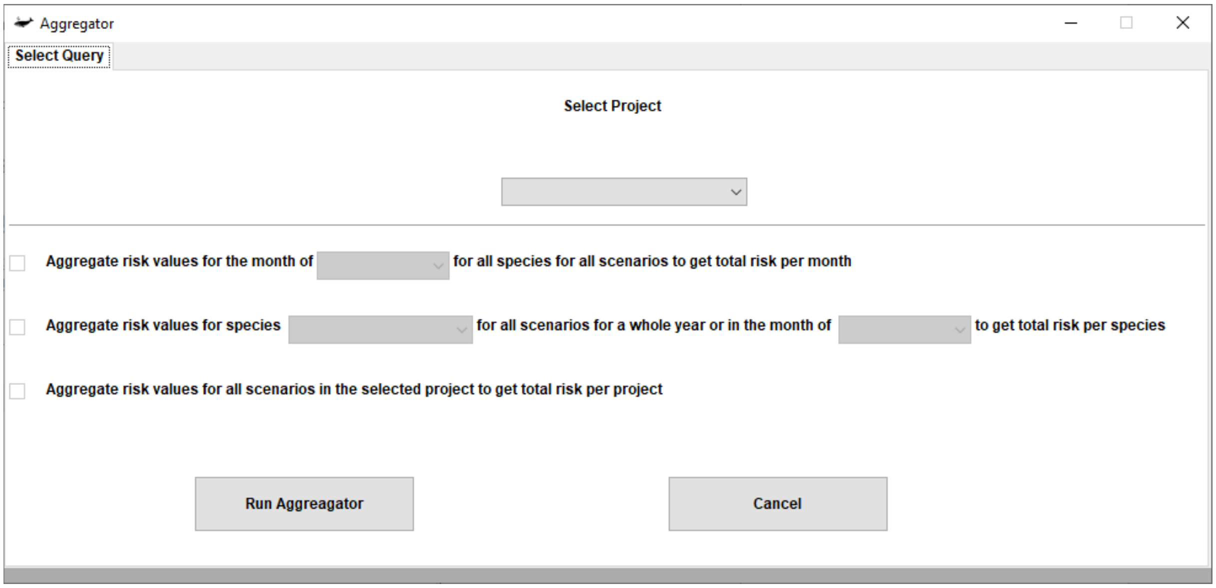


Figure 22. Screen capture of graphical user interface Aggregator Module function

In model development, several encounter factors were tested to determine their individual influence on the encounter probability within a 1 km^2 transit block. Notably, vessel speed, when not integrated with any aversion, does not strongly alter the encounter probability (i.e., the encounter probability is high for both slow- and fast-moving vessels with no aversion). However, when aversion was theoretically included, vessel speed had a more profound effect on encounter risk. This supports the body of literature indicating higher vessel speeds increase strike probabilities.

Results of the analytical model used to compute strike risk were validated against an agent-based model that used more detailed vessel and animal movement inputs. In general, the analytical model showed good agreement with the agent-based model that was run for 10,000 iterations, although it tended to result in a slightly higher (3% to 5%) estimate than the agent-based model. This conservative assessment is appropriate for the intended use of the Calculator. While validating a model with another model does not provide the same level of validation compared to a model validated against empirical data, it does provide some level of affirmation that the model is providing output comparable to existing models being used for scientific and regulatory programs. The Calculator required significant assumptions to meet the temporal and spatial scales of U.S. Atlantic offshore wind development over the next 20+ years. To that end, the Calculator is an early step in identifying specific areas or data gaps that require further investigation or more detailed modeling by providing hot spots where there are high encounter probabilities, which could increase the risk of vessel strikes.



☐ Aggregate risk values for the month of ___ for all species for all scenarios to get total risk per month

☐ Aggregate risk values for species ___ for all scenarios for a whole year or in the month of ___ to get total risk per species

☐ Aggregate risk values for all scenarios in the selected project to get total risk per project

Figure 23. **Screen shot of graphical user interface Aggregator queries**

6 Literature Cited

Abrahms B, Welch H, Brodie S, Jacox MG, Becker EA, Bograd SJ, Irvine LM, Palacios DM, Mate BR, Hazen EL. 2019. Dynamic ensemble models to predict distributions and anthropogenic risk exposure for highly mobile species. Diversity and Distributions. 25(8):1182-1193.

Arendt MD, Segars AL, Byrd JI, Boynton J, Schwenter JA, Whitaker D, Parker L. 2012. Migration, distribution, and diving behavior of adult male loggerhead sea turtles (*Caretta caretta*) following dispersal from a major breeding aggregation in the Western North Atlantic. Marine Biology. 159(1):113-125.

Athreya S, Drewitz A, Sun R. 2019. Random Walk Among Mobile/Immobile Traps: A Short Review. Springer Singapore; Singapore.

Barco S, Law M, Drummond B, Koopman H, Trapani C, Reinheimer S, Rose S, Swingle M, Williard A. 2016. Loggerhead turtles killed by vessel and fishery interaction in Virginia, USA, are healthy prior to death. Marine Ecology Progress Series. 555:221-234.

Baumgartner M, Mate B. 2003. Summertime foraging ecology of North Atlantic right whales. Marine Ecology Progress Series. 264:123-135.

Berman-Kowaleski M, Gulland F, Wilkin S, Calambokidis J, Mate B, Cordaro J, Rotstein D, St Leger J, Collins P, Fahy K et al. 2010. Association between blue whale (*Balnaenoptera musculus*) mortality and ship strikes along the California coast. Aquatic Mammals. 36(1):59-66.

Bezamat C, Wedekin LL, Simões ‐ Lopes PC. 2015. Potential ship strikes and density of humpback whales in the Abrolhos Bank breeding ground, Brazil. Aquatic Conservation: Marine and Freshwater Ecosystems. 25(5):712-725.

Blix S, Folkow L. 1995. Daily energy expenditure in free living minke whales. Acta Physiologica Scandinavica. 153(1):61-66.

Borcuk JR, Mitchell GH, Watwood S, L., Moll T, E., Oliveira EM, Robinson ER. 2017. Dive distribution and group size parameters for marine species occurring in the U.S. Navy's Atlantic and Hawaii-Southern California training and testing study areas. Naval Undersea Warfare Center Division. Newport, Rhode Island. NUWC-NPT Technical Report 12,243.

Calambokidis J, Fahlbusch J, Szesciorka AR, Southall B, Cade DE, Friedlaender A, Goldbogen JA. 2019. Differential vulnerability to ship strikes between day and night for blue, fin, and humpback whales based on dive and movement data from medium duration archival tags. Frontiers in Marine Science. 6:543.

Caretta JV, Forney KA, Oleson EM, Weller DW, Lang AR, Baker J, Muto MM, Hanson B, Orr AJ, Caretta H et al. 2020. U.S. Pacific marine mammal stock assessments: 2019. U.S. Department of Commerce,, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. NOAA Technical Memorandum NMFS-SWFSC-629.

Carretta JV, Helker V, Muto MM, Greenman J, Wilkinson K, Lawson D, Viezbicke J, Jannot J. 2019. Sources of human-related injury and mortality for U.S. Pacific west coast marine mammal stock assessments, 2013-2017. La Jolla, California. NOAA Technical Memorandum NMFS-SWFSC-616.

Cates K, DeMaster D, Brownell RJ, Silber G, Gende S, Ritter F, Panigada S. 2016. Strategic Plan to Mitigate theImpacts of Ship Strikes on Cetacean Populations: 2017-2020. IWC/66/CC20, CC Agenda Item 5.2.

Chaloupka M, Work T, Balazs G, Murakawa S, Morris R. 2008. Cause-specific temporal and spatial trends in green sea turtle strandings in the Hawaiian Archipelago (1982-2003). Marine Biology. 154(5):887-898.

