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Reducing whale-ship collisions by better estimating damages to ships

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Abstract
Collisions between ships and whales raise environmental, safety, and economic concerns. The management of whale-ship collisions, however, lacks a holistic approach, unlike the management of other types of wildlife-vehicle collisions, which have been more standardized for several years now. In particular, safety and economic factors are routinely omitted in the assessment of proposed mitigation solutions to ship strikes, possibly leading to under-compliance and a lack of acceptance from the stakeholders. In this study, we estimate the probability of ship damage due to a whale-ship collision. While the probability of damage is low, the costs could be important, suggesting that property damages are significant enough to be taken into consideration when assessing solutions. Lessons learned from other types of wildlife-vehicle collisions suggest that the whale-ship collision should be managed as wildlife-aircraft collisions. For several years, the International Civil Aviation Organization (ICAO) manages collisions between aircrafts and wildlife at the international level. We advocate that its United Nations counterpart, namely the International Maritime Organization (IMO), get more involved in the whale-ship collision management. Further research is needed to more precisely quantify the costs incurred to ships from damages caused by whale-ship collisions.

Keywords: whale-ship collision, damage, cost, FSA, wildlife-vehicle collision, risk assessment

1 Introduction
Collisions between vehicles and wildlife pose significant threats to wildlife conservation, but also to human safety, and economy (Visintin et al., 2018). While less studied than other types of wildlife-vehicle collisions (e.g., car, aircraft, and train), the literature on collisions between commercial ships and whales, also referred to as ship strikes, has increased in the last years. This increased interest is linked to the identification of those collisions as one of the main human-induced threats for whales (IWC-ACCOBAMS, 2012a; Panigada et al., 2006; Thomas et al., 2016). Recent studies have shown that whale-ship collision events occur more frequently than assumed (Frantzis et al., 2019). The ship crew often fails to detect a collision with a whale, as the difference of rigidity between the two objects leads to a low impact force (IMO, 2009a; Silber et al., 2010). Hence, most of the time, collisions go unnoticed (Peltier and Ridoux, 2015). Furthermore, as the reporting of these events is rarely mandatory, even noticed collisions might not be reported (Lammers et al., 2013).
Many solutions to avoid those collisions have been proposed over the last two decades (IMO, 2009b; Silber et al., 2008). Nevertheless, most of the time, the implementation of these solutions faces low compliance from the shipping industry (Chion et al., 2017; Silber and Bettridge, 2012; Wiley et al., 2008). Silber and Bettridge (2012) identified "lack of public recognition of the rule, disregard for it, or inadequate early enforcement" as potential limiting factors to compliance. More recently, literature started to highlight the lack of risk and economic assessments of these solutions

as a drag to decision-makers recommendations, government enforcement or industries willingness to act upon the problem (Ayyub et al., 2007; Kirchler et al., 2008; Silber et al., 2015, 2012; Whitney et al., 2016). As it has been highlighted at the last International Conference on Marine Mammal Protected Areas (ICMMPA 2019), the lack of a holistic vision prevents the implementation of synergies between the environmental and shipping stakeholders; see also Mansouri et al. (2015) and Venus Lun et al. (2015).
Unlike the whale-ship collision case, holistic approaches are implemented for a long time for other types of wildlife-vehicle collisions (Huijser et al., 2009). The evaluation of wildlife, safety, and economic risks has been used for several decades now to target the most efficient solutions to reduce collisions between wildlife and cars (Seiler et al., 2016; VerCauteren et al., 2006), trains (Seiler and Olsson, 2017) or aircrafts (Crain et al., 2015; ICAO, 2012).
In order to promote a similar holistic approach for whale-ship collision management, Sèbe et al. (2019) adopted a framework used by the International Maritime Organization (IMO), namely the Formal Safety Assessment (FSA), to propose a more holistic assessment of costs, benefits, and risks associated with measures to avoid ship strikes. While the probability of collision between whales and ships is addressed in the literature (e.g., Martin et al., 2015; Rockwood, Calambokidis and Jahncke, 2017), the literature on the economic consequences of a collision is rather scant (e.g., Kite-Powell, 2005; Nathan Associates Inc, 2012). In particular, no extensive research has been undertaken, to our knowledge, to assess the ship damages after a collision with a whale. While this probability has been deemed low (Van Waerebeek and Leaper, 2008), good estimates of both the probability and, actually also, of the monetary consequences from the shipper's perspective are needed to inform a robust assessment of the costs and benefits of proposed mitigation measures, as in the case of other wildlife-vehicle collisions (e.g., Conover et al., 1995; Grift, 1999; Allan, 2000).
The objective of our study is to evaluate the added value of integrating the ship damages to whale-ship collision management. To this end, we assess (1) the probability of ship damage due to a collision with a whale, using, among others, the International Whaling Commission (IWC) ship-strike database, and (2) provide a brief overview of the potential costs for shipping companies.

2 Methodology and data

2.1 Data preparation

Since 2007, the IWC collects worldwide ship-strike events information in a public database. The database includes records from 1970 to 2010; data after 2010 is not publicly available. A cross-reference of the IWC database with other databases and scientific publications (e.g., Laist et al., 2001; Jensen and Silber, 2004; Panigada et al., 2006) was performed to check for duplicate entries and gather supplementary information on the recorded events. Note that, events including non-commercial ships were excluded (e.g., sailing ships and small boats). Of the 501 entries in the IWC database and additional information gathered, 250 were selected for this study (1970-2019). Hereafter, the selected events will be referred as the Updated Database (UD).

2.2 Damage and cost information

For our analysis, we gathered information on the ship speed, length, and associated damages for the collision events in the UD. In the case where the ship's speed or length were not available in the original dataset, we used online databases such as MarineTraffic and VesselFinder to extract the ship's particulars. As ship speed during a strike is sometimes not known provided in the UD, and as ship speed for a given type of ship does not change dramatically over time (1970-2010), when needed, we used average operational speeds based on AIS data for similar ships, as presented in IMO (2014). We believe, though that more information on the exact speed during collisions is needed to get better insights. When the damage status was not available, other

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sources of information were checked to recover damage information related to the UD, such as IWC archives, IMO Global Integrated Shipping Information System archives, scientific publications, and journal articles. Besides, the type and the cost of damages were included in the UD.

