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Economic Loss Analysis of Fishing Boat Collisions Considering Spatial-Temporal Interaction Effects

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Considering unobserved spatial-temporal interaction effects, this study proposes a Bayesian spatial-temporal interaction model for predicting economic loss from fishing boat collisions using 10-year (2004–2014) collision records from six different areas in the waters of Fujian, China. Results show strong spatial heterogeneity and correlation effects in fishing boat collisions, while the economic loss from boat collisions gradually decreases with the time trend. Collision time, collision location, visibility and the involvement of LNG/LPG/chemical-carrying ships show similar marginal effects on the economic loss for the two collision types: fishing boat collisions and collisions involving no fishing boats. Navigational status and the involvement of cargo ships exhibit much bigger effects in fishing boat collisions compared with collisions involving no fishing boat. Unlike collisions involving no fishing boat, fishing boat collisions are associated with reduced economic loss in poor weather conditions characterised by strong wind/waves because in Fujian waters additional safety measures are adopted for fishing boats in such conditions. The proposed model is useful for policymakers in adopting safety enhancement strategies to decrease the economic loss resulting from fishing boat collisions.

KEYWORDS

1. Ship Collision. 2. Modelling. 3. Safety. 4. Uncertainty.

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1. INTRODUCTION. The two-ship collision, defined as an event when a ship strikes or is struck by another ship on the water surface, is one of the most frequent types of accident that occur in water areas (International Maritime Organization, 2002). The risk of a fishing boat being involved in a collision is always a challenge for maritime authorities in improving maritime safety because of the often poor structure of fishing boats and irresponsible navigation behaviour of their crews. In this study, 'fishing boat collision' refers to a collision involving fishing boats. In general, a fishing boat collision may lead to serious consequences in terms of mortality and property damage costs. Note that the consequences of a ship collision could be affected by many influencing factors including collision characteristics, environmental characteristics, and factors related to the cause of the accident. Hence, a comprehensive understanding of the complex relationship between

the consequences and the influencing factors of a fishing boat collision is a key step towards proposing the priority of navigational safety enhancement strategies (Jin et al., 2002; Morel and Chauvin 2006; Oh et al., 2015).

The existing studies on ship collision can be classified into two categories: pre-accident analysis and post-accident analysis. The pre-accident analysis studies mainly employ automatic identification system (AIS) data to predict ship collision frequency, while the post-accident analysis studies primarily use historical accident data to explore the factors contributing to ship collisions. Nevertheless, the majority of post-accident analysis studies do not take into account the unobserved spatial and time variances of ship collisions. Obviously, the neglect of spatial-temporal interaction effects could lead to biased results. In particular, it is already known that there is irregularity in the spatial distribution of fishing ships in specific waters.

The occurrence of ship collisions may result in loss of human life and property damage to the ships involved. However, the literature regarding the analysis of economic loss incorporating loss of human life and cost of property damage in ship collisions is rather limited. In order to reflect accurately the complex relationship between influencing factors and economic loss, this study proposes a Bayesian regression model considering spatial-temporal effects that can also be applied to estimate accurately economic loss caused by fishing boat collisions.

2. LITERATURE REVIEW.

With the increasing application of AIS data mining technology, numerous studies have been conducted to evaluate ship traffic characteristics as well as the frequency of shipping accidents. Mou et al. (2010) presented a collision avoidance analysis in the water area off Rotterdam Port (the Netherlands) where a traffic separation scheme was in operation. They proposed a dynamic methodology to identify the correlation between the CPA (closest point approach) and influencing factors including ship size, speed and course. Weng et al. (2012) used a ship collision frequency model to estimate the ship collision frequency in the Singapore Strait. Zaman et al. (2015) employed a risk-based collision model to predict the accident risk for tanker ships in the Malacca Strait, which was measured by using the CPA and TCPA (time to closest point approach) based on the AIS data. Zhang et al. (2017) used big AIS data to evaluate the spatial-temporal dynamics of ship traffic in Singapore port water areas. Bye and Aalberg (2018) combined AIS data and accident reports from Norwegian waters to estimate the probability of a ship suffering a navigation-related accident by building a multivariate logistic regression model. Altan and Otay (2018) utilised one-year AIS data to evaluate the probability of ship encounters in congested waterways. It was found that the probability of ship collisions increased significantly with narrow passages and sharp turns.