Charif RA, Shiu Y, Muirhead CA, Clark CW, Parks SE, Rice AN. 2020. Phenological changes in North Atlantic right whale habitat use in Massachusetts Bay. Global Change Biology. 26(2):734-745.

Christiansen F, Rasmussen M, Lusseau D. 2011. Inferring surface time of Minke whales from inter-surfacing interval data using a hidden Markov model.

Conn PB, Silber GK. 2013. Vessel speed restrictions reduce risk of collision-related mortality for North Atlantic right whales. Ecosphere. 4(4):1-16.

Crum N, Gowan T, Krzystan A, Martin J. 2019. Quantifying risk of whale–vessel collisions across space, time, and management policies. Ecosphere. 10(4):e02713.

Currie J, Stack S, Kaufman G. 2017. Modeling whale-vessel encounters: the role of speed in mitigating collisions with humpback whales (*Megaptera novaeangliae*). Journal of Cetacean Research and Management. 17:57-64.

Davies K, Brown MW, Hamilton P, Taggart CT. 2019. Variation in North Atlantic right whale *Eubalaena glacialis* occurrence in the Bay of Fundy, Canada, over three decades. Endangered Species Research. 39:159-171.

Department of the Navy. 2007a. Navy OPAREA density estimates (NODE) for the Northeast OPARES: Boston, Narragansett Bay, and Atlantic City. Norfolk, Virginia. Contract N62470-02-D-9997. Task Order 0045. Prepared by Geo-Marine, Inc., Hampton, Virginia

Department of the Navy. 2007b. Navy OPAREA density estimates (NODE) for the Southeast OPARES:VACAPES,CHPT,JAX/CHASN, and Southeastern Florida & AUTEC-Andros. Norfolk, Virginia. Contract N62470-02-D-9997. Task Order 0060. Prepared by Geo-Marine, Inc., Hampton, Virginia

Dolman S, Williams-Grey V, Asmutis-Silvia R, Isaac S. 2006. Vessel collisions and cetaceans: What happens when the don't miss the boat. Wiltshire, United Kingdom.

Douglas A, Calambokids J, Raverty S, Jeffries S, Lambourn D, Norman S. 2008. Incidence of ship strikes of large whales in Washington State. Journal of the Marine Biological Association of the United Kingdom. 88:1121-1132.

Engelhaupt A, Aschettino J. 2020. Personal communication and draft memo, 12 September 2020.

Evans P, Baines M, Anderwald P. 2011. Risk assessment of potential conflicts between shipping and cetaceans in the ASCOBANS Region. ASCOBANS AC18/Doc. 6-04. Progress report submitted by the secretariat of the Sea Watch Foundation to the ASCOBANS Advisory Committee. Paper presented at: 18th ASCOBANS Advisory Committee Meeting.

Foley AM, Stacy BA, Hardy RF, Shea CP, Minch KE, Schroeder BA. 2019. Characterizing watercraft-related mortality of sea turtles in Florida. The Journal of Wildlife Management. 83(5):1057-1072.

Fonnesbeck CJ, Garrison LP, Ward-Geiger LI, Baumstark RD. 2008. Bayesian hierarchical model for evaluating the risk of vessel strikes on North American right whales in the SE United States. Endangered Species Research. 6:87-94.

Gallos LK, Argyrakis P. 2001. Accurate estimation of the survival probability for trapping in two dimensions. Physical Review E - Statistical, Nonlinear, and Soft Matter Physics. 64(5):051111/051111-051111/051116.

Gende S, Hendrix N, Harris K, Eichenlaub B, Nielsen J, Pyare S. 2011. A bayesian approach for understanding the role of ship speed in whale-ship encounters. Ecological Applications. 21(6):2232-2240.

Gende S, Vose L, Baken J, Gabriele C, Preston R, Hendrix N. 2019. Active whale avoidance by large ships: components and constraints of a complementary approach to reducing ship strike risk. Frontiers in Marine Science. 6(592):1-19.

Glass A, Cole T, Garron M. 2009. Mortality and serious injury determinations for baleen whale stocks along the United States eastern seaboard and adjacent Canadian Maritime, 2003-2007. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. Woods Hole, Massachusetts. Northeast Fisheries Science Center Reference Document 09-04.

Gowan T, Ortega-Ortiz JG, Hostetler JA, Hamilton P, Knowlton AR, Jackson KA, George C, Taylor C, Naessig P. 2019. Temporal and demographic variation in partial migration of the North Atlantic right whale. Scientific Reports. 9(1):1-11.

Hain JH, Hampp JD, McKenney SA, Albert J, Kenney RD. 2013. Swim speed, behavior, and movement of North Atlantic right whales (*Eubalaena glacialis*) in coastal waters of northeastern Florida, USA. PLOS One. 8(1):1-9.

Hayes SA, Josephson E, Maze-Foley K, Rosel PE. 2020. U.S. Atlantic and Gulf of Mexico marine mammal stock assessements - 2019. U.S. Department of Commerce,, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. NOAA Technical Memorandum NMFS-NE-264.

Hazel J, Lawler I, Marsh H, Robson S. 2007. Vessel speed increases collision risk for the green turtle *Chelonia mydas*. Endangered Species Research. 3:105-113.

Henderson E, Helble T, Ierley G, Martin S. 2018. Identifying behavioral states and habitat use of acoustically tracked humpback whales in Hawaii. Marine Mammal Science. 34(3):701-717.

International Whaling Commission. 2021.Ship Strike Database Data. [accessed 6 January 2021]. https://portal.iwc.int/shipstrike.

Jensen AS, Silber GK. 2003. Large whale ship strike database. Silver Spring, Maryland. NOAA Technical Memorandum NMFS-OPR.

Kenney RD. 2020. Personal communication and draft memo, 12 September 2020.

Kraus SD, Kenney RD. 1991. Information on Right Whales (*Eubalaena glacialis*) in Three Proposed Critical Habitats in U.S. Waters of the Western North Atlantic Ocean. U.S. Marine Mammal Commission. Washington, D.C. Report T-75133740.

Lagerquist B, Mate B, Ortega-Ortiz JG, Winsor M, Urbán‐Ramirez J. 2008. Migratory movements and surfacing rates of humpback whales (*Megaptera novaeangliae*) satellite tagged at Socorro Island, Mexico. Marine Mammal Science. 24(4):815-830.

Lagerquist B, Stafford KM, Mate B. 2000. Dive characteristics of satellite-monitored blue whales (*Balaenoptera musculus*) off the central California coast. Marine Mammal Science. 16(2):375-391.

Laist DW, Knowlton AR, Mead JG, Collet AS, Podesta M. 2001. Collisions between ships and whales. Marine Mammal Science. 17(1):35-75.

Leaper R. 2019. The role of slower vessel speeds in reducing greenhouse gas emissions, underwater noise, and collision risk to whales. Frontiers in Marine Science. 6:1-8.

Martin J, Sabatier Q, Gowan TA, Giraud C, Gurarie E, Calleson CS, Ortega-Ortiz JG, Deutsch CJ, Rycyk A, Koslovsky SM. 2016. A quantitative framework for investigating risk of deadly collisions between marine wildlife and boats. Methods in Ecology and Evolution. 7(1):42-50.

McKenna MF, Calambokidis J, Oleson EM, Laist DW, Goldbogen JA. 2015. Simultaneous tracking of blue whales and large ships demonstrates limited behavioral responses for avoiding collision. Endangered Species Research. 27:219-232.

Muto MM, Helcker VT, Delean BJ, Angliss RP, Boveng PL, Breiwick JM, Brost BM, Cameron MF, Clapham PJ, Dahle SP et al. 2020. Alaska Marine Mammal Stock Assessments, 2019. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service. NOAA Technical Memorandum NMFS-AFSC-404.

