JOURNAL OF MARITIME RESEARCH

Vol XXIII. No. I (2026) pp 366–376

ISSN: 1697-4840, www.jmr.unican.es

Increase in the Geometric Probability of Collision with Cetaceans in Relation to the Decrease in Speed of Merchant Ships.

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ARTICLE INFO

Article history:
Received 05 Aug 2025;
in revised from 24 Sep 2025;
accepted 16 Nov 2025.

Keywords:
Ship Strikes, Cetacean Conservation, Vessel Collision, Maritime Safety, Whale, Ship Speed.

ABSTRACT

Collisions between ships and cetaceans are a major environmental concern, as they result in the loss of umbrella species, causing significant environmental damage. Several studies relating vessel speed to lethality, reduced collision probability, increased response capacity, and other factors have been conducted to date. To further our understanding of the interaction between different types of vessels and cetaceans, this document calculates the geometric probability of collision between vessels and cetaceans that may appear within their surveillance area while in navigation route, applying nautical principles of naval kinematics and maneuvering board. It also provides the equation for calculating the horizontal surveillance angle, considering the probability of a collision with a cetacean. Finally, it provides a calculation of the maximum increase factor of the probability of collision with respect to the reduction of speed and calculates a vulnerability index for each vessel, based on the probability of collision within the cetacean-protected area.

1. Introduction.

Since the 1990s, the International Maritime Organization and the International Whaling Commission (IWC) have been concerned with preventing collisions with cetaceans, publishing, among others, the GUIDANCE DOCUMENT FOR MINIMIZING THE RISK OF SHIP STRIKES WITH CETACEANS, which includes, among other recommendations, the possibility of reducing the speed of ships. These incidents often cause severe injuries or fatalities and may involve a wide range of vessels, from small recreational boats to large cargo ships (European Union, 2025). Whales experience high ship-strike risk across large extents of the world's oceans, and the majority of high-risk areas lack management efforts aimed at mitigating this issue. Ship-strike management measures, such as vessel speed reductions and changes in vessel routings, must be urgently expanded to conserve and recover the great whales (Nisi et al., 2024). Currently, anecdotal records provide the only information for evaluating vessel operating factors related to ship strikes. Although such records have significant weaknesses, they merit consideration absent other data. Accounts found in this review suggest that most whales hit by ships are not seen beforehand or seen only at the last moment (Laist et al., 2001). Determining collision probabilities will be much more complex as the size and shape of the domain changes, as the number, sizes, and speeds of vessels and how they transit the domain, and the number, sizes, and speeds of whales and how they move within the domain change (Vanderlaan & Taggart, 2007). While feeding, fin whales exhibit irregular movements in a zig-zag pattern or circular motion (Tort et al., 2017). Moreover, travelling, and resting behaviour have been identified in this area. While travelling, fin whales conduct a linear path with a constant speed. (Tort et al., 2017). Vessel collisions can also pose a threat to human safety when ships sink after such collisions (Neilson et al., 2012; Peel et al., 2018; Ritter, 2012), people are injured (Dolman et al., 2006; Ritter, 2010)

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or even killed (De Stephanis & Urquiola, 2006). Ship-cetacean collisions can also have economic impacts on the maritime industry, such as the loss of vessels (Laist et al., 2001; Ritter 2012), changes in major shipping routes, and speed restrictions (Frisch, 2022). There is no reasonable transiting speed at which large vessels could strike a whale without a large risk of lethally injuring the animal, and that vessels of all sizes pose a threat to seriously injure or kill whales. The analysis for large vessels reveals that the speed limits commonly under discussion in the research and management communities (i.e., 10 knots) will provide only small reductions in the probability of lethal ship strikes (Kelley et al., 2020). Very large vessels have a high fatality rate at all operating speeds (Garrison et al., 2025). Most Collision Risk Hotspots Have Not Implemented Risk Mitigation Measures (Wang et al., 2025).

This article aims to advance the calculation of the probability of collision with cetaceans for merchant ships categorized as ships in Conditional Navigation.

As an alternative to certain current trends that advocate for the generic application of speed reduction as a solution to collisions with cetaceans—a solution suitable for free navigation—This article aims to add to current scientific knowledge the geometric probability based on the possible collision area between ships and cetaceans, applying nautical principles of kinematics. This document adds a new perspective to consider when managing areas particularly sensitive to the presence of cetaceans. These are areas where the probability of collision decreases as the service speeds of certain types of vessels increase. Furthermore, it proposes a method for calculating a vulnerability index for these areas. This index can be useful in assessing the appropriateness of implementing measures such as speed reduction or the establishment of traffic separation schemes or determining their optimal location.

1.1. Definitions.

Free Navigation: Navigation undertaken by ships and vessels whose speed and/or course vary in a non-predetermined, random manner, or at the request of interests other than those related to efficient navigation planning. This includes boat tours, ships and vessels engaged in military operations or participating in research, recreational, or sailing activities.

Conditional Navigation: Navigation conducted on predefined routes to a destination and at service speeds in accordance with the design of the propulsion and maneuvering elements, to comply with construction specifications, maneuverability (OMI, 2002), environmental emission standards, and safety margins necessary for safe navigation. Fatality in the event of a collision is assumed at all service speeds of these vessels, as previously mentioned (Garrison et al., 2025).

Merchant ships are designed to comply with classification society requirements, the statutory requirements of the flag state, and IMO requirements when engaged in international voyages. These specifications include maneuverability requirements related to the ship's length, regardless of its design speed. Specifically, the advance should not exceed 4.5 ship lengths, and the tactical diameter should not exceed 5 ship lengths in the turning circle maneuver. Similarly, the initial turning ability after turning the rudder 10° to port/starboard dictates that the ship should not have travelled more than 2.5 ship lengths before the course changes by 10° from the original heading. In other words, the maneuverability required to avoid a collision is related to the length at the design speed of each vessel.

2. Objectives.

The objective of this study is to analyze the geometric probability of the collision area with cetaceans, relating to the maximum cruising speed of the cetaceans to be protected, the speed of vessels under conditioned navigation, and the areas where both are present. In other words, it analyzes the probability of collision for vessels navigating at constant design speeds and on predetermined courses as they pass through areas of cetacean concentration with which they may collide.

While the geometric probability component is not expected to be the only element to consider when deciding on management measures within a sensitive area due to the presence of protected cetaceans, it is understood to be necessary to analyze the high magnitude of these values to compare it with other factors to consider.