2.3 Probability and damage costs

Vanderlaan and Taggart (2007) proposed a methodology to define the 'probability of lethal whale injury based on ship speed' when struck. The methodology used the IWC ship strike database to derive the probability of lethal injury and has, since then, been widely used as a basis for risk assessment studies (Martin et al., 2015; Nichol et al., 2017). We, therefore, follow the same reasoning to derive the probability of ship damage as a result of a whale-ship collision, depending on ship length and speed. Only events for which information on ship speed, length, and damages were reported are included in the analysis.

The probability of ship damages subsequent to a collision with a whale as a function of the ship speed or length, and their ratio, was calculated by performing a logistic regression analysis, with bootstrapping, using "R" (R Development Core Team, 2008). A lack of observations limited the needed degrees of freedom and prevented a logistic regression of both the speed and length variable (Peduzzi et al., 1996). As a result, we used the use of the ratio of the variables as a proxy. Note that the logistic regression is the appropriate regression analysis when the dependent variable, in our case, the damage to the ship, is dichotomous (binary). Bootstrapping is a type of resampling where large numbers of smaller samples of the same size are repeatedly drawn, with replacement, from a single original sample – in our analysis, 1,000 iterations were performed (Haman and Avery, 2019; Venables and Ripley, 2002). To illustrate our results, we then compute the probability of damages on four typical ships, which are often involved in collisions (oil tanker, bulk carrier, container and cargo-ferry ships).

3 Results

3.1 Descriptive results

Most of the events in the UD (N=250) do not include any information on ship damages. Only 16.4% of the events describe the damage status (Fig. 1a). Of this 16.4%, 36.6% exhibit proof of damage, whereas the remaining 63.4% attest to the absence of damage to the ship. Most of the events in the UD do not include information on the area where the ship was struck (58.4%; Fig. 1b). Collisions in the front part of the ship seem to be the most frequent type of collision. 82.8% of these events were most likely noticed because the whales were stuck on the bow. Hence, the proportion of frontal impacts may be an overestimation in comparison to non-frontal impacts. Non-frontal impacts include events that occurred on the ship draft, except the bow section (fore draft).

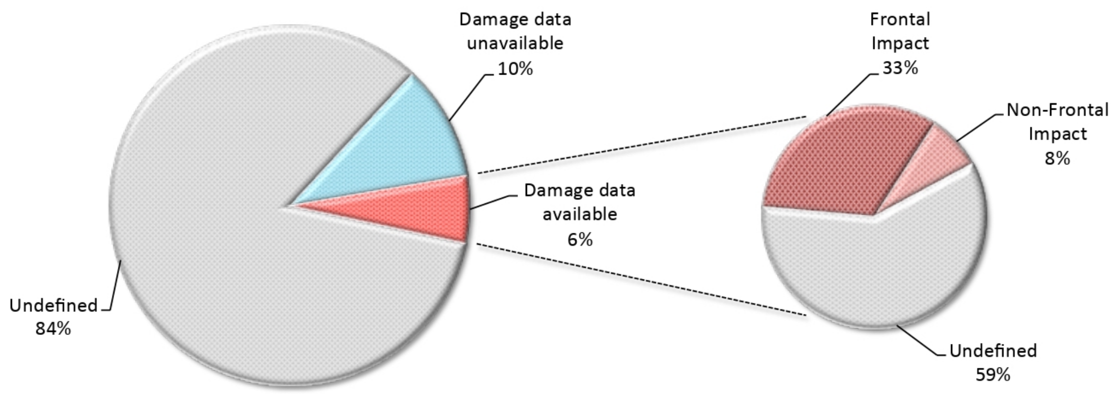

Figure 1: Damage status (left) and area of collisions on ships (right) in the UD in percentages.

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The primary damages identified were done to the following appendixes:

- Bow (hull);
- Hull;
- Propeller blade;
- Propeller shaft;
- Rudder;
- Steering arm;
- Stabilizer;
- T-foil.

There is very limited information regarding the damage costs in the database, as only 3 records include the costs of damages (1.2% of the UD). First, the replacement of a propeller blade was estimated at $125,000 ($US\$_{1991}$). Second, multiple damages to the steering arm and to the hull, which lead to a waterway, of a ship were evaluated at $1,000,000 ($US\$_{1991}$). Finally, several damages on a shipping company fleet between 2004 and 2006 led to an overall cost of $3,500,000 ($US\$_{2006}$). Some events described speed reduction due to whales stuck on the bow, which may have resulted in additional expenses as a result of increased fuel costs due to the increased time at sea, and to the delayed arrival at ports. Note also that, in total, 2 human losses and 194 human injuries (three events are responsible for this total) are reported in the UD.

3.2 Regression results

Based on extensive analysis and cross-references with other sources, we were able to obtain the required information for the regression (i.e., joint information on the ships' speed, length, and the damage status subsequent to a whale-ship collision) for 12.8% of the events in the UD. These events were used in the regression analysis.

We performed three separate regressions: one taking only ship speed into account, another with ship length only, and one with the ratio of speed to length; see Table 1 for the results. As the models are estimated through a maximum likelihood method, the Akaike Information Criterion (AIC) can be used to select the best model; in our case the specification with the ratio of speed/length has the best overall performance (i.e., having the lowest AIC; Figure 2; DeLeeuw, 1992). A large dataset, of course, would allow for the testing of more specifications. Based on the model using speed/length, the probability of ship damage can be calculated as:

$P_{damage} = \frac{1}{1+e^{-(\alpha+\beta\times\chi)}}$, where α, β, and χ (Table 1 and Figure 2).