Besides the pre-accident analysis studies mentioned above, considerable efforts have been made in post-accident analysis which mainly relies on historical ship accident data. In general, historical accident records may contain more useful information (e.g. weather conditions, crew status) that might not be extracted from the AIS data (Talley et al., 2008; Kujala et al., 2009; Weng et al., 2018a). Using archived accident records, some researchers (e.g., Akten, 2004; Birpinar et al., 2009; Aydogdu et al., 2012) attempted to enhance navigational safety in the Istanbul Strait by analysing shipping accident risk in different ways. These post-accident analysis studies can be divided into two groups in terms of the subjects of analysis. The first group focuses on the relationship between severity of injury in ship accidents and influencing factors (e.g., Jin, 2014; Weng et al., 2018a). The major focus of the second group is to assess the consequences of ship accidents such as injury or loss of human life (e.g., Jin et al. 2001; Talley et al., 2006; Perez-Labajos et al. 2009; Yip et al., 2015; Weng et al., 2016) and property damage cost (e.g., Talley et al., 2008; Weng et al., 2018b). Nevertheless, there is only a limited number of studies (Weng et al., 2019) focusing on the assessment of ship accident economic loss which is a major concern of insurance companies.

Compared with accidents involving other types of ship, fishing boats have received much more attention because they usually have relatively poor ship structure and their crews sometimes engage in aggressive or risky navigation behaviour, so accidents involving fishing boats can lead to more serious consequences (Jin et al. 2001; Jin and Thunberg, 2005; Perez-Labajos et al., 2006). The mistakes usually made by fishing boat crews can be attributed to the fact that they are generally unaware of the underlying dangers in complex waterways or of the navigational status of other ships nearby. For instance, the majority of fishing boat crews tend to bypass the bows of large ships that they encounter sailing across their navigation routes. In addition, the crews of fishing boats are more inclined to navigate at excessive speed. Furthermore, some fishing boat crews may be unfamiliar with the use of advanced navigational facilities.

The existing post-accident analysis studies do not take into account the unobserved spatial and temporal variances of ship collisions. In order to incorporate the spatial-temporal effects, Aguero-Valverde and Jovanis (2006) addressed a full Bayes spatial-temporal analysis of fatal and injury crashes using road traffic accident data from Pennsylvania. Meng et al. (2017) built a Bayesian space-time logistic model to analyse the severity of injuries in taxi crashes. Liu and Sharma (2018) presented a multivariate spatial model, a multivariate temporal model, and a multivariate spatial-temporal interaction model to account for possible correlations across injury severities. Considering the fact that the spatial-temporal effects on the consequences of ship collisions have not been fully understood, this study presents a spatial-temporal Bayesian log-normal model to estimate the economic loss caused by fishing boat collisions.

3. METHODOLOGY.

In general, a Bayesian log-normal model can be employed to describe the quantitative relationship between influencing factors and economic loss in fishing boat collisions. Let $Y_{i,p,t}$ be the economic loss from observed collision i occurring in the water area p at time t. Therefore, the model can be formulated as follows

$$\log(Y_{i,p,t}) \sim N(\mu_i, \tau_h) \tag{1}$$

$$\log(Y_{i,p,t}) = \beta_0 + \sum_{k=1}^{k} \beta_k x_{i,p,t,k} + \varepsilon_i \tag{2}$$

where $x_{i,p,t,k}$ is the kth explanatory variable, β_0 is the intercept and β_k is the coefficient to be determined for $x_{i,p,t,k}$. The error ε_i follows the standard normal distribution $\varepsilon_i \sim N(0, \sigma^2)$.