Furthermore, this study includes a quick and simple calculation of the Angular Sector understood as the probable collision sector with cetaceans within the ship's surveillance area, and a calculation of the Maximum Collision Increase Factor understood as the increase in the probability of collision with cetaceans considering only the normal speed of the vessel and the reduced speed; both could be incorporated into training standards for captains and officers (Rodríguez Covián et al., 2025) and could aid in optimizing automatic cetacean detection systems. Finally, a vulnerability index for the protected area is included, which could help compare management alternatives of the cetacean area or Particularly Sensitive Sea Area (PSSA).

3. Methodology.

To incorporate the geometric probability of the area with cetaceans on a possible collision course- geometric probability of collision P(C) -on board ships with conditional navigation we will consider the following terms.

Total sample area: It will be the largest area of space with the possibility of collision with cetaceans determined by either the possibility that any cetacean may collide with a vessel traveling a certain distance on a course at reduced speed, in application of naval kinematics, or the entire area protected by the presence of cetaceans.

Favorable event: This is the area within the total sample space, in which a ship has the possibility of colliding with a cetacean in application of the rules of naval kinematics.

Ship Conditions: as the vessel is in conditioned navigation, speed and course remain constant.

Conditions of cetaceans as potential collision targets: Speed is considered to be the maximum cruising speed of protected cetaceans (Sc), although they may alter their course, stop, or reduce this speed for feeding or other reasons (Tort et al., 2017). These changes in course and speed do not alter the result, since the maximum area of possible collision is calculated, which may include cetaceans that could surface.

Therefore, the geometric probability of collision P(C), would be expressed according to the following equation (1):

$$P(C) = \frac{Favorable\ Event}{total\ sample\ area} = \frac{Probable\ \ Collision\ Area}{Max.\ \ probable\ Area} \quad (1)$$

In addition, key concepts of naval kinematics must be taken into consideration, even though ships must maintain effective surveillance in accordance with (International Maritime Organization, 1972) COLREG, rule 5, depending on their relative speed to the target with which they may collide, there will be angular sectors of greater probability of collision, up to 360º of the entire horizon, where these possible targets are found with different speeds and changing directions.

3.1. Angular Sector.

To explain the significant differences in the angular sector where a collision can occur—that is, the angle that contains the area of the favorable event—three possible scenarios are analyzed: Sv>Sc; Sv=Sc; Sv<Sc, where Sv refers to the speed of the vessel and Sc refers to the speed of the cetacean. The number of cetaceans affected depend on the duration of these situations. In other words, it depends on the area affected, as it is shown below.

The probable arc to port and starboard is determined using the Angular Sector equation (2). The sector will be tangent to the maximum circle of possible collisions generated by the cetacean's speed.

$$Angular\ Sector\ \ (C^{o}) = 2\ arcosen\left(\frac{Sc}{Sv}\right) \quad (2)$$

Once the highest cruising speed of the cetaceans has been determined, this equation provides the officer on watch with the probable angle of collision or cone of concern.

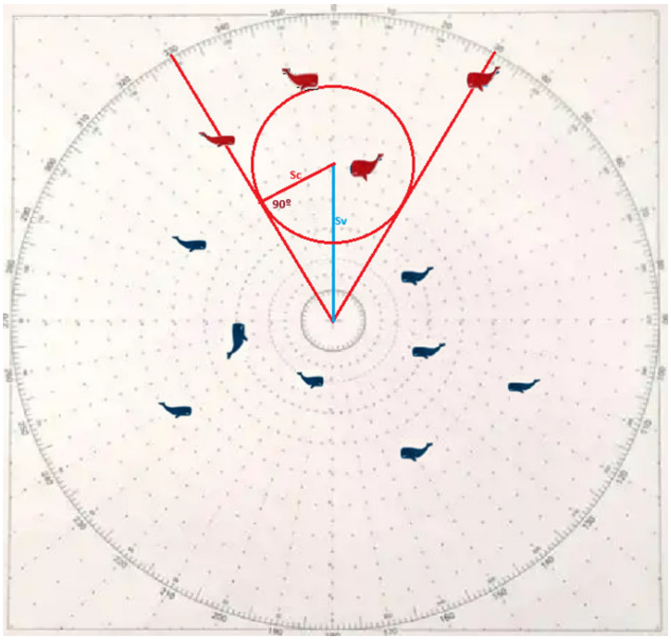
a.- ***Sv>Sc.*** Fig.1 shows the angular sector where the ship's speed is greater than the highest cruising speed of the protected cetaceans. e.g. Sc=2Sv.

$$Angular\ Sector\,(C^{o}) = 2\ arcosen\left(\frac{1}{2}\right) = 60^{o} = 30^{o}Pr\&30^{o}St$$

b.- ***Sv=Sc.*** As can be seen in Fig. 2, when both speeds are equal the surveillance sector is established in an arc of 90º to port and starboard, mathematically 180º tangent to all the possible collision scenarios, although in practice the angle is somewhat smaller**.**

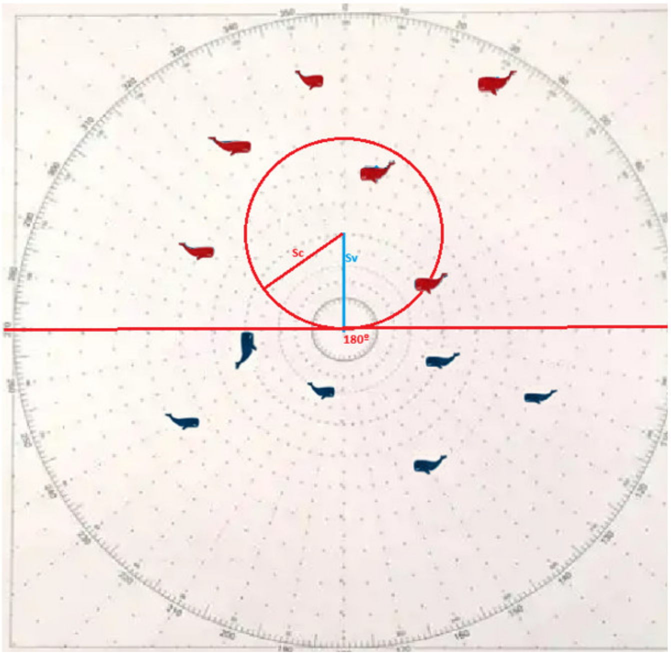
$$Angular\ Sector\ \ (C^{o}) = 2\ arcosen\,(1) = 180^{o}$$

Figure 1: Angular sector when *Sv=2Sc*.



Source: Authors.