Table 1: Logistic regression results

Logistic regression	α [CI]	β [CI]	χ	P-value	Adjusted R^2	AIC
With speed only	-4.194 [-7.829; -1.753]	0.176 [0.064; 0.347]	Speed	0.0006	0.409	35.55
With length only	0.728 [-0.461; 2.034]	-0.017[-0.034; -0.004]	Length	0.005	0.286	39.52
With a speed/length proxy	-2.377 [-4.053; -1.097]	3.346 [1.485; 5.935]	Speed/Length	9×10^{-5}	0.505	32.08

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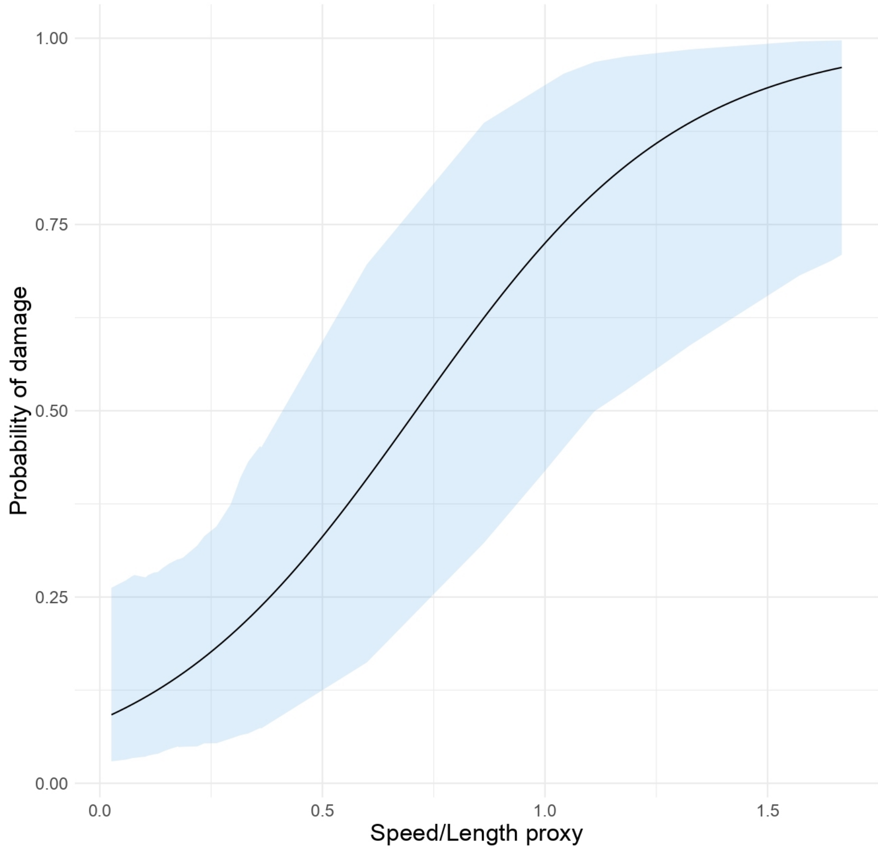

Figure 2: Probability of ship damage depending on a speed/length proxy. The blue area represents the confidence interval.

We illustrate our findings using four "hypothetical" ship types to show the impacts of ship length and speed on the probability of damage. We use the best model (with the speed/length proxy) to calculate the probability of damage for these typical ships (Table 2). Our study focuses on large commercial ships, as these are the ones that inflict most damages to whales (ACCOBAMS-Pelagos, 2005; Ritter and Panigada, 2019). These are also the focus of potential risk and economic assessments of mitigation measures within the International Maritime Organisation (Sèbe et al., 2019).

Table 2: Results of the logistic regression model on the hypothetical ships selected for the study

Ship category	Oil Tanker	Bulk Carrier	Container ship	Cargo-Ferry
IHS StatCode5v	A13	A21	A33	A34
Ship type	Suezmax oil tanker	Panamax bulk carrier	Container ship	Ro-Ro-pax
Capacity	166,300 DWT	63,580 DWT	5,150 DWT	9,710 DWT
Length overall (L_{oa})	281.1 m	199.9 m	147.7 m	165.25 m
Selected speed (MarineTraffic)	13.3 kn	13.7 kn	12 kn	18.5 kn
Speed/Length proxy	0.0473	0.0685	0.0815	0.1120
Probability of damage after a whale-ship collision (P_{damage})	0.0981	0.1046	0.1086	0.1190

The logistic regression model results show that the probability of damage for the typical commercial ships is around 0.10 (Table 2). In other words, after a whale-ship collision, there is 1 out of 10 chance that a commercial ship would exhibit some damages. The Cargo-Ferry (A3) category seems to be the most at risk as some of these ships can achieve very high speeds. For example, high-speed passenger ships exhibit the most damages in the UD, as their Speed/Length proxy is high (e.g., Ryu et al., 2010).

4 Discussion

4.1 Descriptive results

The UD includes a limited amount of data in comparison with other wildlife-vehicle collisions datasets. In contrast, the Federal Aviation Administration (FAA) gathered 99,530 collisions events between 1990 and 2014 (vs. 250 for the UD in 40 years; Dolbeer et al., 2015). Nevertheless, some interesting comparisons can be made. Indeed, the percentage of damage status mentioned in the wildlife-aircraft collision reports is between 16% and 45%, and damage costs are mentioned in 5% of the events (Anderson et al., 2015; Dolbeer, 2011). These percentages are higher – or roughly equal for the lower bound – to the ones presented in the UD (16.4% and 1.2%, respectively). By taking into account that reporting is more standardized for aviation (ICAO, 2017a), we can assume that reporting standardization of whale-ship collisions would lead to an increased percentage of damage information in the UD. Furthermore, while the number of collisions between aircrafts and wildlife is higher than the ones between whales and ships, it is interesting to notice that, in the USA, in 2014, there were 32.52 strikes per 100,000 aircraft movements (Dolbeer et al., 2015). In comparison, from Panigada et al., 2006 and Rendell and Frantzis, 2016, we can account for around more than 50 whale collisions per 140,000 ship movements in the Mediterranean Sea, which is equivalent to 35.71 ship strikes per 100,000 ship movements (gross estimation of ship movements based on AIS data from the ENVIGIS software). Of course, further research needs to be performed, but the order of magnitude expressed in this paper advocates for a similar risk, in terms of probability of occurrence.

4.2 Probability of ship damage

Our study estimates the probability of ship damage as a result of a whale-ship collision by using a logistic regression model in line with Vanderlaan and Taggart (2007). Similarly to their study, the limitation of data, and the non-integration of relevant variables to shipping (e.g., thickness of the hull, material resistance; Zhang, 1999), or whales (e.g., size, direction) results in large confidence intervals. Nevertheless, our results represent the first step towards the integration of ship damages in whale-ship collision risk assessments.

Results show that Cargo-Ferries (A3) ships face the most significant risk for damage, especially passenger ferries and high-speed passenger ships. The literature revealed several events of severe impacts involving these ship categories. These events lead to a sudden loss of speed, damages requiring towage, or human injuries and fatalities (Laist et al., 2001; Ryu et al., 2010). Other ship categories exhibit lower probabilities of damages. Nevertheless, the overall probability of ship damage for large commercial ships seems to be around $P_{damage} \approx 0.10$, although again, we want to stress out that the dataset is very limited. This observation may indicate that some damages may go unnoticed, or are not linked to a ship-strike, even when the ship requires repairs.