Muto MM, Helker V, Angliss P, Boveng L, Breiwick JM, Cameron F, Clapham PJ, Dahle SP, Dahlheim ME, Fadely BS et al. 2019. Alaska Marine Mammal Stock Assessments, 2018. Seattle, Washington. NOAA Technical Memorandum NMFS-AFSC-393.

National Marine Fisheries Service. 2019. Draft 2019 Marine Mammal Stock Assessment Report, U.S. Atlantic and Gulf of Mexico Draft Marine Mammal Stock Assessment.

National Marine Fisheries Service. 2020.Marine Mammal Unusual Mortality Events. [accessed 18 June 2020]. https://www.fisheries.noaa.gov/national/marine-mammal-protection/marine-mammal-unusual-mortality-events.

Neilson J, Gabriele C, Jensen AS, Jackson K, Straley J. 2012. Summary of reported whale-vessel collisions in Alaskan waters. Journal of Marine Biology. 2012:1-18.

Noad M, Cato D. 2007. Swimming speeds of singing and non‐singing humpback whales during migration. Marine Mammal Science. 23(3):481-495.

Nowacek D, Johnson M, Tyack P. 2004. North Atlantic right whales (*Eubalaena glacialis*) ignore ships but respond to alerting stimuli. Proceedings of the Royal Society B: Biological Sciences. 271(1536):227-231.

O'Neil K, Cunningham E, Moore D. 2019. Sudden seasonal occurrence of humpback whales *Megaptera novaeangliae* in the Firth of Forth, Scotland and first confirmed movement between high-latitude feeding grounds and United Kingdom waters. Marine Biodiversity Records. 12(1):1-5.

Pace R. 2011. Frequency of whale and vessel collisions on the US eastern seaboard: Ten years prior and two years post ship strike rule. Woods Hole, Massachusetts. Northeast Fisheries Science Center Reference Document 11-15.

Parks SE, Searby A, Célérier A, Johnson M, Nowacek D, Tyack P. 2011. Sound production behavior of individual North Atlantic right whales: implications for passive acoustic monitoring. Endangered Species Research. 15(1):63-76.

Parks SE, Warren J, Stamieszkin K, Mayo C, Wiley D. 2012. Dangerous dining: surface foraging of North Atlatic right whales increases risk of vessel collisions. Biology Letters. 8(1):57-60.

Redfern JV, Mckenna MF, Moore TJ, Calambokidis J, Deangelis ML, Becker EA, Barlow J, Forney K, Fiedler PC, Chivers SJ. 2013. Assessing the risk of ships striking large whales in marine spatial planning. Conservation Biology. 27(2):292-302.

Richardson WJ, Greene Jr. C, Malme CI, Thomson D. 1995. Marine Mammals and Noise. San Diego, California: Academic Press.

Roberts J. 2018. Revised habitat-based marine mammal density models for the U.S. Atlantic and Gulf of Mexico. Unpublished data files received with permission to use September 2018.

Roberts J. 2020. Revised habitat-based marine mammal density models for the U.S. Atlantic and Gulf of Mexico. Unpublished data files received with permission to use, August 2020.

Roberts J, Best B, Mannocci L, Fujioka E, Halpin P, Palka D, Garrison LP, Mullin K, Cole T, Khan C et al. 2016. Habitat-based cetacean density models for the U.S. Atlantic and Gulf of Mexico. Scientific Reports. 6(22615).

Rockwood C, Calambokidis J, Jahncke J. 2018. High mortality of blue, humpback and fin whales from modeling of vessel collisions on the U.S. west coast suggests population impacts and insufficient protection. PLOS One. 13(7):e0201080.

SAS Institute, Inc. 2016. SAS 9.4 Software Package. Cary, North Carolina.

Schoeman R, Patterson-Abrolat C, Plön S. 2020. A glocal review of vessel collision with marine mammals. Frontiers in Marine Science. 7:Article 292.

Silber GK, Bettridge S. 2010. Vessel operations in right whale protection areas in 2009. Silver Spring, Maryland. NOAA Technical Memorandum NMFS-OPR-44.

Silber GK, Slutsky J, Bettridge S. 2010. Hydrodynamics of a ship/whale collision. Journal of Experimental Marine Biology and Ecology. 391(1-2):10-19.

Szesciorka AR, Allen AN, Calambokidis J, Fahlbusch J, McKenna MF, Southall B. 2019. A case study of a near vessel strike of a blue whale: perceptual cues and fine-scale aspects of behavioral avoidance. Frontiers in Marine Science. 6(761).

Tulloch V, Plagányi É, Brown C, Richardson A, Matear R. 2019. Future recovery of baleen whales is imperiled by climate change. Global Change Biology. 25(4):1263-1281.

United States Coast Guard. 2016. Atlatic Coast Port Access Study: The Atlantic Coast from Maine to Florida. Washington, D.C. Docket Number USCG-2001-0351.

van der Hoop J, Vanderlaan ASM, Cole T, Henry A, Hall L, Mase-Guthrie B, Wimmer T, Moore M. 2015. Vessel strikes to large whales before and after the 2008 Ship Strike Rule. Conservation Letters. 8(1):24-32.

van der Hoop J, Vanderlaan ASM, Taggart CT. 2012. Absolute probability estimates of lethal vessel strikes to North Atlantic right whales in Roseway Basin, Scotian Shelf. Ecological Applications. 22(7):2021-2033.

van Waerebeek K, Baker A, Felix F, Gedamke J, Iniguez M, Sanino G, Secchi E, Sutaria D, Van Helden A, Wang Y. 2006. Vessel collisions with small cetaceans worldwide and with large whales in the southern hemisphere, an initial assessment. Paper SC/58/BC6. Paper presented at: IWC 58th Annual Meeting. St. Kitts.

Vanderlaan ASM, Taggart CT. 2007. Vessel collisions with whales: The probability of lethal injury based on vessel speed. Marine Mammal Science. 23(1):144-156.

Ventikos N, Rakas D. 2015. Avoiding collisions, enhancing marine safety - a simplified model for the Aegean Sea. Zeszyty Naukowe Akademii Morskiej w Szczecinie. 42(114):78-85.

Wang C, Lyons SB, Corbett J, Fireston J. 2007. Using ship speed and mass to describe potential collision severity with whales: An application of the ship traffic, energy and environment model (STEEM). Paper presented at: Transportation Research Board 86th Annual Meeting. Washington D.C.

Watwood S, L., Buonantony DM. 2012. Dive distribution and group size parameters for marine species occuring in Navy training and testing areas in the North Atlantic and North Pacific oceans. Newport, Rhode Island. NUWC-NPT Technical Document 12,085.

Whitney P, Wilson S, Chaston S, Elkinton C, Uriate A. 2016. The Identification of Port Modifications and the Environmental and Socioeconomic Consequences. U.S. Department of the Interior,, Bureau of Ocean Energy Management, Office of Renewable Energy Program. Washington, DC. OCS Study BOEM 2016-034.

Wiley D, Mayo C, Maloney E, Moore M. 2016. Vessel strike mitigation lessons from direct observations involving two collisions between noncommercial vessels and North Atlantic right whales (*Eubalaena glacialis*). Marine Mammal Science. 32(4):1501-1509.

Williams R, O'Hara P. 2010. Modelling ship strike risk to fin, humpback and killer whales in British Columbia, Canada. Journal of Cetacean Resaearch and Management. 11(1):1-8.

Yin Z-C, Hui L, Zhang Z-J, Jin Z-H-N, Li S-J, Xiao J-Q. 2019. Probabilistic model of random encounter in obstacle space. International Journal of Geo-Information. 8(1):32-50.