Considering possible spatial autocorrelation and temporal effects, we can add three more factors to the model: the structured spatial correlation factor (s_p), the unstructured spatial heterogeneity factor (u_p) and the temporal heterogeneity factor (t_y). The structured spatial

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correlation factor (s_p) supposes a structured adjacent matrix among different water areas, and the spatial factor (u_p) follows a random normal distribution to vary across the areas. In addition, the temporal effect (t_y) during the analysis period could be considered as a random time trend fluctuating in different time periods.

The spatial autocorrelation effects may change over time, however, and vice versa (Aguero-Valverde and Jovanis, 2006). Therefore, the spatial-temporal interaction factor has to be considered in the Bayesian log-normal model. The expression of the spatial-temporal interaction model is shown below:

$$\log(Y_{i,p,t}) = \beta_0 + \sum_{k=1}^{k} \beta_k x_{i,p,t,k} + s_p + u_p + (\varphi + \eta_p)\tau_t \tag{3}$$

where φ represents the overall mean time trend, η_p is the spatial-temporal interaction factor for the water area p and τ_t is the selected time period t.

According to the study of Besag et al. (1991), a conditional autoregressive prior is specified to the structured spatial correlation factor s_p and spatial-temporal interaction factor η_p:

$$s_p \sim N\left(\frac{\sum_{p\neq q} \zeta_{pq} s_q}{\sum_{p\neq q} \zeta_{pq}}, \frac{\sigma_s^2}{\sum_{p\neq q} \zeta_{pq}}\right) \tag{4}$$

$$\eta_p \sim N\left(\frac{\sum_{p\neq q} \zeta_{pq} \eta_q}{\sum_{p\neq q} \zeta_{pq}}, \frac{\sigma_\eta^2}{\sum_{p\neq q} \zeta_{pq}}\right) \tag{5}$$

where ζ_{pq} is a proximity matrix to characterise the adjacent relationship between water areas p and q. If areas p and q are adjacent, then $\zeta_{pq} = 1$ and 0 otherwise. As the variance factors, it is reasonable to assume that the priors of σ_s^2 and σ_η^2 follow the inverse-gamma distribution (e.g., Wakefield et al., 2000). In addition, u_p and φ are assumed to follow standard normal distributions, namely,

$$u_p \sim N(0, \sigma_u^2) \tag{6}$$

$$\varphi \sim N(0, \sigma_\varphi^2) \tag{7}$$

In order to estimate the spatial-temporal effects considered as model parameters, the Markov chain Monte Carlo (MCMC) technique can be adopted to construct the complex statistical model (Spiegelhalter et al., 2002). The Gibbs sampling method could be utilised to integrate the prior distribution of the model parameters. More details of this method can be found in the study of Geman and Geman (1984). The deviance information criterion (DIC) is calculated to assess the complexity and superiority of the model. The DIC value can be calculated, according to Spiegelhalter et al. (2002), as

$$\text{DIC} = \bar{D} + p_D = D(\bar{\theta}) + 2p_D \tag{8}$$

where $\bar{D}$ is the posterior mean of the deviance, $\bar{\theta}$ is the posterior mean of parameters of interest, $D(\bar{\theta})$ is the calculated deviance of $\bar{\theta}$, and p_D is the effective number of coefficients.

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4. DATA.