Figure 2: Angular sector when *Sv=Sc*.

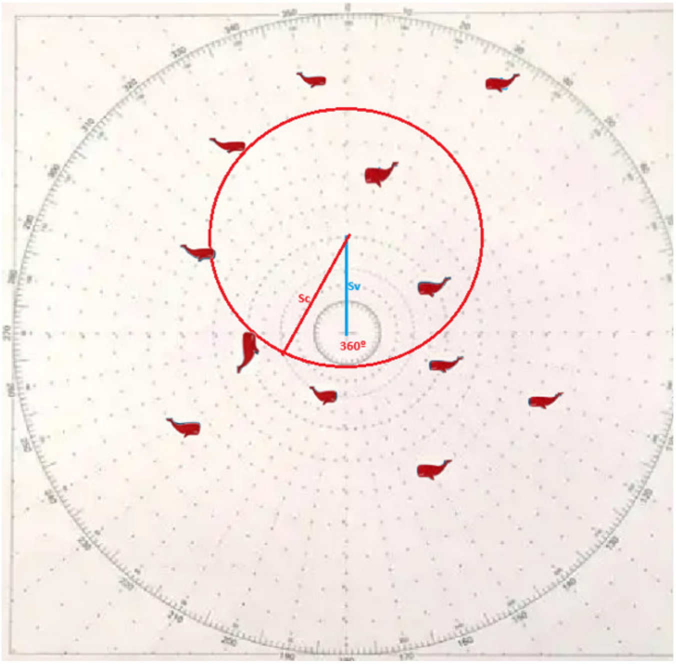


Source: Authors.

c.- ***Sv<Sc.*** As shown in Fig. 3, the maximum circumference describing the most likely points of possible collision is all around the vessel, so tangency of the sector will never occur. The equation used produces an error because the speed ratio is greater than 1. Clearly, the Angular Sector (Cº) is equal to 360º, provided that Sv < Sc. That is, a collision would be probable at any point around the vessel, since the cetacean can reach the vessel even when it is abaft of the vessel's beam.

$$Angular\ Sector\ (C^{o}) = 360^{o}$$

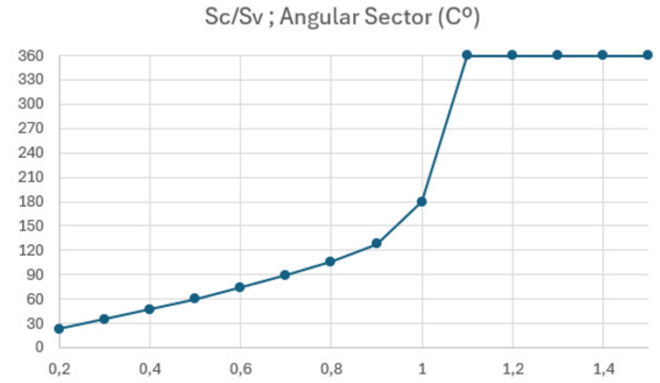
Figure 3: Angular sector when Sv<Sc.



Source: Authors.

In addition, Fig. 4 shows the relationship between Sc/Sv ratio and angular sector. It can be observed that the angular sector increases with increasing of Sc/Sv ratio, and therefore so does the probability of collision.

Figure 4: Relationship between speeds ratio and angular sector.



Source: Authors.

It can be concluded that the probable angle at which a favorable event leading to a collision between a vessel under conditioned navigation and a cetacean may occur, increases linearly as the vessel's speed decreases until the ratio between the two speeds approaches 0.7 or 0.8. From this point, it increases exponentially until the vessel's speed is less than the cetacean's speed, at which point the angle reaches its maximum of 360°. The probable angle represents the arc in degrees at which surveillance should be increased. As the vessel's speed decreases, the surveillance sector should be further expanded.

3.2. Calculation of the probable collision area.

Once the probable collision angles have been studied, calculated considering the speed relationship between the targets and the vessel, the calculation of the probable collision area or favorable event is presented, applying the time factor to the speed.

When calculating the probable area, three speed scenarios are again taken into consideration: Sv > Sc, Sv = Sc and Sv < Sc. For this study, it is considered that a ship takes a certain time at a speed Sv to travel a distance from point A to point B, called reference distance. During this time, cetaceans swim at a speed Sc. Graphically, the ship is located at the center, and the reference distance is equal to the ship's speed multiplied by the time it takes to travel that distance. At the end of the distance to be traveled, the center of a circle whose radius is equal to the cetacean's speed multiplied by the time it takes the ship to travel the reference distance is located. This draws the maximum circle from which the vessel can find a cetacean with which to collide, if the ship maintains that cruising speed on a collision course. This occurs on the perimeter of that circle or on the perimeter of the angular sector and arc formed by tangent to the drawn circle. In addition, within this perimeter, collisions may occur with cetaceans that change their cruising speed or course, or those that emerge within this area while crossing the reference distance.

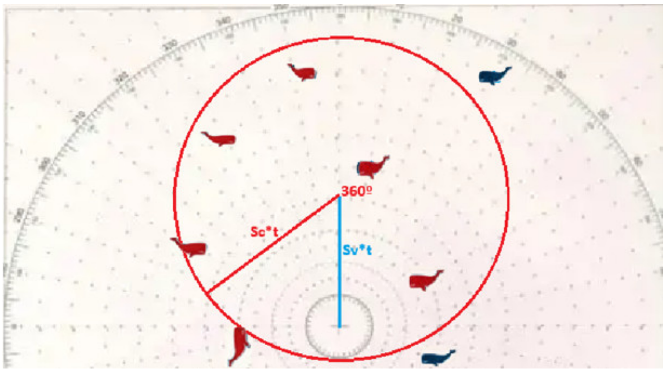
In the scenarios where *Sv=Sc and Sv<Sc* the probable collision area and the probable collision area as a function of time are calculated as follows in the equation (3):

$$Probable\ area\ of\ collision = \pi(Sc)^2$$

$$Probable\ area\ of\ collision\ (t) = \pi(tSc)^2 \qquad (3)$$

The result is shown in Fig. 5.

Figure 5: Geometric area of possible collision determined by the space as a function of *t*, where Sv≤Sc.