Appendix A: Sample Large Whale Physical Standards and Monthly Dive Activity Look up Tables

Table A-1. North Atlantic right whale activity look up table (Baumgartner and Mate, 2003; Borcuk et al., 2017; Engelhaupt and Aschettino, 2020; Hain et al., 2013; Hayes et al., 2020; Kenney, 2020; Kraus and Kenney, 1991; Parks et al., 2011; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

North Atlantic right whale (*Eubalaena glacialis*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	Jan	0.258	15	3	80	17	3	84	10	6	71	29	0	85	15	0
	Feb	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Mar	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Apr	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	May	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Jun	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Jul	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Aug	0.258	15	3	90	7	3	84	10	6	71	29	0	85	15	0
	Sep	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Oct	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Nov	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
	Dec	0.258	15	3	48	49	3	84	10	6	71	29	0	85	15	0
Mid-Atlantic	Jan	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Feb	0.82	15	3	5	80	15	84	10	6	71	29	0	85	15	0
	Mar	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	Apr	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	May	0.82	15	3	15	70	15	84	10	6	71	29	0	85	15	0
	Jun	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Jul	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Aug	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0

Table A-1. North Atlantic right whale activity look up table (Continued)

North Atlantic right whale (*Eubalaena glacialis)*																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Mid-Atlantic	Sep	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Oct	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Nov	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
	Dec	0.82	15	3	5	88	7	84	10	6	71	29	0	85	15	0
Southeast	All	0.4	15	3	0	5	95	84	10	6	71	29	0	85	15	0

Table A-2. Humpback whale activity look up table (Borcuk et al., 2017; Engelhaupt and Aschettino, 2020; Hayes et al., 2020; Kenney, 2020; Noad and Cato, 2007; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

Humpback Whale (*Megaptera novaeangliae)*																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	Jan	1.76	15	3	90	5	5	79	12	9	20	20	60	40	26	34
	Feb	1.76	15	3	90	5	5	79	12	9	20	20	60	40	26	34
	Mar	1.76	15	3	90	5	5	79	12	9	20	20	60	40	26	34
	Apr	1.76	15	3	90	5	5	79	12	9	20	20	60	40	26	34
	May	1.76	15	3	90	5	5	79	12	9	20	20	60	40	26	34
	Jun	1.76	15	3	95	0	5	79	12	9	20	20	60	40	26	34
	Jul	1.76	15	3	95	0	5	79	12	9	20	20	60	40	26	34
	Aug	1.76	15	3	95	0	5	79	12	9	20	20	60	40	26	34
	Sep	1.76	15	3	95	0	5	79	12	9	20	20	60	40	26	34
	Oct	1.76	15	3	95	0	5	79	12	9	20	20	60	40	26	34
	Nov	1.76	15	3	80	15	5	79	12	9	20	20	60	40	26	34
	Dec	1.76	15	3	80	15	5	79	12	9	20	20	60	40	26	34
Mid-Atlantic	Jan	0.92	15	3	82	13	5	79	12	9	20	20	60	40	26	34
	Feb	0.92	15	3	82	13	5	79	12	9	20	20	60	40	26	34
	Mar	0.92	15	3	60	35	5	79	12	9	20	20	60	40	26	34
	Apr	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	May	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Jun	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Jul	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Aug	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Sep	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Oct	0.92	15	3	40	55	5	79	12	9	20	20	60	40	26	34
	Nov	0.92	15	3	60	35	5	79	12	9	20	20	60	40	26	34
	Dec	0.92	15	3	82	13	5	79	12	9	20	20	60	40	26	34

Table A-2. Humpback whale activity look up table (Continued)

Humpback Whale (*Megaptera novaeangliae)*																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Southeast	All	0.99	15	3	0	95	5	79	12	9	20	20	60	40	26	34

Table A-3. Fin whale activity look up table (Borcuk et al., 2017; Calambokidis et al., 2019; Engelhaupt and Aschettino, 2020; Kenney, 2020; Roberts, 2018; Watwood and Buonantony, 2012)

Fin Whale (*Balaenoptera physalus*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	Jan	1.6	24	3.8	80	19	1	47	11	43	47	11	43	47	11	43
	Feb	1.6	24	3.8	80	19	1	47	11	43	47	11	43	47	11	43
	Mar	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Apr	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	May	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Jun	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Jul	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Aug	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Sep	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
	Oct	1.6	24	3.8	80	19	1	47	11	43	47	11	43	47	11	43
	Nov	1.6	24	3.8	80	19	1	47	11	43	47	11	43	47	11	43
	Dec	1.6	24	3.8	80	19	1	47	11	43	47	11	43	47	11	43
Mid-Atlantic	All	1.6	24	3.8	80	15	5	47	11	43	47	11	43	47	11	43
Southeast	All	1.6	24	3.8	0	99	1	47	11	43	47	11	43	47	11	43

Table A-4. Minke whale activity look up table (Borcuk et al., 2017; Christiansen et al., 2011; Engelhaupt and Aschettino, 2020; Hayes et al., 2020; Kenney, 2020; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

Minke Whale (*Balaenoptera acutorostrata*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	Jan	1.9	10.6	1.7	90	5	5	40	40	20	40	40	20	40	40	20
	Feb	1.9	10.6	1.7	90	5	5	40	40	20	40	40	20	40	40	20
	Mar	1.9	10.6	1.7	85	10	5	40	40	20	40	40	20	40	40	20
	Apr	1.9	10.6	1.7	80	15	5	40	40	20	40	40	20	40	40	20
	May	1.9	10.6	1.7	80	15	5	40	40	20	40	40	20	40	40	20
	Jun	1.9	10.6	1.7	95	0	5	40	40	20	40	40	20	40	40	20
	Jul	1.9	10.6	1.7	95	0	5	40	40	20	40	40	20	40	40	20
	Aug	1.9	10.6	1.7	95	0	5	40	40	20	40	40	20	40	40	20
	Sep	1.9	10.6	1.7	95	0	5	40	40	20	40	40	20	40	40	20
	Oct	1.9	10.6	1.7	95	0	5	40	40	20	40	40	20	40	40	20
	Nov	1.9	10.6	1.7	80	15	5	40	40	20	40	40	20	40	40	20
	Dec	1.9	10.6	1.7	80	15	5	40	40	20	40	40	20	40	40	20
Mid-Atlantic	All	1.9	10.6	1.7	55	40	5	40	40	20	40	40	20	40	40	20
Southeast	All	1.9	10.6	1.7	55	40	5	40	40	20	40	40	20	40	40	20

Table A-5. Sei whale activity look up table (Borcuk et al., 2017; Engelhaupt and Aschettino, 2020; Hayes et al., 2020; Kenney, 2020; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

Sei Whale (*Balaenoptera borealis*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	All	1.9	16	2.5	80	19	1	30	30	40	30	30	40	30	30	40
Mid-Atlantic	All	1.9	16	2.5	80	15	5	30	30	40	30	30	40	30	30	40
Southeast	All	1.9	16	2.5	0	99	1	30	30	40	30	30	40	30	30	40

Table A-6. Blue whale activity look up table (Borcuk et al., 2017; Engelhaupt and Aschettino, 2020; Hayes et al., 2020; Kenney, 2020; Lagerquist et al., 2000, Calambokidis, 2019; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

Blue Whale (*Balaenoptera musculus*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	Jan	1.5	30.2	4.4	80	19	1	43	29	28	43	29	28	43	29	28
	Feb	1.5	30.2	4.4	80	19	1	43	29	28	43	29	28	43	29	28
	Mar	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Apr	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	May	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Jun	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Jul	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Aug	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Sep	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
	Oct	1.5	30.2	4.4	80	19	1	43	29	28	43	29	28	43	29	28
	Nov	1.5	30.2	4.4	80	19	1	43	29	28	43	29	28	43	29	28
	Dec	1.5	30.2	4.4	80	19	1	43	29	28	43	29	28	43	29	28
Mid-Atlantic	All	1.5	30.2	4.4	80	15	5	43	29	28	43	29	28	43	29	28
Southeast	All	1.5	30.2	4.4	0	99	1	43	29	28	43	29	28	43	29	28