4.1. *Fishing fleet.* The active fishing fleet in Fujian waters consists of 58,420 ships with lengths ranging from 15 metres to 67 metres. A total of 535 navigational aids are distributed in the Fujian fishing grounds, including 17 lighthouses, 208 light beacons, 19 leading marks, seven beacons, 219 light-buoys, 41 radar responder beacons, one directional radio beacon, two RBN/DGPS beacons, two AIS base stations, 10 bridge marks, and nine other navigational aids. The majority of fishing boats in this water area are equipped with shipborne AIS. Fishing operations in Fujian waters can be divided into seven categories: trawl, stow net, gillnet, purse seine, angling, traps and light liftnet. Fishing boat with gillnet is the dominant ship type in this water area (34%), fishing boat with trawl accounts for 14%, stow net accounts for 22%, purse seine accounts for 4%, angling accounts for 5%, and others account for 21%. Major fisheries that are pursued in the Fujian waters include: *Pseudosciaena crocea*, ribbonfish, butterfish, herring, mackerel, snapper, matreel, eel, inkfish, jellyfish, prawn, *Acete chinensis*, portunid, clam and oyster. Fishing trips tend to be of relatively short duration (3–5 days) though larger ships may take longer trips (5–10 days). The fishing trip duration for smaller ships may even be less than 24 h.

The spatial distribution of fishing ports and fishing grounds for this study was mainly obtained from the Fujian Provincial Department of Ocean and Fisheries. These fishing ports and fishing grounds are mainly supervised by the authorities of six major fishing cities: Ningde, Fuzhou, Putian, Quanzhou, Xiamen and Zhangzhou. Fujian fishing area consists of five fishing grounds: Minwai, Mindong, Minzhong, Minnan and Taiwan bank (see Figure 1). At present, there is a total of 245 fishing ports in this water area, including nine central fishing ports, 13 primary fishing ports, 39 secondary fishing ports, and 184 tertiary fishing ports. Ningde has two of the central fishing ports: Shacheng and Sansha. The other seven central fishing ports are: Huangqi (Fuzhou), Dongao (Fuzhou), Chongwu (Quanzhou), Xiangzhi (Quanzhou), Shenghu (Quanzhou), Mintai (Xiamen) and Daao (Zhangzhou).

4.2. *Collision accident data.* In this study, accident data from a total of 184 fishing ship collisions that occurred in Fujian water areas between 2004 and 2014 were collected for the analysis. The exact locations of the fishing boat collisions and fishing ports in Fujian province are marked in Figure 2, where red dots represent fishing boat collisions; dark blue dots represent central fishing ports; and light blue dots represent other fishing ports, including primary fishing ports, secondary fishing ports and tertiary fishing ports. It can clearly be seen that numerous fishing boat collisions occurred near the coastline, especially in the Mindong, Minzhong and Minnan fishing grounds. Furthermore, the frequency of fishing ship collisions in water areas around Mintai and Daao central fishing ports is greater than in other water areas. Figure 3 shows the locations of fishing boat collisions near Mintai central fishing port (Xiamen). Apparently, there are more collisions occurring at the intersections of commercial routes and narrow waterways. The locations of fishing boat collisions near Daao central fishing port (Zhangzhou) are shown in Figure 4. Likewise, the majority of fishing boat collisions occurred near the commercial shipping routes.

As to the distribution of economic loss from fishing boat collisions in Fujian waters, the largest economic loss caused by a fishing boat collision accident was RMB 12·88 million, and the minimum was RMB 2,000. Meanwhile, we also extracted the records of collisions involving no fishing boats for the purpose of model comparison. According to the collected data, the economic loss caused by collisions involving no fishing boats ranged from RMB 5,000 to RMB 32 million. Figure 5 depicts the spatial distributions of economic

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Figure 1. Fishing grounds of Fujian Provincial Department of Ocean and Fisheries.