By using a logistic regression model, our study allows a straightforward assessment of the risk reduction induced by a particular collision mitigation solution: speed reduction. When implementing speed reduction, one can observe a reduction in the probability of whale lethal injury (Parrott et al., 2016; Vanderlaan and Taggart, 2007; Wiley et al., 2011). Based on our study, the probability of damage can also be estimated to expose the risk reduction in ship damages for this mitigation solution. If a Cargo-Ferry of 165 meters length and navigating at a speed of 18.5kn ($P_{damage} = 0.119$) is asked to reduce its speed to 12kn, it reduces the risk of damage by 11% ($P_{damage} = 0.106$). To be noted that at the same time, the probability of lethal injury to whales is reduced by 45% (from 0.937 to 0.507 based on the model derived by Vanderlaan and Taggart, 2007).

Note that this study assesses the probability of damage but does not deal with the severity of the damages, as there are not sufficient data in the IWC database. The severity depends on several factors, such as the thickness of the hull, the material resistance, or the shape of the bow (Liu et al., 2018; Rio et al., 2017). Some hydrodynamic models were used to study the behavior of these parameters under different scenarios, i.e., ship-ship, ship-container, and ship-floating log collisions, or groundings (Zhang, 1999). Some researchers studied the hydrodynamics of a whale-ship collision, but in order to assess damages to whales (Knowlton et al., 1998, 1995; Silber et al., 2010). To our knowledge, there are no similar studies on ship damages. The undertaking of such studies focusing on the damages to ships after whale-ship collisions would improve our understanding of these events and help improve the management of the risk that ships face as a result of ship strikes. Note that there is a parallel body of literature on dynamic models for wildlife-vehicle collisions (e.g., car and train), which could be applied to whale-ship collisions (Anderson et al., 2015; Visintin et al., 2018).

4.3 Costs of damage

Damage costs to ships can be divided into two categories. One is related to the ship repair cost, which dependents on several factors, such as the extent of the damage, the cost of replacement parts, the place of repair (difference in labor costs and raw materials depending on localization of the repair yard), the docking time required and the workload of the yards (IMO, 2010). The second category is the loss of earnings, as the ship is unable to trade (Stopford, 2009).
Estimating these costs is very challenging as there is a significant variation in costs between ship categories (Stopford, 2009). The costs of damages in the UD are expressed only for 3 records; more observations would obviously result in more accurate assessments of these costs. Nevertheless, the literature allows giving an insight on costs associated with whale-ship collisions. According to the UD, the damages to the hull, and the propeller blades can be extensive. Below, we highlight the estimations of some repair costs related to these damages.

The cost of repair for a breached or warped hull depends on labor costs, the price of steel, and the price of docking. The steel work associated with this repair would require between 60 and 105 man-hours for the hypothetical ships selected in the study (Butler, 2012). The number of docking days associated with these man-hours will depend on the number of workers and the length of shifts. The amount of steel needed would be of between 260 and 470 kg, which would not be expensive as the price of steel is at 711 $/t (worldsteelprices.com, accessed on 09/25/2019). The dry-docking costs for repair differ depending on various factors (Hansen, 2013), but can be estimated at a few thousand dollars per day (Guarin, Konovessis and Vassalos, 2009; IMO, 2010, Piriou company, comm.pers.)

The cost of repair for a damaged propeller blade also depends on labor costs, the price of replacement parts, the price of docking. According to Butler (2012), the work needed to replace the propeller blade can vary between 100 and 240 man-hours for the ships that were studied. The price of parts replacement will depend on various parameters. For instance, the UD described that the replacement of a propeller was estimated at $125,000 ($US\$_{1991}$) for a 126m naval ship. Of course, the replacement cost of a propeller will depend on the size and type of the ship, and the value here given is purely indicative of an example of cost. Similarly to hull work, the dry-docking costs can be estimated at a few thousand dollars per day (Guarin, Konovessis and Vassalos, 2009; IMO, 2010, Piriou company, comm.pers.)

Revenue losses are determined based on the time during which the ship has been deprived of income (the loss of time) and the loss of income per day (the daily amount). The income of the ships depends on various parameters, including the type of trade and charter (e.g., if the ship is time-chartered or in the spot market), the ship type and commodity carried, amongst others. The income of ships (even for the same ship, carrying the same commodity on the same route) varies substantially, mainly as a result of the supply of the ships and the demand for transport work (Stopford, 2009). For instance, a bulk carrier (e.g. the one presented in Table 2) chartered for 1 year had an average per day revenue of around 10,000 US$ per day in 2017 and 13,029 US$ per day in 2018. On the other hand, a very large oil tanker carrying oil from the Arab Gulf to Japan had an average net profit of around 20,000 US$ in 2018. Every day lost in the shipyard for repairs would therefore have a significant economic impact (Clarksons Research, 2019).

To sum up, repair costs are, in general, lower than the loss of revenue due to a whale-ship collision. Direct costs of damages linked to the repairs may be worth from a few thousand to several hundreds of thousands of dollars depending on the work needed, the docking time, and the replacement of parts. Due to the lack of data on costs in the UD, we want to highlight that this section provided an overview of the potential costs, but did not provide a full assessment of the costs. Indirect costs involve the revenue loss endured by the company during the repair time. These costs might be higher, as it is linked to the freight rate and the type of merchandise (Stopford, 2009). We should stress out that the costs of repairs are most of the time covered by the ship's insurance, while this is not always the case for revenue losses (Stopford, 2009). In any case, insurance is not taken into consideration in the IMO decision-making framework (Sèbe et al., 2019).

4.4 Implication for the whale-ship collision management

The assessment of damages and costs is crucial to managing more efficiently the whale-ship collisions. Lessons can be learned from the management of other wildlife-vehicle cases. While deemed low by the transportation industry, the damages, and their associated costs are often taken into account in balancing the benefits and costs (ICAO, 2009). This accounting helps decision-makers to define fund allocations for existing mitigation solutions, research and development (R&D), or even for fixing penalties (Allan, 2000; Dolbeer et al., 2015; Lienhoop et al., 2015; VerCauteren et al., 2006). The literature highlights several regional, national, or international policies advocating for the accounting of the damages in the management of wildlife-vehicle collisions.