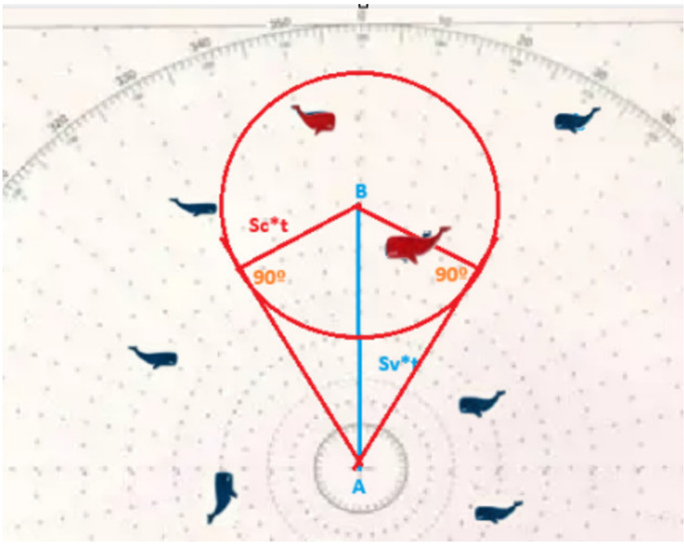


Source: Authors.

On the other hand, in the case that Sv>Sc the area equation would be solved by calculating the area of the circle plus the area formed from the ship to the tangents, which is equal to the area of the triangles formed by points A,B and the points of tangency, minus the area of the circular sector. The result is shown in Fig (6) and in equation 4.

$$\text{Area}_{P\,r(t)} = \pi(t\,sc)^2 + \left(t\,sc^2\sqrt{(t\,sv)^2 - (t\,sc)^2} - \frac{\pi(t\,sc)^2\left(2\,\text{arccos}\left(\frac{sc}{sv}\right)\right)}{360}\right) \quad (4)$$

Figure 6: Geometric area of possible collision determined by the space as a function of t, where Sv>Sc.

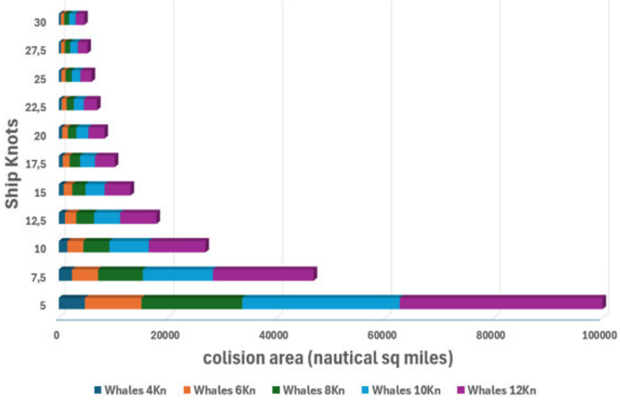


Source: Authors.

3.3. *Calculation of the Probable Area when traveling the reference distance.*

Fig. 7 shows the relationship between the decrease in vessel speed and the increase in probable area of collision, considering different cruising speeds of marine mammals at risk (Sc = [4-12] kn), compared to vessels at different speeds in 2.5 knot increments (Sv = [5-30] kn), with a reference distance of 25 nautical miles. It is observed that this area increases exponentially as speed decreases.

Figure 7: Exponential increase in the probable area of collision as vessel speed decreases.



Source: Authors.

3.4. *Calculation of P(C) being the total sample space determined by the sensitive sea area by the presence of cetaceans.*

Once the probable area of collision by traveling the reference distance has been calculated, the geometric probability of collision of each vessel referred to the sensitive sea area that it is going to navigate can be calculated. The results are shown in equations (5) and (6).

a.- ***Sv ≤ Sc***

$$P\,(C) = \frac{\pi\,(tS\,c)^2}{total\ protected\ area} \quad (5)$$

b.- ***Sv > Sc***

$$P\,(C) = \frac{?(tS\,c)^2 + \left(tS\,c\sqrt[2]{(tS\,v)^2 - (tS\,c)^2} - \frac{?(tS\,c)^2\left(2\cdot arcos\,\frac{S\,c}{S\,v}\right)}{360}\right)}{total\ protected\ area} \quad (6)$$

3.5. *Calculation of the Vulnerability Index of the Sensitive Sea Area.*

If we obtain the average speed and number of vessels crossing a Particularly Sensitive Sea Area (PSSA), a vulnerability index (Iv) for this area can be calculated.

This index could be related to cetaceans injured by large vessels, to cetacean sighting or to the cetacean population in the PSSA. Furthermore, calculating this index would help to manage the area by evaluating different alternatives based on it.

$$Iv = \frac{\left(Area\ v_{med}\cdot\frac{Vessel}{hour,day\ or\ year}\right)}{total\ area} \quad (7)$$

3.6. *Calculation of P(C) in the Sample Area Determined by a Reduced Speed. P(ΔSv).*

P(C) can be calculated considering that the total sample area is equal to the probability area when traveling the reference distance at a speed lower than the ship's usual service speed. For this calculation Svmin is the decreased speed and t' the time needed to travel the reference distance at this speed. Three different scenarios are taken into consideration: Sv and Svmin are lower than Sc; Svmin is lower than Sc but Sc is lower than Sv; and that Svmin and Sv are greater than Sc. Equations (8), (9), and (10) are a combination of equations (3) and (4).

*a.- **Svmin ≤ Sv < Sc***

$$P(\Delta S\,v) = \frac{\pi\,(tS\,c)^2}{\pi\,(t'S\,c)^2} \quad (8)$$

*b.- **Svmin ≤ Sc < Sv***

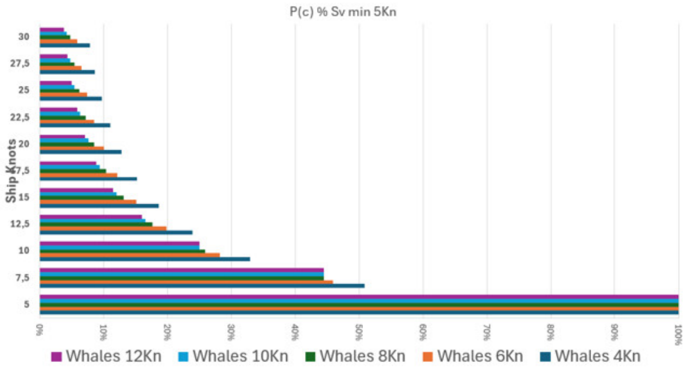
$$P(\Delta S\,v) = \frac{\pi(tS\,c)^2 + tS\,c\sqrt[2]{(tS\,v)^2 - (tS\,c)^2} - \frac{\pi(tS\,c)^2\left(2\cdot arcos\,\frac{S\,c}{S\,v}\right)}{360}}{\pi\ \ (t'S\,c)^2} \quad (9)$$

c.- **Sc < Svmin < Sv**

$$P(\Delta S\,v) = \frac{\pi(tS\,c)^2 + tS\,c\sqrt[2]{(tS\,v)^2 - (tS\,c)^2} - \frac{\pi(tS\,c)^2\left(2\cdot arcos\,\frac{S\,c}{S\,v}\right)}{360}}{\pi(t'S\,c)^2 + t'S\,c\sqrt[2]{(t'S\,vmin)^2 - (t'S\,c)^2} - \frac{\pi(t'S\,c)^2\left(2\bullet arcos\,\frac{S\,c}{S\,vmin}\right)}{360}} \quad (10)$$

Fig. 8 shows the probability of collision once the vessel has reduced its speed from 30 to 5 knots in the presence of cetaceans with traveling speeds ranging from 4 to 12 knots.