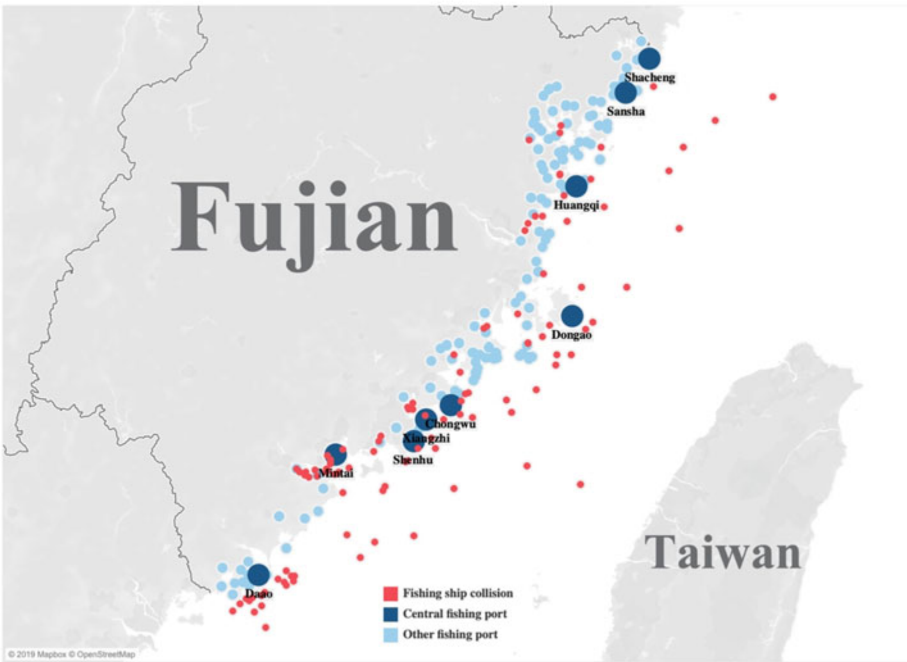

Figure 2. Locations of fishing boat collisions and fishing ports in Fujian waters.

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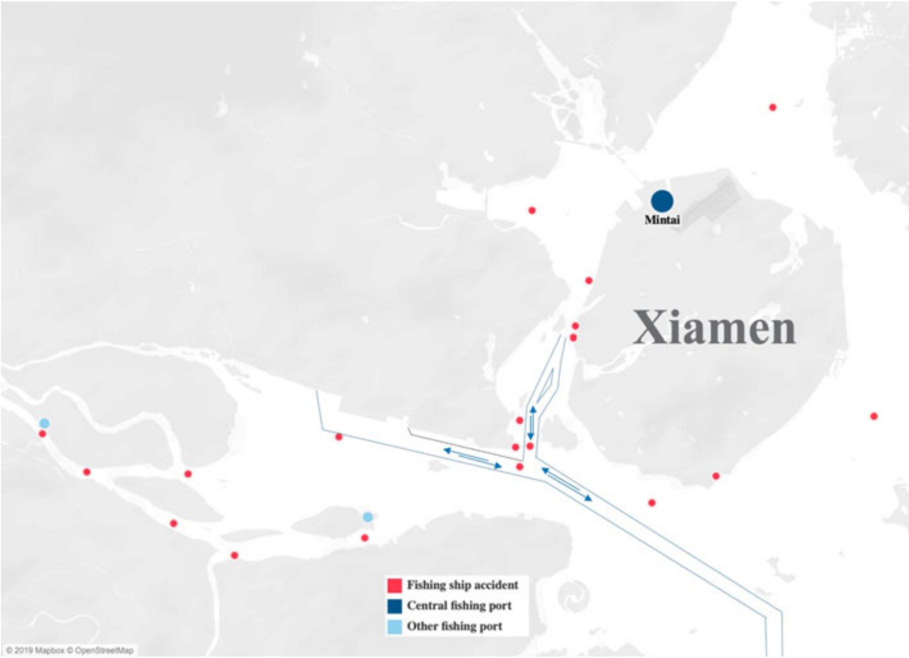

Figure 3. Locations of fishing boat collisions near Mintai central fishing port.

Figure 4. Locations of fishing boat collisions near Daao central fishing port.