Various collisions management initiatives exist at regional and national levels. For wildlife-car collisions, the costs of damages are often integrated into cost-effectiveness or cost-benefit assessments to define the most efficient mitigation solution depending on the study site characteristics (Gren and Jägerbrand, 2019; Kušta et al., 2015; Mrtka and Borkovcová, 2013; Santos et al., 2018; Seiler et al., 2016). More recently, investigations into wildlife-train collisions have been undertaken to define damages, delays, animal suffering, and driver stress caused by those events (Seiler and Olsson, 2017). The wildlife-aircraft collisions issue was identified early, as its management was motivated by some marking accidents, which lead to human losses (Dolbeer et al., 2015). Since 1988, an FAA National Wildlife Strike Database has been implemented in the U.S. to prevent human loss and aircraft damages (Devault et al., 2009). The assessment of the damages allows both to reduce the costs of mitigation solutions, and to reduce the environmental and human risks associated with collisions (Bissonette et al., 2008; Huijser et al., 2009; Visintin et al., 2018).

Wildlife-aircraft collisions management is the most standardized one at the international level. In 1990, following the national database initiatives, the International Civil Aviation Organization (ICAO), which is the United Nations specialized agency "whose mission is to achieve safe, secure, and sustainable development of civil aviation", started getting involved in the collision issue and helped to standardize the management process (Devault et al., 2009; Dolbeer and Wright, 2009). Among other things, the ICAO maintains a bird-aircraft strike database (the ICAO Bird Strike Information System; IBIS), encourages the reporting of strikes and the damages related with them, and advocates for holistic risk assessments, through guidelines and standardized process, such as the Safety Management System (SMS) (Allan et al., 2002; Devault et al., 2009; Dolbeer and Wright, 2009; ICAO, 2017a, 2017b, 2012). Nowadays, these initiatives allow pro-active management of bird-aircraft collisions, such as better airport site selection, seasonal adaptation of the traffic, anticipated mitigation solutions, or government compensation (Anderson et al., 2015; Devault et al., 2009).

Following the ICAO approach, Sèbe et al. (2019) advocated for the involvement of the IMO into whale-ship collision management. The IMO represents the counterpart of the ICAO for maritime transport, as it is a United Nations specialized agency (Tarelko, 2012). IMO provides guidance for maritime-related risk assessment, through the so-called Formal Safety Assessment (FSA; IMO, 2018). FSA is a similar process to SMS, or other guidelines provided by the ICAO. Usually used for human safety or pollution (Haapasaari et al., 2015; Kontovas and Psaraftis, 2008), Sèbe et al. (2019) conceptualized the use of this framework to standardize the management of whale-ship collisions at an international level.

However, the lack of knowledge on damages associated with whale-ship collisions is a barrier to the successful implementation of one of the critical steps of the FSA, the Cost-Benefit assessment. This FSA step aims to identify the costs and benefits associated with the implementation of a mitigation solution. One of the benefits is the avoided cost, such as damage costs. Unlike other wildlife-vehicle collisions database, the IWC ship strike database is limited by the number of events recorded and by the lack of intelligence on the details of the events (e.g., speed, length, damage). Several factors explain those limitations. While some collisions might go unnoticed, many are underreported as shipping companies guidelines do not compel the crew to do it, or to avoid bad publicity (David et al., 2011; IWC-ACCOBAMS, 2012b). Besides, the lack of coordination between organizations can be at the expense of the assessment of costs associated with whale-ship collisions. The IMO Casualty database (GISIS) does not provide any links to the IWC database, and hence whale-ship collisions do not appear into the scope of the IMO casualty events (Sèbe et al., 2019). Improvements in the collision reporting are therefore essential for the integration of the damages in the FSA, allowing for a holistic integration of the whale-ship management at the IMO level.

5 Conclusions and perspectives

The management of whale-ship collisions lacks of holistic risk assessment approaches. Similarly to what is done by the ICAO for wildlife-aircraft collisions, Sèbe et al. (2019) conceptualized a risk assessment approach to ship strikes using IMO's Formal Safety Assessment methodology. Nevertheless, limited knowledge hampers the application of such risk assessment techniques, especially related to the lack of information on the damages. Our works provide a first study on the subject by estimating the probability of ship damage. There is evidence that further research is required to improve the results. Better and standardized reporting would increase data availability and, thus, the robustness of the regression analysis. We acknowledge the fact that some other parameters such as the type of ship and species may provide more explanatory power for the model. However, the small size of our dataset prohibited the use of more than one variable in our prediction model (e.g., Peduzzi et al., 1996). Besides, as we have mentioned in the Introduction section, data after 2010 are not publicly available. There is, therefore, a clear need for more open and better data.

Furthermore, the extensive involvement of shipyards and shipping companies is needed to assess the costs of damages. Further research could also be undertaken for high-speed passenger ships, which have the highest damage probability, in order to prevent human losses. Lastly, the integration of the damages and the costs would provide a more transparent way for assessing the mitigation solutions' effectiveness, similar to what is performed on other wildlife-vehicle collisions.

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References

ACCOBAMS-Pelagos, 2005. Report of the joint ACCOBAMS / Pelagos workshop on fin whales in the Mediterranean Sea.

Allan, J.R., 2000. The costs of bird strikes and bird strike prevention, Human Conflicts with Wildlife: Economic Considerations, USDA National Wildlife Research Center Symposia.

Allan, J.R., Orosz, A., Badham, A., Bell, J., 2002. Development of birdstrike risk assessment procedures, their use on airports, and the potential benefits to the aviation industry, Bird Strike Committee-USA/Canada, 4th Annual Meeting, Sacramento, CA. 4.

Anderson, A., Carpenter, D.S., Begier, M.J., Blackwell, B.F., DeVault, T.L., Shwiff, S.A., 2015. Modeling the cost of bird strikes to US civil aircraft. Transp. Res. Part D 38, 49–58. https://doi.org/10.1016/j.trd.2015.04.027

Ayyub, B.M., McGill, W.L., Kaminskiy, M., 2007. Critical asset and portfolio risk analysis: An all-hazards framework. Risk Anal. 27, 789–801. https://doi.org/10.1111/j.1539-6924.2007.00911.x

Bissonette, J.A., Kassar, C.A., Cook, L.J., 2008. Assessment of costs associated with deer–vehicle collisions : human death and injury, vehicle damage, and deer loss. Human–Wildlife Conflicts 2, 17–27.