Figure 8: Comparison of the probability of collision with cetaceans at different speeds by reducing the ship speed from 30 to 5 knots..



Source: Authors.

3.7. Maximum Collision Increase Factor.

Fig. 8 shows a semi-parabolic trend in probability across all cases. The greatest increase in probability occurs when Svmin ≤ Sv < Sc, equation (8). Therefore, the equation can be developed to find the probability without knowing the speed of the cetaceans or the reference distance, taking into account only the change in speed. As shown in equation (11).

$$P(\Delta Sv) = \frac{\pi\,(tSc)^2}{\pi\,(t'Sc)^2} = \frac{t^2}{t'^2} = \frac{\left(\frac{AB}{Sv}\right)^2}{\left(\frac{AB}{Svmin}\right)^2} = \left(\frac{Svmin}{Sv}\right)^2 \qquad (11)$$

In other words, the geometric probability of a collision when reducing speed will be multiplied by at least a factor equal to the square of the ratio of the reduced speed to the current speed. This is called the Maximum Collision Increase Factor, F(ΔSv). See equation (12).

The maximum collision increase factor should be taken into consideration by the officer on watch and automatic cetacean detection systems when slowing down, easily calculating the maximum increase in collision probability when reducing speed.

$$F(\Delta Sv) = \left(\frac{Sv}{Svmin}\right)^2 \geq \frac{1}{P(\Delta Sv)} \qquad (12)$$

Thus, if it is assumed that a ship at 15kn must reduce its speed to travel a reference distance in a protected area where the speed is set at 10kn, the increase factor is calculated as follows:

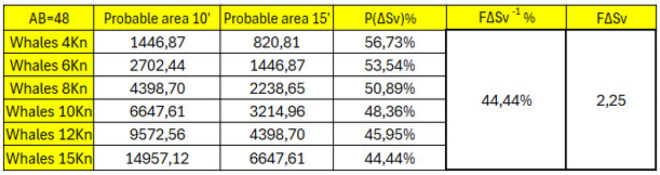
$$F(\Delta sv) = \left(\frac{10}{15}\right)^2 = 2{,}25 \qquad (13)$$

This means that the vessel's geometric probability of colliding with a cetacean increase by 2.25 times when it reduces its speed from 15 to 10 knots, regardless of the reference distance and the ratio of its speed to that of the cetacean. F(ΔSv) is the most conservative calculation in the most unfavorable situation.

Fig. 9 provides a comparative table between the exact calculation of P(ΔSv) of a ship at 15kn within certain total sample areas determined when traveling a reference distance of 48 nautical miles at a speed of 10 knots in the presence of cetaceans at different speeds, where P(ΔSv) and F(ΔSv) are set at the same figure when the speed of the cetacean is greater than that of the ship, a probability that match with the ratio of the speeds squared, that is, with the inverse of the maximum collision increase factor.

Figure 9.

Figure 9: Comparison between the exact calculation and the maximum collision increase factor.



AB=48	Probable area 10'	Probable area 15'	P(ΔSv)%	FΔSv $^{-1}$ %	FΔSv
Whales 4Kn	1446,87	820,81	56,73%	44,44%	2,25
Whales 6Kn	2702,44	1446,87	53,54%		
Whales 8Kn	4398,70	2238,65	50,89%		
Whales 10Kn	6647,61	3214,96	48,36%		
Whales 12Kn	9572,56	4398,70	45,95%		
Whales 15Kn	14957,12	6647,61	44,44%		

Source: Authors.

3.8. Limitations of Application of P(ΔSv) and P(c).

It should be noted that P(ΔSv) and P(C) are based on the calculation of surfaces related to naval kinematics for vessels under conditioned navigation, representing the probable collision area with surfaces shaped like water droplets or circles. However, it is important to remember that when a vessel approaches the coast, these surfaces are intersected by the coastline, whether due to navigating through narrow channels, entering port, rounding headlands, and areas near to shore, glaciers, or icebergs. Therefore, the mathematical formulation must be geo-processed in a Geographic Information System for the correct calculation of the areas. Due to the reduction in area, it is possible that a reduction in speed in certain cases will not result in significant differences in the probability of collision, allowing other factors that prevent collisions, such as the reaction time between sighting and maneuvering, to become more relevant. For this reason, a detailed study must be carried out for each case, establishing maximum speeds according to those distances to shore, based on the geometric probability based on kinematics and other factors that are relevant in each case.

3.9. Practical Implementation.

The protection measures for Particularly Sensitive Sea Areas (International Maritime Organization, 2005) allow for the designation of special areas under MARPOL 73/78; adoption of ships' routeing and reporting systems, separation zones in an area contiguous to the specific location, or core zone, that is to be protected from maritime traffic, provided their necessity is justified; and the development and adoption of other measures intended to protect certain marine areas against environmental damage caused by ships, provided they have a specific legal basis, such as speed reduction. To understand the practical usefulness of the vulnerability index (IV), a case study is presented on the implementation of management measures in the archipelagic sensitive sea area (PSSA). The management measures considered are speed reduction and the creation of a traffic separation scheme (TSS) within and outside the sensitive area.

a.- *Vulnerability index when speed is reduced.*

If a vessel crosses the 32400 square nautical mile PSSA, traveling a reference distance of 46 nautical miles at a speed of 15kn (Sv), and a Sc of 10kn is established considering that the highest cruising speed for protected cetaceans is that of the sperm whale at about 9kn, the calculation of the angular sector, probable area of collision and geometric probability of collision applying previous equations is as follows:

$$\text{Angular Sector } (C^{\circ}15) = 2 \cdot \arccos\left(\frac{10}{15}\right) = 84^{\circ}$$

$$\text{Area } Pr(15; 3h) = 3214{,}96 \text{ mil}^2$$

$$P(C\,15'; 3h) = \frac{3214{,}96}{32400} = 0{,}1318 = 9{,}92\%$$

The probable angle of collision ranges from 42° to starboard to 42° to port side. It will take 3 hours and 4 minutes to cross the PSSA; and the geometric probability of collision of the vessel referred to the protected area to be crossed is 9,92%.