Table A-7. Sperm whale activity look up table (Borcuk et al., 2017; Engelhaupt and Aschettino, 2020; Hayes et al., 2020; Kenney, 2020; Roberts, 2018, 2020; Watwood and Buonantony, 2012)

Sperm Whale (*Physeter macrocephalus*)																
Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Density Foraging	% Density Migrating	% Population Calf-rearing	% Time Foraging 0–10 m	% Time Foraging 11–20 m	% Time Foraging >20 m	% Time Migrating 0–10 m	% Time Migrating 11–20 m	% Time Migrating >20 m	% Time Calf-rearing 0–10 m	% Time Calf-rearing 11–20 m	% Time Calf-rearing >20 m
Northeast	All	0.88	14	2.2	80	10	10	10	10	80	10	10	80	40	10	50
Mid-Atlantic	All	0.88	14	2.2	80	10	10	10	10	80	10	10	80	40	10	50
Southeast	All	0.88	14	2.2	80	10	10	10	10	80	10	10	80	40	10	50

Table A-8. Sea Turtle activity look up table (Arendt et al., 2012; Borcuk et al., 2017; Department of the Navy, 2007a,b; Watwood and Buonantony, 2012)

Sea Turtle Species	Region	Month	Travel Speed (m/s)	Length (m)	Beam (m)	% Time (all activities) 0–10 m	% Time (all activities) 11–20 m	% Time (all activities) >20 m
Loggerhead (*Caretta caretta*)	ALL	ALL	0.64	0.89	0.89	0.61	0.16	0.23
Green (*Chelonia mydas*)	ALL	ALL	0.56	0.83	0.75	0.76	0.19	0.05
Leatherback (*Dermochelys coriacea*)	ALL	ALL	0.70	3.00	1.50	0.19	0.65	0.16
GENERAL Chelonid	ALL	ALL	0.60	0.61	0.59	0.68	0.17	0.14
Hawksbill (*Eretmochelys imbricata*)	ALL	ALL	0.60	0.52	0.46	Insufficient data. All data are from coral reef habitat. Use general chelonid.		
Kemps ridley (*Lepidochelys kempii*)	ALL	ALL	0.60	0.21	0.27	Insufficient data. All data are from coral reef habitat. Use general chelonid.		

Appendix B: Agent-based Strike Probability Matrix Tool

Overview

This appendix provides a brief description of the Agent Based Strike Probability Matrix Tool and its development. Whilst it was initially planned for this agent based to form the Strike Probability Tool data limitations regarding aversion render the additional complexity of the agent based model unnecessary as the problem can, in the absence of aversion (and other behavioral characteristics, such as detailed dive profiles, aggregation etc.). be solved analytically. Ultimately this model was used to validate the analytical solution by turning off all aversion and behavioral characteristics.

A set of animations are included with this document that showcase key features of the model.

B.1 Development Environment

Developed using Python 3.7 and IDLE. Main dependencies within python can be acquired using pip. These include: time, numpy, scipy and matplotlib.

B.2 Input Parameters

Ultimately, the Strike Probability Matrix Tool is used to evaluate relative probabilities of vessel strike. In other words, how incremental changes in vessel or animal characteristics, behavior etcetera affect the strike probability. The characteristics and behavior of vessels and animals are defined by input parameters. A list of all input parameters along with brief descriptions are shown in **Table B-1**.

Table B-1. List of Parameters

Input Parameter	Description
CellDim	Dimension of square model domain in meters
TStepLen	Length of each timestep in minutes
ShipVelocity	Ship velocity in meters/minute
ShipLength	Length of vessel in meters
ShipWidth	Width of vessel in meters
ShipAngle	Degrees of vessel heading relative to the x-axis (typically 0)
ShipMaxDecel	Maximum rate of vessel deceleration
ShipLoudness	Ship engine loudness in dB @ 1 Pa, 1m depth
ShipEngineFreq	Representative frequency of engine noise
SpotterPresent	Flag indicating whether vessel spotter is present. If True, vessel performs evasive maneuver when animal is spotted.
SpotterRadius	Distance spotter can view
SpotterAngleRange	Degrees that spotter view window can rotate through
SpottterViewWindow	Degrees that spotter view window can see (aperture).
Oscillation Period	Number of times SpottterViewWindow rotates through SpotterAngleRange each minute.
N_Animals	Number of animal agents in simulation
AnimalVelocity	Velocity of animal in meters/minute
AnimalAngle	Angle (degrees ccw) of animal heading relative to x-axis (range between 0 and 60 degrees)
CalfPresent	Flag indicating whether calf is present with each animal. (can be different for each animal)

Table B-1. List of Parameters (Continued)

Input Parameter	Description
AnimalAversion	Flag indicating whether animal exhibits aversion behavior
AnimalDiving	Flag indicating whether animal exhibits diving behavior
AnimalDiveSignal	1 dimensional vector describing animal dive signal

B.3 Agent Movement

A single vessel along with one or more animals are modelled as independent agents. The shape of an agent is described by a set of circular hull elements, undergoing a rigid body translation by the agents' center of mass. The movement of a given agents center of mass is governed by its velocity and a unit direction vector, which will change throughout time depending on the agents' behavioral characteristics. At each time t the position of the agents' center of mass $X_t = (x_t, y_t)$ is given by

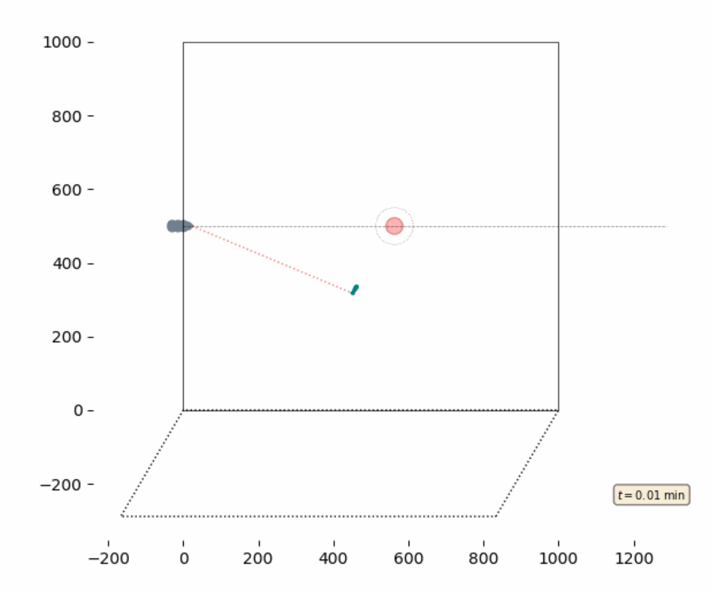
$$X_t = X_{t-1} + v_t d_t \quad 1$$

Where v_t is the agents' linear velocity and d_t is a two-dimensional unit vector describing the directional components of velocity. In the most basic case, agents move at a constant velocity and direction for the entire duration of the simulation. Trajectories are then modified by introducing collision aversion and other behavioral characteristics.

B.4 Collision Detection

In all simulations, there is one vessel agent and one or more animal agents. At each timestep, and for each ship-animal pair, the vector separating the closest two hull elements of the vessel and animal is determined. If the length of this vector is shorter than a specified distance, then a collision flag is raised, and the simulation terminates.

In the animation (**Animation B-1**), a red circle appears if a collision between vessel and animal agent is likely given no modifications to their initial trajectories. This early detect feature can be used to see how behavioral modifications affect the outcome of simulations. Double click on the animation below.



Animation B-1. Basic collision animation

B.5 Animal Diving Behavior

If AnimalDiving = True, then a dive signal is generated for each animal. Dive profiles include percent time spent at surface, percent time spent at or above 10m depth, percent time spent below 10 m depth. Dive profiles can be lumped into “behavioral modes” like foraging or migrating.