Butler, D., 2012. A guide to ship repair estimates in man-hours - 2nd Edition. Elsevier Ltd. https://doi.org/10.1016/B978-0-7506-4834-9.X5000-7

Chion, C., Lagrois, D., Dupras, J., Turgeon, S., Mcquinn, I.H., Michaud, R., Ménard, N., Parrott, L., 2017. Underwater acoustic impacts of shipping management measures : Results from a social-ecological model of boat and whale movements in the St . Lawrence River Estuary (Canada). Ecol. Modell. 354, 72–87. https://doi.org/10.1016/j.ecolmodel.2017.03.014

Clarksons Research, 2019. Shipping Intelligence Network – Timeseries - Available at https://sin.clarksons.net/ (accessed 20 December 2019).

Conover, M.R., Pitt, W.C., K.K., K., Dubow, T.J., Sanborn, W.A., 1995. Review of human injuries, illnesses, and economic losses caused by wildlife in the United States. Wildl. Soc. Bull. 23, 407–414.

Crain, A.R., Belant, J.L., DeVault, T.L., 2015. Carnivore incidents with U.S. civil aircraft. Transp. Res. Part D 36, 160–166. https://doi.org/10.1016/j.trd.2014.12.001
David, L., Alleaume, S., Guinet, C., 2011. Evaluation of the potential of collision between fin whales and maritime traffic in the North-Western Mediterranean Sea in summer, and mitigation solutions. J. Mar. Anim. Their Ecol. 4, 17–28. https://doi.org/1911-8929 (ISSN)
DeLeeuw, J., 1992. Introduction to Akaike (1973) information theory and an extension of the maximum likelihood principle, in: Breakthroughs in Statistics. Springer, New York, NY, pp. 599–609. https://doi.org/10.1007/978-1-4612-0919-5_37
Devault, T.L., Fernández-Juricic, E., Dolbeer, R.A., 2009. Wildlife collisions with aircraft : A missing component of land-use planning for airports. Landsc. Urban Plan. J. 93, 1–9. https://doi.org/10.1016/j.landurbplan.2009.07.005
Dolbeer, R., 2011. Increasing trend of damaging bird strikes with aircraft outside the airport boundary : implications for mitigation measures. Human–Wildlife Interact. 5, 1–15. https://doi.org/10.26077/dnvb-x958
Dolbeer, R.A., Wright, S.E., 2009. Safety management systems : how useful Will the FAA National Wildlife Strike Database be ? Human–Wildlife Conflicts 3, 1–13. https://doi.org/10.26077/kt7q-b287
Dolbeer, R.A., Wright, S.E., Weller, J.R., Anderson, A.L., Begier, M.J., 2015. Wildlife strikes to civil aircraft in the United States, 1990-2014, Report of the Associate Administrator of Airports, Office of Airport Safety and Standards, Airport Safety & Certification, Serial Report Number 21. https://doi.org/10.13140/RG.2.1.2370.6649
Frantzis, A., Leaper, R., Alexiadou, P., Prospathopoulos, A., Lekkas, D., 2019. Shipping routes through core habitat of endangered sperm whales along the Hellenic Trench , Greece : Can we reduce collision risks ? PLoS One 14, 1–21. https://doi.org/10.1371/journal.pone.0212016 February
Gren, I., Jägerbrand, A., 2019. Calculating the costs of animal-vehicle accidents involving ungulate in Sweden. Transp. Res. Part D 70, 112–122. https://doi.org/10.1016/j.trd.2019.03.008
Grift, E.A. Van Der, 1999. Mammals and railroads : Impacts and management implications. Lutra 42, 1–23.
Guarin, L., Konovessis, D., Vassalos, D., 2009. Safety level of damaged RoPax ships : Risk modelling and cost-effectiveness analysis. Ocean Eng. 36, 941–951. https://doi.org/10.1016/j.oceaneng.2009.06.005
Haapasaari, P., Helle, I., Lehikoinen, A., Lappalainen, J., Kuikka, S., 2015. A proactive approach for maritime safety policy making for the Gulf of Finland : Seeking best practices. Mar. Policy 60, 107–118. https://doi.org/10.1016/j.marpol.2015.06.003
Haman, J., Avery, M., 2019. ciTools: Confidence or Prediction Intervals, Quantiles, and Probabilities for Statistical Models, R package version 0.5.1.
Hansen, K.F.S., 2013. Analysis of estimations, quotations and actual costs related to dry-docking. Thesis Vestfold Univ. Coll. Univ. Horten, Norw. 1–47.
Huijser, M.P., Duffield, J.W., Clevenger, A.P., Ament, R.J., McGowen, P.T., 2009. Cost-benefit analysis of mitigation measures aimed at reducting collisions with large ungulates in the United States and Canada, a decision support tool. Ecol. Soc. 14, 1–26. https://doi.org/10.1016/j.contraception.2009.11.002
ICAO, 2017a. 2008 - 2015 Wildlife strike analyses (IBIS), International Civil Aviation Organization - EB 2017/25.
ICAO, 2017b. Safety Management Manual (SMM) - 4th Edition, ICAO, Doc. 9859-AN/474.
ICAO, 2012. Airport Services Manual - Part 3 Wildlife Control and Reduction, Doc 9137, AN/898, Approved by the Secretary General and published under his authority.
ICAO, 2009. Managing wildlife hazards to aircraft, Tenth Meeting of Directors of Civil Aviation of the Central Caribbean (C/CAR/DCA/10) - Agenda Item 4: Aviation Safety Matters - 4.6 Other Aviation Safety Matters - Presented by the United States.