Let's assume that the same ship reduces its speed Sv to 10,0 Kn, due to the possible presence of cetaceans. The new angular sector is bigger than the previous one:

$$\text{Angular Sector } (C\,10') = 2 \cdot \arccos\left(\frac{10}{10}\right) = 180^{\circ}$$

$$\text{Area } Pr(10'; 4{,}6h) = 6647{,}61 \text{ mil}^2$$

$$P(C\,10'; 4{,}6h) = \frac{6647{,}61}{32400} = 20{,}52\%$$

The probable angle of collision ranges from 90º to starboard to 90º to port. It will take 4,6 hours to cross; and the geometric probability of collision of the vessel referred to the protected area to be crossed is 20,52%.

The officer on watch can calculate the maximum increase in collision probability without needing any data on the PSSA or speed of the cetaceans applying equation (12) as follows:

$$F(\Delta sv) = \left(\frac{sv}{sv_{\min}}\right)^2 = \left(\frac{15}{10}\right)^2 = 2{,}25$$

The maximum increase in the probability of collision is 2.25. The ratio between probabilities is less than or equal to the maximum collision increase factor.

$$\frac{P(C\,10'; 4{,}6h)}{P(C\,15'; 3h)} = \frac{20{,}25}{9{,}92} = 2{,}04 < 2{,}25 = F(\Delta sv)$$

On the other hand, if we assume that the average annual speed of vessels freely navigating the PSSA is 15 knots with an average reference distance of 46 miles, and that 4.5 vessels per hour are registered traveling in this area, then 39,420 vessels are navigating within the PSSA per year. The vulnerability index is calculated applying the equation (7) as follows:

$$Iv(ZMES\,15) = \frac{3214{,}96 \cdot 4{,}5}{32400} = 0{,}46$$

When considering restricting the maximum speed to 10kN, the vulnerability index increases.

$$Iv(ZMES\,10) = \frac{6647{,}61 \cdot 4{,}5}{32400} = 0{,}92$$

b.- *Vulnerability index within a TSS in the PSSA.*

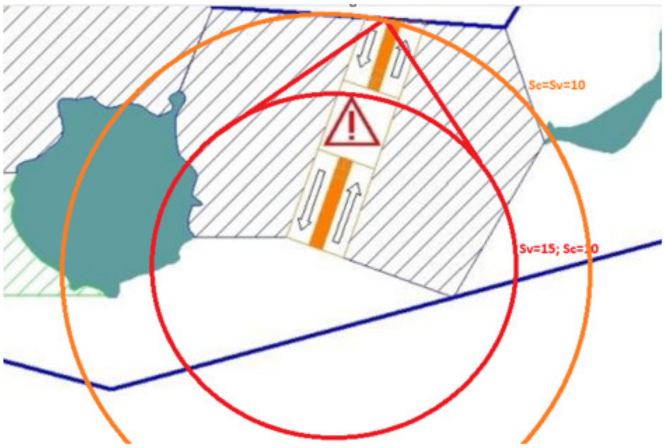
It is decided to establish a traffic separation scheme that will be used by a half of the ships; the rest of the ships are assumed to be coastal vessels or those making a stopover within the PSSA.

Regardless of the speed at which vessels transit the TSS, due to the high frequency of vessels (more than one per hour), the probable collision area occupied by vessels within the TTS, as shown in Fig. 10, is excluded from the total surface area of the PSSA, for the purpose of calculating the vulnerability index. This increases the vulnerability index. The land area is not considered to make the calculations more dynamic.

$$Iv(ZMES - DST10) = \frac{6647{,}61 \cdot 4{,}5}{32400 - 6647{,}61} = 1{,}16$$

$$Iv(ZMES - DST15) = \frac{3214{,}96 \cdot 4{,}5}{32400 - 3214{,}96} = 0{,}49$$

Figure 10: Representation of the probable collision sector within a single vessel at 10 and 15 knots in a TSS.



Source: Authors.

c.- *Vulnerability index within PSSA with an outside TSS.*

It is decided to move the TSS outside the PSSA, thus reducing the number of ships within the total sensitive area, without any probable area remaining within the PSSA. The new vulnerability index is as follows.

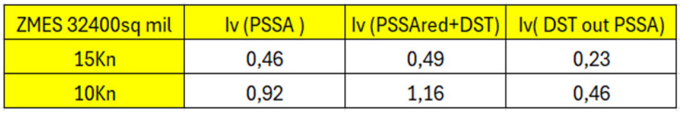
$$Iv\left(ZMES\ 10; \frac{V}{2}\right) = \frac{6647{,}61 \cdot 2{,}25}{32400} = 0{,}46$$

Finally, the speed restriction in the PSSA is removed resulting in a notable reduction in the vulnerability index.

$$Iv\left(ZMES\,15;\frac{1}{2}\right)=\frac{3214{,}96\cdot 2{,}25}{32400}=0{,}23$$

The results of the vulnerability index calculation for the different measures to be implemented in the PSSA are shown in Fig. 11.

Figure 11: Summary table of the vulnerability index based on possible measures of speed change, a TTS, inside or outside a PSSA.



ZMES 32400sq mil	Iv (PSSA)	Iv (PSSAred+DST)	Iv(DST out PSSA)
15Kn	0,46	0,49	0,23
10Kn	0,92	1,16	0,46

Source: Authors.

In the case presented, the probability of collision increases with lower speeds, and the vulnerability index can rise when the measures implemented are not aligned with cetacean protection. Based on the calculated vulnerability indexes, the decision to locate the TSS outside the PSSA would improve the probability of collision between vessels engaged in conditioned navigation and cetaceans, without implementing any speed restriction measures.

4. Discussion.

The hypothesis that ships in conditioned navigation with higher design speeds have a lower probability of collisions leads to the analysis of some studies that recommend speed reduction as a solution to collisions.