Values within the dive profiles range between 0 and 1. At each timestep, the radius and relative distances between every element in the animal hull are scaled by this value. If the current value is zero, then the animal is “submerged”, and will not collide with the vessel, or be detectable by the observer (if present). An example dive signal is shown in **Figure B-1**, the y-axis values are correlated with dive depth and range from 0 to 1. Double click on the **Animation B-2**.

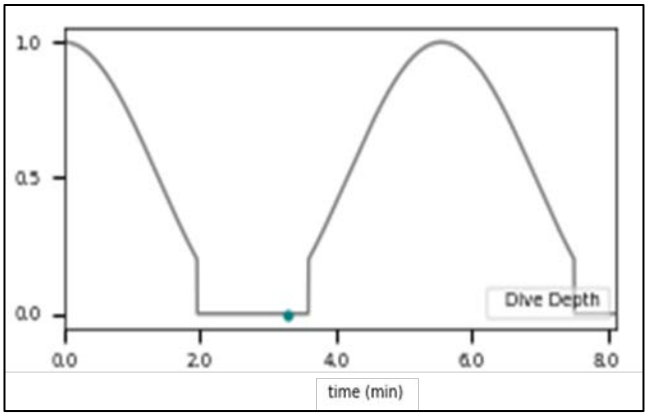
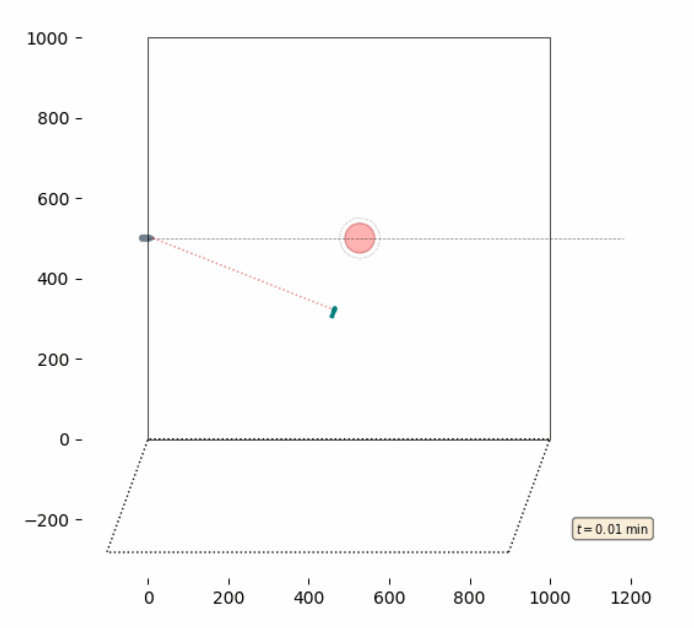


Figure B-1. Example animal dive profile
The y- axis is correlated with dive depth.



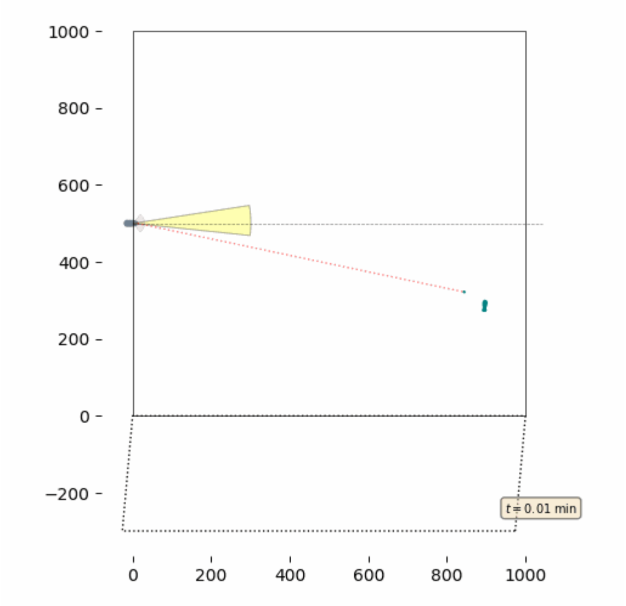
Animation B-2. Diving animation

B.6 Animal Calf Behavior

If *CalfPresent* = *True*, then animals are assigned a calf. The calf is modelled as modification to the "parent" animal agent. A single circular hull element is added to animal agents travelling with a calf. The calf hull element rotates about the animals' center of mass at a defined speed and radius (**Animation B-3**). At each timestep, the position of the calf hull element X_t^{Calf} relative to the animal center of mass is computed as

$$X_t^{Calf} = X_{t-1}^{Calf} + v_{calf} R(d\theta_t, r_t, d_t), \quad 2$$

Where v_{calf} is the linear velocity of the calf motion, and $R(d\theta_t, r_t, d_t)$ is an operator that rotates a unit direction vector d_t counterclockwise by $d\theta_t$ degrees along a circle of radius r_t. The calf behavior can be modified by specifying appropriate values of r_t, $d\theta_t\ , or\ v_{calf}$ throughout time.



Animation B-3. Diving parent-calf animation

This sensitivity analysis was performed to allow a check of the lookup table data used in the strike risk model. For the strike risk model, dive depths for cow-calf pairs were assigned dive depths as a pair rather than as individual animals with differential dive behaviors. There are limited data from tagged cow-calf pairs of multiple species.

B.7 Ship Spotter and Evasion

If $SpotterPresent = True$, then a spotter will be added to the vessel. The spotters' primary function is to scan the area in front of the vessel for animals, triggering an evasive maneuver if one is spotted. The spotter behavior is parameterized by *SpotterViewWindow*, *SpotterAngleRange*, *SpotterRadius* and *OscillationPeriod*. These parameters are described in Table 1. The relative efficiency of the spotter can be improved by increasing the *SpotterViewWindow*, *SpotterRadius* and decreasing *OscillationPeriod*.

The yellow region in front of the vessel in **Figure B-2** shows the spotters field of view, which rotates back and forth through the range of angles enclosed by the light gray shaded region at its base. If an animal is spotted, an evasive maneuver is initiated, which involves the vessel turning away from the animal at minimum turning radius (vessel characteristic dependent) and decelerating at a rate equal to *ShipMaxDecel*.

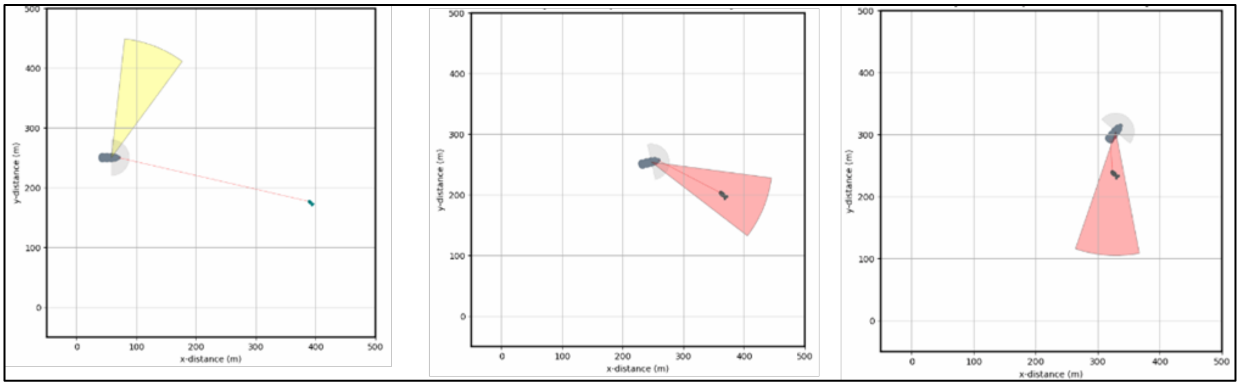


Figure B-2. Snapshot showing ship identifying animal and performing evasive maneuver