IMO, 2018. Revised guidelines for Formal Safety Assessment (FSA) for the use in the IMO rule-making process, International Maritime Organization - MSC-MEPC.2/Circ.12/Rev.2.
IMO, 2010. IACS FSA study – Steps 3 and 4 (Risk control options and Cost benefit assessment). Int. Marit. Organ. - Submitt. by Int. Assoc. Classif. Soc. - MSC 88/INF.6 92.
IMO, 2009a. Development of a guidance document for minimizing the risk of ship strikes with cetaceans, International Maritime Organization - Submitted by Italy, Spain, France and Monaco - MEPC 59/18.
IMO, 2009b. Guidance document for minimizing the risk of ship strikes with cetaceans. Int. Marit. Organ. - MEPC.1/Circ.674.
IWC-ACCOBAMS, 2012a. Report of the Joint IWC-ACCOBAMS Workshop on Reducing Risk of Collisions between Vessels and Cetaceans. Agenda 1–42.
IWC-ACCOBAMS, 2012b. Report of the joint IWC-ACCOBAMS workshop on reducing risk of collisions between vessels and cetaceans, IWC/63/CC 8 - Agenda item 4.1.
Jensen, A.S., Silber, G.K., 2004. Large whale ship strike database, U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-OPR, U.S. Department of Commerce, NOAA Technical Memorandum. NMFS-OPR. https://doi.org/10.1093/nar/gki014
Kirchler, E., Hoelzl, E., Wahl, I., 2008. Enforced versus voluntary tax compliance: The "slippery slope" framework. J. Econ. Psychol. 29, 210–225. https://doi.org/10.1016/j.joep.2007.05.004
Kite-Powell, H., 2005. Economic implications of possible reductions in Boston port calls due to ship strike management measures, Report produced for NOAA National Marine Fisheries and MASSPORT, Report produced for NOAA National Marine Fisheries and MASSPORT.
Knowlton, A.., Korsmeyer, F.., Hynes, B., 1998. The hydrodynamic effects of large vessels on Right whales: Phase two. NMFS - Final Rep. - Contract No 46EANF60004 13.
Knowlton, A.., Korsmeyer, F.., Kerwin, J.., Wu, H.-Y., Hynes, B., 1995. The hydrodynamic effects of large vessels on right whales. NMFS - Final Rep. - Contract No 40EANFF400534 81.
Kontovas, C.A., Psaraftis, H.N., 2008. Marine environment risk assessment : a survey on the disutility cost of oil spills. Proc. 2nd Int. Symp. Sh. Oper. Manag. Econ. SNAME Greek Sect. Athens 1–13.
Kušta, T., Keken, Z., Jezek, M., Kuta, Z., 2015. Effectiveness and costs of odor repellents in wildlife–vehicle collisions : A case study in Central Bohemia, Czech Republic. Transp. Res. Part D 38, 1–5. https://doi.org/10.1016/j.trd.2015.04.017
Laist, D.W., Knowlton, A.R., Mead, J.G., Collet, A.S., Podestà, M., 2001. Collisions between ships and whales. Mar. Mammal Sci. 17, 35–75. https://doi.org/10.1111/j.1748-7692.2001.tb00980.x
Lammers, M.O., Pack, A.A., Lyman, E.G., Espiritu, L., 2013. Trends in collisions between vessels and North Pacific humpback whales (Megaptera novaeangliae) in Hawaiian waters (1975-2011). J. Cetacean Res. Manag. 13, 73–80.
Lienhoop, N., Bartkowski, B., Hansjürgens, B., 2015. Informing biodiversity policy: The role of economic valuation, deliberative institutions and deliberative monetary valuation. Environ. Sci. Policy 54, 522–532. https://doi.org/10.1016/j.envsci.2015.01.007
Liu, B., Terndrup, P., Zhu, L., Zhang, S., 2018. Review of experiments and calculation procedures for ship collision and grounding damage. Mar. Struct. 59, 105–121. https://doi.org/10.1016/j.marstruc.2018.01.008
Mansouri, S.A., Lee, H., Aluko, O., 2015. Multi-objective decision support to enhance environmental sustainability in maritime shipping: A review and future directions. Transp. Res. Part E Logist. Transp. Rev. 78, 3–18. https://doi.org/10.1016/j.tre.2015.01.012
Martin, J., Sabatier, Q., Gowan, T.A., Giraud, C., Gurarie, E., Calleson, C.S., Ortega-Ortiz, J.G., Deutsch, C.J., Rycyk, A., Koslovsky, S.M., 2015. A quantitative framework for investigating risk of deadly collisions between marine wildlife and boats. Methods Ecol. Evol. 42–50. https://doi.org/10.1111/2041-210X.12447
Mrtka, J., Borkovcová, M., 2013. Estimated mortality of mammals and the costs associated with

animal–vehicle collisions on the roads in the Czech Republic. Transp. Res. Part D 18, 51–54. https://doi.org/10.1016/j.trd.2012.09.001
Nathan Associates Inc, 2012. Economic analysis of North Atlantic right whale ship strike reduction rule, A report prepared for the NOAA, NMFS and the Office of Protected Resources, 2008.
Nichol, L.M., Wright, B.M., O'Hara, P., Ford, J.K.B., 2017. Risk of lethal vessel strikes to humpback and fin whales off the west coast of Vancouver Island, Canada. Endanger. Species Res. 32, 373–390. https://doi.org/10.3354/esr00813
Panigada, S., Pesante, G., Zanardelli, M., Capoulade, F., Gannier, A., Weinrich, M.T., 2006. Mediterranean fin whales at risk from fatal ship strikes. Mar. Pollut. Bull. 52, 1287–1298. https://doi.org/10.1016/j.marpolbul.2006.03.014
Parrott, L., Chion, C., Turgeon, S., Menard, N., Cantin, G., Michaud, R., 2016. Slow down and save the whales. Solutions 6, 40–47.
Peduzzi, P., Concato, J., Feinstein, A.R., Halford, T.R., 1996. A simulation study of the number of events per variable recommended in multivariable regression analyses. J. Clin. Epidemiol. 49, 1373–1379. https://doi.org/10.1016/0197-2456(93)90084-q
Peltier, H., Ridoux, V., 2015. Marine megavertebrates adrift: A framework for the interpretation of stranding data in perspective of the European Marine Strategy Framework Directive and other regional agreements. Environ. Sci. Policy 54, 240–247. https://doi.org/10.1016/j.envsci.2015.07.013
R Development Core Team, 2008. R: A language and environment for statistical computing. R Found. Stat. Comput. Vienna, Austria. ISBN 3-900051-07-0, URL http//www.R-project.org.
Rendell, L., Frantzis, A., 2016. Mediterranean Sperm Whales, Physeter macrocephalus: The Precarious State of a Lost Tribe, in: Advances in Marine Biology. Elsevier Ltd., pp. 37–74. https://doi.org/10.1016/bs.amb.2016.08.001
Rio, A., Myung, D., Min, J., Fauzan, A., Cao, B., Wang, Q., 2017. Analysis of structural damage on the struck ship under side collision scenario. Alexandria Eng. J. 57, 1761–1771. https://doi.org/10.1016/j.aej.2017.05.002
Ritter, F., Panigada, S., 2019. Collisions of Vessels With Cetaceans — The Underestimated Threat, in: World Seas: An Environmental Evaluation. Elsevier Ltd., pp. 531–547. https://doi.org/10.1016/B978-0-12-805052-1.00026-7
Rockwood, R.C., Calambokidis, J., Jahncke, J., 2017. 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 12, 1–24. https://doi.org/10.1371/journal.pone.0183052
Ryu, J.H., Yeom, S.R., Jeong, J.W., Kim, Y.I., Cho, S.J., 2010. Characteristics and triage of a maritime disaster: an accidental passenger ship collision in Korea. Eur. J. Emerg. Med. 17, 177–180. https://doi.org/10.1097/MEJ.0b013e328330f452
Santos, R.A.L., Mota-Ferreira, M., Aguiar, L.M.S., Ascensão, F., 2018. Predicting wildlife road-crossing probability from roadkill data using occupancy-detection models. Sci. Total Environ. 642, 629–637. https://doi.org/10.1016/J.SCITOTENV.2018.06.107
Sèbe, M., Kontovas, A.C., Pendleton, L., 2019. A decision-making framework to reduce the risk of collisions between ships and whales. Mar. Policy 109, 1–12. https://doi.org/10.1016/j.marpol.2019.103697
Seiler, A., Olsson, M., 2017. Wildlife Deterrent Methods for Railways — An Experimental Study, in: Railway Ecology. pp. 277–291. https://doi.org/10.1007/978-3-319-57496-7
Seiler, A., Olsson, M., Rosell, C., Grift, E. Van Der, 2016. Cost-benefit analyses for wildlife and traffic safety, SAFEROAD Technical report No. 4.
Silber, G.K., Adams, J.D., Asaro, M.J., Cole, T.V.N., Moore, K.S., Ward-Geiger, L.I., Zoodsma, B.J., 2015. The right whale mandatory ship reporting system: a retrospective. PeerJ 3, 1–18. https://doi.org/10.7717/peerj.866
Silber, G.K., Bettridge, S., 2012. An assessment of the final rule to implement vessel speed