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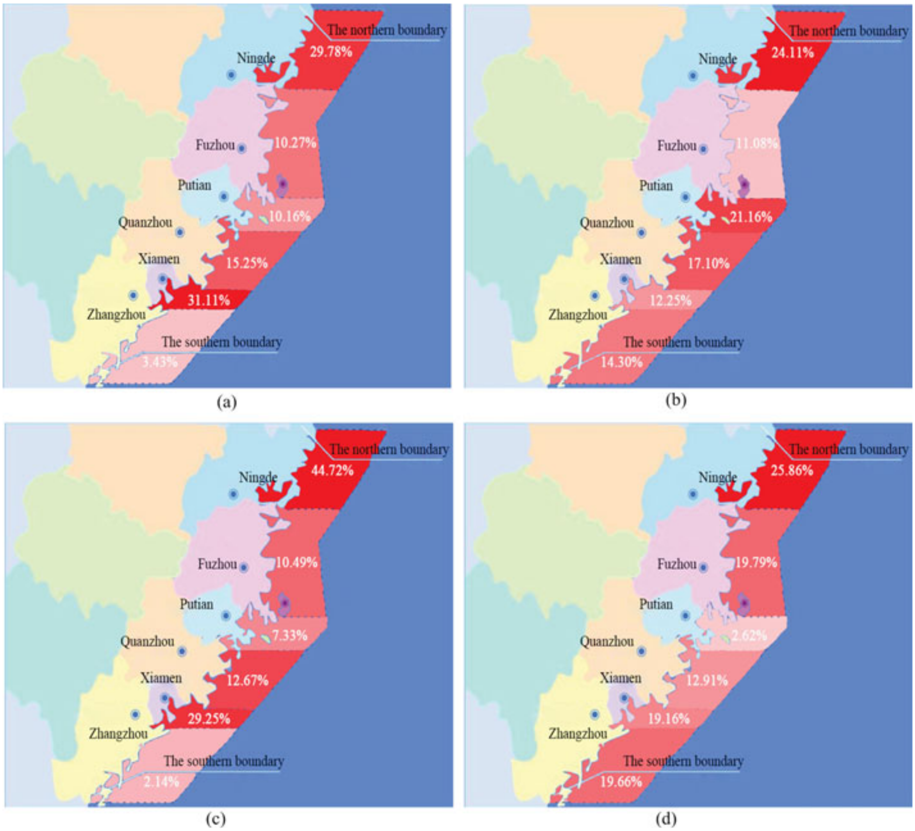

Figure 5. Spatial distribution of economic loss from ship collisions in different water areas: (a) total economic loss from fishing boat collisions; (b) average economic loss from each fishing boat collision; (c) total economic loss from collisions involving no fishing boat; (d) average economic loss from each collision involving no fishing boat.

loss for both fishing boat collisions and collisions involving no fishing boats, respectively. More specifically, Figure 5(a) shows that the economic loss caused by fishing boat collisions is largest in the water area of Xiamen (31·11%), whereas the smallest total economic loss from fishing boat collisions occurred in Zhangzhou water areas (3·43%). It should be pointed out that the average economic loss for each fishing boat collision is not the largest in Xiamen water area, as shown in Figure 5(b). This implies that there are fewer big fishing boat collisions that cause larger economic loss.

Figure 5(c) shows that the distribution of economic loss from collisions involving no fishing boats is similar across six different water areas, as are the data related to fishing boat collisions. More specifically, the Zhangzhou water area is also associated with the least total economic loss (2·14%) caused by collisions involving no fishing boats. The comparison of average economic loss between both collision types reveals that collision accidents occurring in the Ningde water area were most likely to cause more serious consequences, no matter whether fishing boats were involved or not, as shown in Figures 5(b)