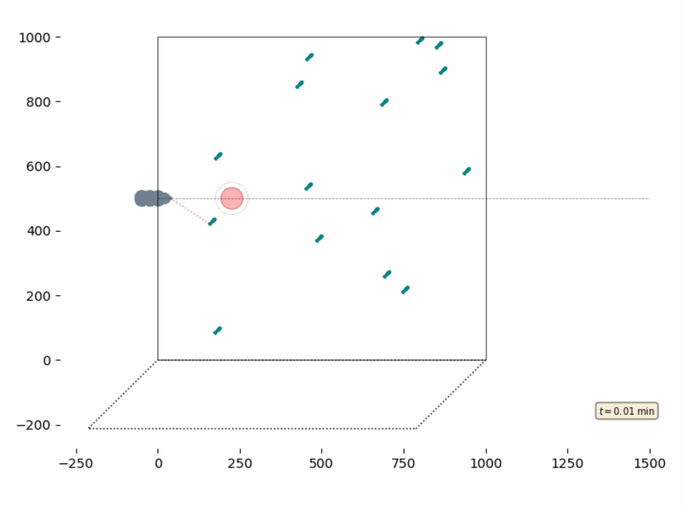
B.8 Ship Noise and Animal Aversion

If *AnimalAversion* = *True*, vessel noise is simulated using a very simplified "Source-Path-Receiver" type model. A representative vessel noise loudness and frequency are specified, and the intensity of noise (in AdB) is computed for each animal agent as

$$NoiseLevel = ShipLoudness - 20\log_{10} r_{sep} \,, \tag{3}$$

Where r_{sep} is the distance between the vessel center of mass and the animal center of mass. If the noise level for an animal agent exceeds a certain threshold, the heading and velocity of the animal could be modified to avoid the vessel.

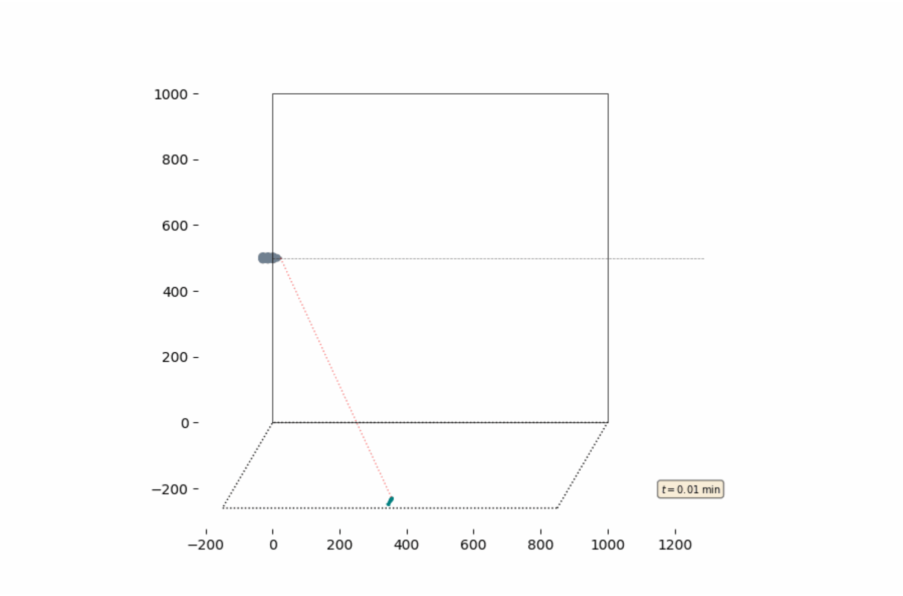
See **Animation B-4** (this animation is sped up 10x actual speed).



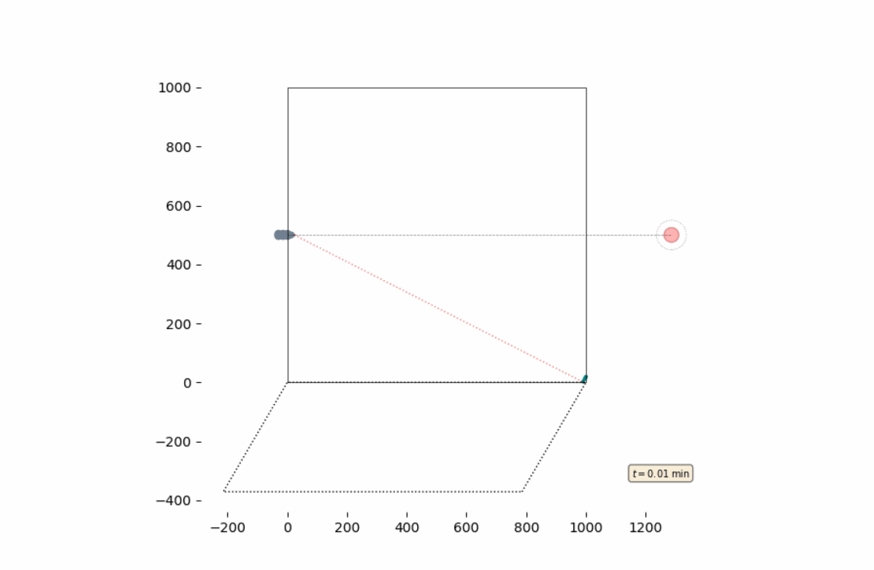
Animation B-4. Animal behavior animation

B.9 Model Domain Extension

The model domain extension is included to account for cases where an animal travels into the square domain while the vessel is traveling through (**Animations B-5** and **B-6**).



Animation B-5. Model domain extension



Animation B-6. Model domain extension 2

A single vessel travels at a constant velocity V_S along the line AC. At the beginning of the simulation, one or more animals are placed at random within the eligible spawn region, shown as the shaded area in **Figure B-3**. Animals travel at a constant velocity V_A along a heading of θ_A degrees clockwise from the positive y-axis. The square portion of the region extends a distance AB from the origin O in the positive x-direction and the positive y-direction. The parallelogram portion of the eligible spawn region is defined such that an animal starting anywhere along the line GF will reach its respective position along the line OD in the time required for the vessel to travel the distance AB. For example, an animal originating at the point F will travel the path FD in the same amount of time required for the vessel to travel the path AC, resulting in an encounter with no strike.

$$DE = \frac{V_A}{V_s} AB \cos(\theta_A) \tag{4}$$

$$FE = DE \tan(\theta_A), \tag{5}$$

$$BC = \left(\frac{AB}{2} + DE\right) \tan(\theta_A) - FE \tag{6}$$

For cases when the relative velocity between animal and vessel is small, animals originating at point D may collide with the vessel at point C. The maximum possible simulation time t_{max} can then be determined as the time required for the vessel to travel the line AC.