Most of these studies are based on the database that relates ship speed to collisions, which was made up of about 50 elements in the first decade of this century (Laist et al. 2001; Vanderlaan & Taggart, 2007), doubling these figures in 2019 (Winker, 2020). Currently, access to the IWC Ship Strike Database is restricted. Given the scarcity of data, studies that do not differentiate between free and conditional navigation could be applicable only to free navigation, since vessels in free navigation exhibit periods of operation similar to those in restricted navigation, but not vice versa. Therefore, results not specifically referring to conditioned navigation cannot be applied to this type of navigation, thus excluding data related to whale watching vessels, recreational vessels, boat tours, fishing vessels, pilot boats, and other vessels clearly engaged in free navigation.

4.1. *Relationship Between Speed and Lethality.*

It is understood that lethality is assured for cetaceans in the event of a collision with vessels engaged in conditional navigation, taking into account the definition provided for this type of navigation and due to the energy of these vessels in such an event, as well as the widespread use of propulsion systems such as variable-pitch propellers that allow speed to be reduced at the same propeller revolutions, or due to the lethal shapes of certain vessels. Therefore, studies such as those by (Pace and Silber, 2005) or (Vanderlaan and Taggart 2007) [2], which relate speed to lethality based on the limited number of collisions reports available at the time, would be applicable exclusively to small vessels in free navigation.

4.2. *The Use of Probabilistic Mathematical Models.*

Studies based on mathematical models that calculate the encounters probability have no practical application in conditional navigation because they do not consider naval kinematics applied to ships sailing on pre-established courses at constant speeds, nor do they take into account that increasing the probable geometric area the number of potential targets also increases. Examples of such studies that would not be applicable to conditional navigation include the model of a random whale walk (Gallos & Argyrakis, 2001), the effect of traps presence (vessels) within a 1 km^2 domain (Vanderlaan & Taggart, 2007) and other models that use the encounter rate method, such as the manatee model (Martin et al., 2015). However, these superficially bounded mathematical models are applicable to vessels and craft in free navigation, since changes in course or speed occur within a defined area without the sole intention of crossing it, as in whale-watching, recreational, and fishing vessels.

It is worth noting that The Whale Model (Martin et al., 2015), which does consider crossing a distance on a fixed course and at two fixed speeds, limits the study area to approximately 220 square nautical miles and includes only one whale at low speed in this area; Therefore, the results do not align with those presented in this article, perhaps due to the small modeling area, the non-inclusion of more whales in the model and the failure to consider that ships in conditioned navigation can continue sailing and collide with more than one whale.

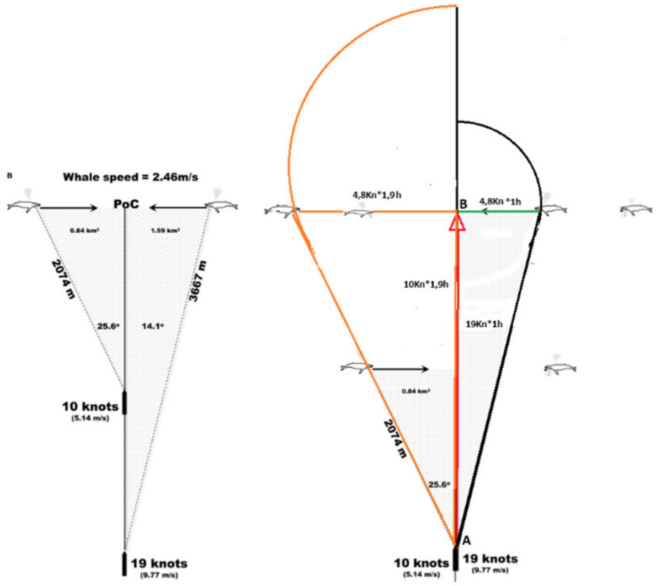
4.3. *Kinematics and the Distance Travelled During the Response Time.*

On the other hand, a study that partially considers the kinematics and speed of large vessels is the one published by (Gende et al., 2019). This article demonstrates how, “in certain scenarios,” slower vessels may have greater opportunities to avoid whales, both through manoeuvring and detection. It indicates that faster vessels, by definition, cover greater distances than slower ones over a given period. Relating the evasive manoeuvre to the time to collision, and therefore assuming that slower vessels would have more time, the study does not consider international standards for vessel manoeuvring, which determine the appropriate manoeuvring equipment in relation to the vessel’s length and not to its speed or time (IMO 2002). When deciding on generic measures affecting vessel speed, it seems more reasonable to take decisions based on minimum international standards that apply to most of the fleet rather than on specific scenarios. The IMO has been concerned about the safety consequences of poor ship manoeuvrability since the 1968 meeting of the Ship Design and Equipment Subcommittee. Circular MSC/Circ.389, entitled ”Interim Guidelines for Assessing Ship Manoeuvrability During the Design Phase,” dated 10 January

1985, encouraged the integration of manoeuvrability requirements into the ship design process through the systematic collection and evaluation of information on ship manoeuvrability. Subsequently, in 1987, resolution A.601(15), entitled "Provision and Display in Visible Places on Board Ships of Manoeuvrability Information," was adopted. In November 1993, the IMO approved the Provisional Standards on Ship Manoeuvrability, through resolution A.751(18) and circular MSC/Circ.644, entitled "Explanatory Notes to the Provisional Standards on Ship Manoeuvrability", dated 6 June 1994. This process culminated during the 76th session of the Maritime Safety Committee, held in December 2002, through resolution MSC 137(76), where the "Standards on Ship Manoeuvrability" were adopted.

The same scenario analysed from the perspective described here is proposed to show in Fig. 12 the difference in probable collision area and its increase at lower speeds, being F∆Sv=3.61.

Figure 12: Comparison of sighting distances and collision probability with cetaceans located symmetrically to a vessel at 10 and 19 knots.



Source: Authors.

Therefore, lower speeds do not significantly improve course change time; rather, it depends on several factors. More distance is covered at higher speeds during the command process, but this gain is not comparable to the increase in probable collision area that would be obtained by reducing speed. In open water, navigating at lower speeds than projected ones increase the likelihood of collision, as shown in Fig. 12.

4.4. *Multiple Factor Analysis.*

Finally, due to the stagnation of measures in the United States because of the more than 90,000 public comments on the proposed 10-knot speed reduction rule(National Oceanic and Atmospheric Administration, 2025), with the intention of providing a perspective consistent with the geometric probability of naval kinematics, the speed reduction rule 50 CFR 224.105 (NOAA NMFS, 2026) is analysed, through the article "Modelling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary, USA" (Wiley et al., 2011). In this article, comprehensive AIS data of ship traffic in the 2181 km^2 Stellwagen Bank National Marine Sanctuary (SBNMS), were collected in 2006 to create 1.85 km^2 cells (N = 810) covering the SBNMS. The predicted probability of lethal collisions (PLETH) of each cell was then determined from the cell's average speed and a mortality curve. It applies speed limits of 16, 14, 12, and 10 knots to transits and recalculates the speed of PLETH for each scenario, classifying ships into five categories: cargo/container, tanker, tug, service/research, passenger, and fishing. For each category, it calculates the number of ships, number of transits, total percentage (ships and transits), and, applying a speed-related lethality probability curve of 42 vessels (Pace and Silber, 2005), calculates the probability of a fatal collision.