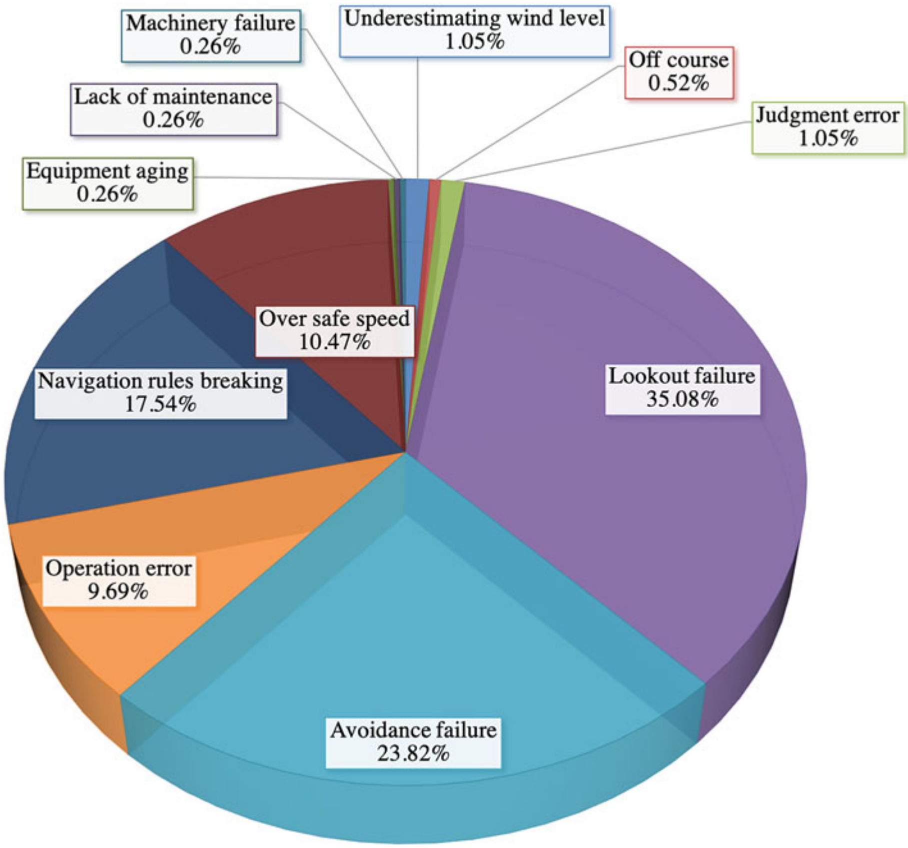

Figure 6. Distribution of accident cause factors in fishing boat collisions.

and 5(d). This implies that more attention should be paid to reducing the likelihood of serious collisions occurring in the Ningde water area.

For the analysis, we extracted full information from the collected fishing collision accidents that occurred in six different water areas including environmental characteristics, collision characteristics, and accident cause factors. Collision location, involved_cargo_ship, involved_passenger_ship, involved_oil_ship, involved_big_ship, navigational status and ship tonnage are regarded as collision characteristics. Environmental characteristics comprise: strong wind/waves, visibility and collision time. Different kinds of accident cause factors were provided in the raw accident records, including underestimating wind level, judgement error, lookout failure, avoidance failure, operation error, breaking navigation rules, sailing at unsafe speeds, overloading, equipment aging, lack of maintenance, and machinery failure. The distributions of various accident cause factors in fishing boat collisions can be seen in Figure 6. For simplicity, we classified these accident cause factors into four main factors: judgement error (including underestimating wind level), operation error (including failure of avoidance, breaking navigation rules, sailing at unsafe speeds, etc.), lookout failure, and machinery failure (equipment aging and lack of maintenance). The locations of collision accidents are divided into two groups: coastal/harbour/port areas and

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Table 1. Variables and descriptive statistics for ship collision accidents.