$$t_{max} = \frac{AC}{V_S} \tag{7}$$

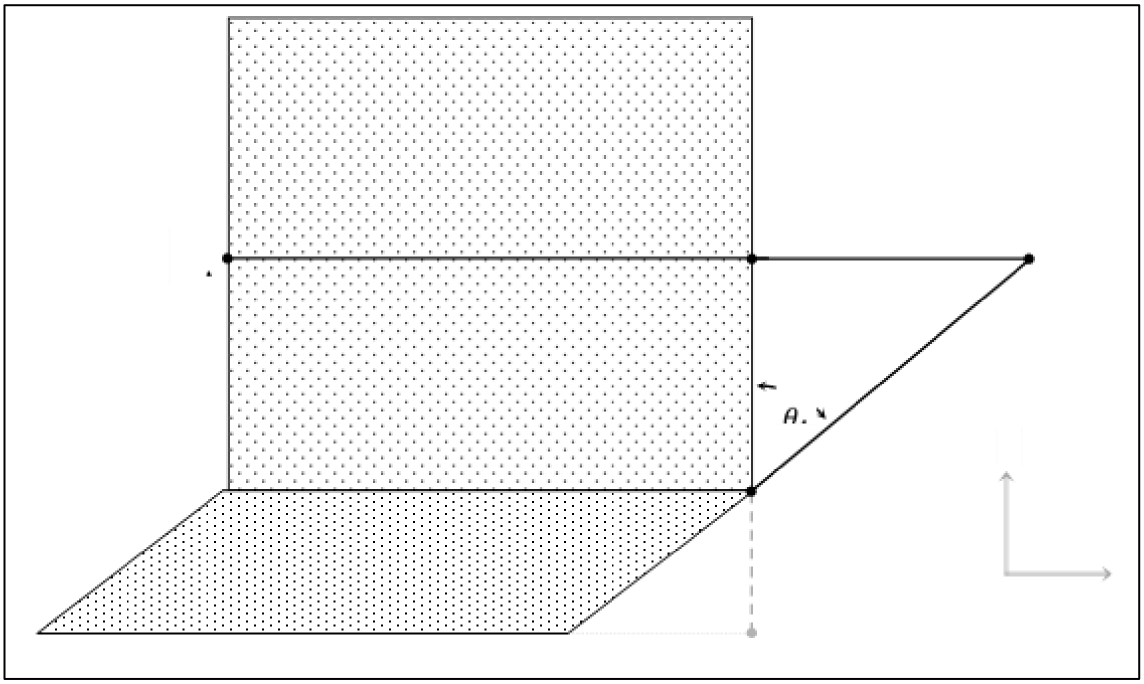


Figure B-3. Numerical model domain extension

Appendix C: Detailed Description of User Inputs and Graphical User Interface Outputs

C.1 Vessel Transit Animal Encounters (linear and unit area prediction)

C.1.1 User Inputs to the GUI

- The other major inputs, but not user-managed, are the probability solutions accessed by the various user inputs.
- Data are entered using month as the default unit of time.
- Vessel categories.
- Vessel speed (underlying zones [harbor, open-water transit] have default vessel speeds associated with vessel category).
- Target species.
- Season:
    - Density from underlying data (Roberts et al., 2016, Roberts, 2020).
    - Primary activity will default to 100% foraging, migrating, or calf-care depending on the species, region, and month.
    - Slide bars are available only for the foraging and migrating percentages when calf-care is not the primary default activity.
    - When changing the percent population activity between foraging and migrating, the primary activity will have two sliders that must add to 95%; 5% will always remain as calf-care. Sliding one affects the other to ensure a constant total of 100%; each activity has an associated percent time at surface.
        - One slider for percent of population foraging between 0 and 95; and
        - One slider for percent of population migrating (95 - foraging).
- No time-of-day effect (day/night).
- Vessel route (underlying zones [harbor, open-water transit] have default vessel speeds associated with vessel category; all vessels follow this line).
    - Pre-selected: Pre-programmed, anticipated routes from key ports to the nearest portion of subject wind farms will be pre-loaded and selectable; speeds per vessel route segment are adjustable.
    - User-defined: This will include selection of a particular wind farm; all vessel speeds are defined by underlying zones (e.g., transit from ports to a wind farm) through which a vessel route passes.
- Number of trips for a defined vessel route by vessel category (this allows the user to alter the effect of multiple transits, with the result being another cumulative probability based on vessel activity in a given season).
- Number of trips will be defined by trips per specific month.

- Aversion coefficient (this is because encounter ≠ mortality; encounter frequency is negatively asymptotic while mortality is linear with velocity; avoidance [by animal or vessel operator] reduces encounter frequency and mortality as a result of an impact upon encounter). This is applied at the end as a simple percent reduction of the final probability solution from all other factors. The final probability would be:

  $\text{Prob}_{\text{fin}} = \text{Prob}_{\text{vessel1}} . \text{AvCoefficient}_{\text{Vessel1}} . \text{NumTrips}_{\text{ Vessel1}} + \text{Prob}_{\text{vessel2}} . \text{AvCoefficient}_{\text{Vessel2}} . \text{NumTrips}_{\text{ Vessel2}} + \text{Prob}_{\text{vessel3}} . \text{AvCoefficient}_{\text{Vessel3}} . \text{NumTrips}_{\text{ Vessel3}} + \text{Prob}_{\text{vessel4}} . \text{AvCoefficient}_{\text{Vessel4}} . \text{NumTrips}_{\text{ Vessel4}} + \text{Prob}_{\text{vessel5}} . \text{AvCoefficient}_{\text{Vessel5}} . \text{NumTrips}_{\text{ Vessel5}} + \text{Prob}_{\text{vessel6}} . \text{AvCoefficient}_{\text{Vessel6}} . \text{NumTrips}_{\text{ Vessel6}} + \text{Prob}_{\text{vessel7}} . \text{AvCoefficient}_{\text{Vessel7}} . \text{NumTrips}_{\text{ Vessel7}}$

  Where AvCoefficient is vessel aversion coefficient and NumTrips are number of trips:

  - Selection should be a user entry on some relative coefficient (e.g., the estimated percentage of time such as 0 to 100 in 10% increments [dropdown]) that aversion occurs and results in successful avoidance of a strike by the animal.
  - Selection should be a user entry on some relative coefficient (e.g., the estimated percentage of time such as 0 to 100 in 10% increments [dropdown]) that aversion occurs and results in successful avoidance of a strike by the vessel.
  - Aversion is computed as the maximum aversion from either source (animal or vessel).

C.1.2 GUI Outputs

- Number of encounters per kilometer of vessel route (downloadable text file).
- Cumulative encounter count for an entire, discrete vessel route for a species in a season (adding up all 1-km encounter counts; downloadable text file).
- Heat map:
  - Mid-points of every kilometer along the vessel route are color-ramped to encounter probability at that point along the line.
  - Each 1-km^2 pixel intersected by the vessel route is color-ramped to encounter counts at that square kilometer.

C.2 Within Wind Farm Animal Encounters (unit area prediction)

C.2.1 User Inputs at the GUI

- The other major inputs, but not user-managed, are the probability solutions accessed by the various user inputs.
- Data are entered, using month as the default unit of time.
- Vessel categories (see **Table 1** in main text); Characteristics (e.g., speed bins) of vessel in these categories may be different in the wind farm than in the transit routes.
- Number of vessels in that category.
- Time period in the wind farm.
- Size of the wind farm.
- Percent of the wind farm area visited.
- Default is that vessel enters every 1-km pixel in the wind farm.
- Vessel speed (default speed associated with vessel category).
- Target species.

- Season:
    - Density.
    - Primary activity – two sliders – both must add to 100%; sliding one affects the other to ensure a constant total of 100%; each activity has an associated percent time at the surface.
        - One slider for percent of population foraging; and
        - One slider for percent of population migrating.
- No time of day effect (day/night).
- Aversion coefficient (this is because encounter ≠ mortality; encounter frequency is negatively asymptotic while mortality is linear with velocity; avoidance [by animal or vessel operator] reduces encounter frequency and mortality as a result of an impact upon encounter). This is applied at the end as a simple percent reduction of the final probability solution from all other factors. The final probability would be: $\text{Prob}_{\text{fin}} = xxxx$
    - Selection should be a user entry on some relative coefficient (e.g., the estimated percentage of time such as 0 to 100 in 10% increments [dropdown]) that aversion occurs and results in successful avoidance of a strike by the animal.
    - Selection should be a user entry on some relative coefficient (e.g., the estimated percentage of time such as 0 to 100 in 10% increments [dropdown]) that aversion occurs and results in successful avoidance of a strike by the vessel.

C.2.2 GUI Outputs

- Counts of encounter per linear km^2 of vessel track within the wind farm (downloadable text file).
- Cumulative encounter count for the entire wind farm (downloadable text file).
- Aggregated counts of encounters/risk estimation (through aversion utilization) for a user-defined suite of model run scenarios.

Department of the Interior (DOI)

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation’s trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM’s Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).