restrictions to reduce the threat of vessel collisions with North Atlantic right whales, U.S. Dept. of Commer., NOAA Technical Memorandum NMFS-OPR-48. https://doi.org/NMFS-OPR-48

Silber, G.K., Bettridge, S., Cottingham, D., 2008. Report of a workshop to identify and asess technologies to reduce ship strikes of large whales, NOAA technical memorandum, NMFS-OPR-42.

Silber, G.K., Slutsky, J., Bettridge, S., 2010. Hydrodynamics of a ship/whale collision. J. Exp. Mar. Bio. Ecol. 391, 10–19. https://doi.org/10.1016/j.jembe.2010.05.013

Silber, G.K., Vanderlaan, A.S.M., Tejedor Arceredillo, A., Johnson, L., Taggart, C.T., Brown, M.W., Bettridge, S., Sagarminaga, R., 2012. The role of the International Maritime Organization in reducing vessel threat to whales: Process, options, action and effectiveness. Mar. Policy 36, 1221–1233. https://doi.org/10.1016/j.marpol.2012.03.008

Stopford, M., 2009. Maritime Economics - 3rd edition, Taylor & F. ed. Routledge.

Tarelko, W., 2012. Origins of ship safety requirements formulated by International Maritime Organization. Procedia Eng. 45, 847–856. https://doi.org/10.1016/j.proeng.2012.08.249

Thomas, P.O., Reeves, R.R., Brownell, R.L., 2016. Status of the world's baleen whales. Mar. Mammal Sci. 32, 682–734. https://doi.org/10.1111/mms.12281

Van Waerebeek, K., Leaper, R., 2008. Second report of the IWC vessel strike data standardisation working group. IWC 60th Annu. Meet. SC/60/BC 5, 8. https://doi.org/10.13140/RG.2.1.2020.2001

Vanderlaan, A.S.M., Taggart, C.T., 2007. Vessel collisions with whales: The probability of lethal injury based on vessel speed. Mar. Mammal Sci. 23, 144–156. https://doi.org/10.1111/j.1748-7692.2006.00098.x

Venables, W.N., Ripley, B.D., 2002. Modern Applied Statistics with S, Fourth Edition. Springer, New York.

Venus Lun, Y.H., Lai, K. hung, Wong, C.W.Y., Cheng, T.C.E., 2015. Environmental governance mechanisms in shipping firms and their environmental performance. Transp. Res. Part E Logist. Transp. Rev. 78, 82–92. https://doi.org/10.1016/j.tre.2015.01.011

VerCauteren, K.C., Lavelle, M.J., Hygnstrom, S., 2006. Fences and deer-damage management : A review of designs and efficacy. Wildl. Soc. Bull. 34, 191–200. https://doi.org/10.2193/0091-7648(2006)34[191:FADMAR]2.0.CO;2

Visintin, C., Golding, N., Ree, R. Van Der, Mccarthy, M.A., 2018. Managing the timing and speed of vehicles reduces wildlife-transport collision risk. Transp. Res. Part D 59, 86–95. https://doi.org/10.1016/j.trd.2017.12.003

Whitney, C.K., Gardner, J., Ban, N.C., Vis, C., Quon, S., Dionne, S., 2016. Imprecise and weakly assessed: Evaluating voluntary measures for management of marine protected areas. Mar. Policy 69, 92–101. https://doi.org/10.1016/j.marpol.2016.04.011

Wiley, D.N., Moller, J.C., Pace, R.M., Carlson, C., 2008. Effectiveness of voluntary conservation agreements: Case study of endangered whales and commercial whale watching. Conserv. Biol. 22, 450–457. https://doi.org/10.1111/j.1523-1739.2008.00897.x

Wiley, D.N., Thompson, M., Pace, R.M., Levenson, J., 2011. Modeling speed restrictions to mitigate lethal collisions between ships and whales in the Stellwagen Bank National Marine Sanctuary, USA. Biol. Conserv. 144, 2377–2381. https://doi.org/10.1016/j.biocon.2011.05.007

Zhang, S., 1999. The Mechanics of Ship Collisions, Ocean Engineering journal - Department of Naval Architecture and offshore engineering - Technical University of Denmark.