Figure 13: Modelling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary.

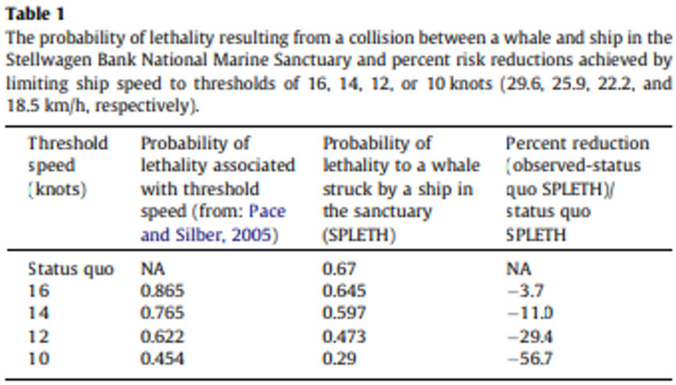


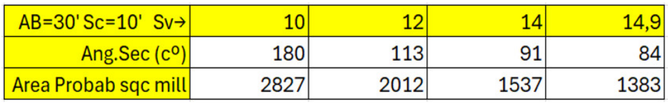
Table 1
The probability of lethality resulting from a collision between a whale and ship in the Stellwagen Bank National Marine Sanctuary and percent risk reductions achieved by limiting ship speed to thresholds of 16, 14, 12, or 10 knots (29.6, 25.9, 22.2, and 18.5 km/h, respectively).

Threshold speed (knots)	Probability of lethality associated with threshold speed (from: Pace and Silber, 2005)	Probability of lethality to a whale struck by a ship in the sanctuary (SPLETH)	Percent reduction (observed-status quo SPLETH)/ status quo SPLETH
Status quo	NA	0.67	NA
16	0.865	0.645	−3.7
14	0.765	0.597	−11.0
12	0.622	0.473	−29.4
10	0.454	0.29	−56.7

Source: Wiley, Thompson, Pace and Levenson (2011), Biological Conservation, 144(9), 2377-2381.

To include P(C) within this multifactorial analysis and referring to the collision itself rather than the lethality, a geometric probability analysis only for vessels in conditional navigation within the final part of the TSS is performed: Cargo/container 16.2 Kn; Passenger 14.4 Kn; and Tanker 14.0 Kn; understanding the rest to be in free navigation. Therefore, the average speed Sv = 14.90 Kn and the reference distance 30 miles.

Figure 14: Comparative table of the Angular sector and probable areas at average speed and proposed speeds.

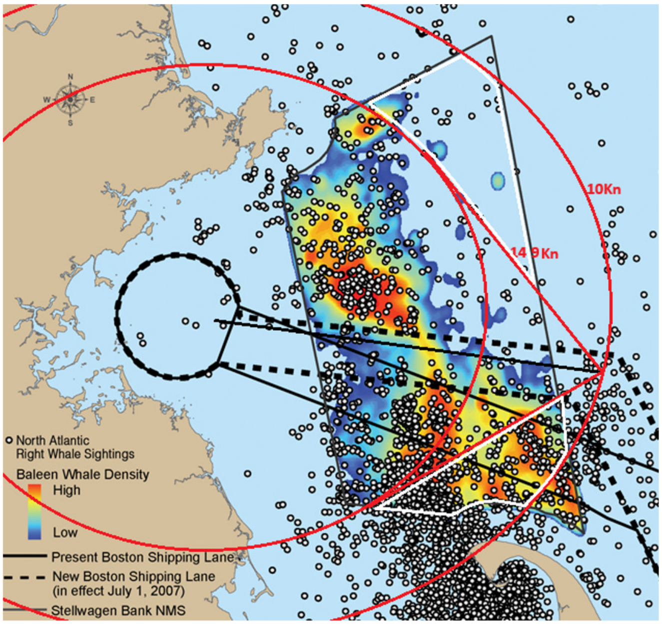


AB=30' Sc=10' Sv→	10	12	14	14,9
Ang.Sec (cº)	180	113	91	84
Area Probab sqc mill	2827	2012	1537	1383

Source: Authors.

The areas calculated in Fig. 15 should be corrected using GIS software by removing land areas or zones without cetaceans. Even so, in the example presented here, the values would vary proportionally. Therefore, from a geometric probability standpoint, the calculation's approximation might suggest that it is advisable not to reduce the speed, at least in the first third of the represented route. On the other hand, if the speed restriction of 10 kN is maintained, it would be advisable to expand the sensitive zone.

Figure 15: Approximate geometric probability of collision at 10 knots and 14 knots, based on: Stellwagen Bank National Marine Sanctuary.



Source: National Oceanic and Atmospheric Administration (NOAA).

Conclusions.

The data obtained indicate that, in open waters, the higher the service speed of vessels under conditioned navigation relative to the speed of cetaceans, the lower the geometric probability of collision within the area where cetaceans are present, and the smaller the angular sector of collision probability. This sector requires increased surveillance and is where evasive manoeuvres are likely to be necessary.

The longer it takes a vessel under conditioned navigation to cross an area where cetaceans are present at a lower speed, the larger the area where cetaceans with a probability of collision are likely to be encountered.

Calculating vulnerability indexes that take geometric probability into account is essential for evaluating management measures in cetacean-protected areas. The inclusion of the geometric probability index (Iv) is crucial in multifactorial management analyses that include, at a minimum, cetacean and vessel density maps, the possibility of rerouting or TSS, and temporary speed reductions for vessels under conditional navigation when arriving at or departing from ports, narrow channels, or fairways where P(ΔSv) or P(C) does not have a determining value.

The results of any study that does not consider data on vessels under conditioned navigation separately from vessels in free navigation, or that is not based on the fundamental principles of naval kinematics, cannot be extended to vessels under conditional navigation.

It would be advisable to include in the training of captains and skippers quick and intuitive methods for calculating the probability of collision based on vessel speed and the calculation of the probable angular collision sector. Also, both calculations can help optimize automatic cetacean detection equipment.

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