Variable	Description	Fishing boat collisions		Collisions involving no fishing boats	
		Mean	S.D.	Mean	S.D.
Economic loss	Economic loss resulting from two-ship collisions *(million RMB)*	1·402	2·256	1·071	2·806
Collision characteristics					
Collision location	0 for coastal_harbour_port area, 1 for straits/sea area	0·712	0·454	0·372	0·484
Involved_cargo _ship	1 for the involvement of cargo/container ship, otherwise 0	0·793	0·402	0·915	0·279
Involved_passenger_ship	1 for the involvement of passenger/cruise/ferry ship, otherwise 0	0·016	0·127	0·033	0·180
Involved_oil_ship	1 for the involvement of oil tanker or LNG/LPG/chemical ship, otherwise 0	0·109	0·312	0·118	0·323
Involved_big_ship	1 for the involvement of big ship, otherwise 0	0·019	0·104	0·060	0·239
Ship tonnage	The sum of tonnage for two ships involving in the collision accident	5,673	11,083	9,315	21,307
Navigational status	1 if underway, 0 if moored or docked	0·957	0·204	0·861	0·346
Environmental characteristics					
Visibility	1 for poor visibility conditions, 0 for good visibility conditions	0·375	0·485	0·329	0·471
Strong wind/waves	1 if yes, otherwise 0	0·158	0·365	0·133	0·340
Collision time	1 for nighttime, 0 for daytime	0·484	0·501	0·532	0·500
Accident cause factors					
Judgement error	1 for judgement error, otherwise 0	0·022	0·146	0·100	0·300
Lookout failure	1 for lookout failure, otherwise 0	0·728	0·446	0·520	0·500
Machinery failure	1 for machinery failure, otherwise 0	0·011	0·104	0·024	0·154
Operation error	1 for operation error, otherwise 0	0·799	0·402	0·828	0·378
Spatial and temporal effects					
Water area	5 for Xiamen; 6 for Zhangzhou	*	*	*	*
Year	Year in which the collision accident occurred	*	*	*	*

strait/sea areas. In general, there are two outcomes for the navigational status depending on whether the ships are underway or not.

Table 1 presents more details on the extracted explanatory variables mentioned above. It can be found from the table that the average value of economic loss caused by fishing

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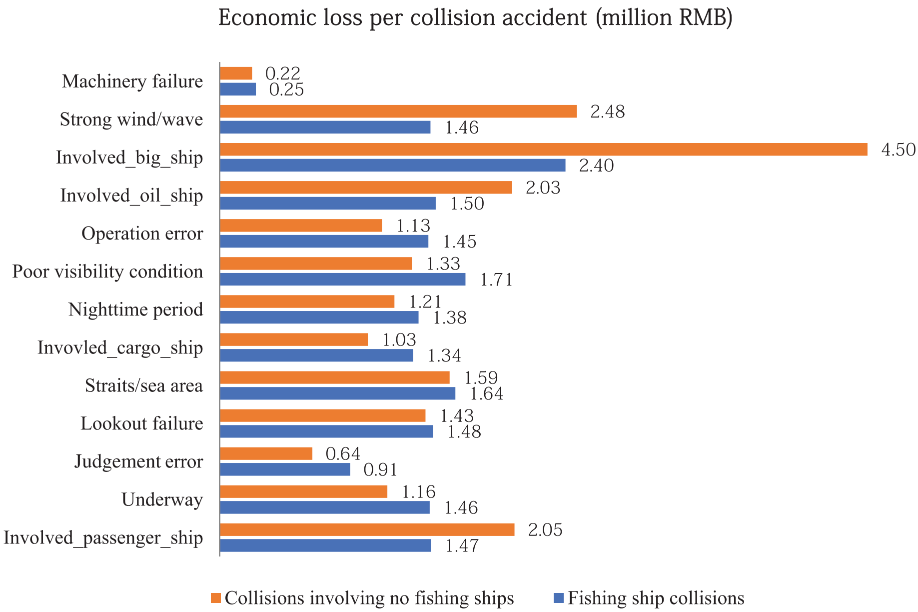

Figure 7. Comparison of average economic loss between fishing boat collisions (blue) and collisions involving no fishing boat (orange).

boat collisions is RMB 1·402 million across the six different water areas, which is a little larger than that from collisions involving no fishing boats (RMB 1·071 million). This implies that fishing boat collisions are generally more serious than collisions involving no fishing boat in terms of the resulting economic loss. From the mean of variables provided in Table 1, we can see that approximately 11% of the fishing boat collisions involved an oil tanker or an LNG/LPG/chemical ship. Similar statistics are also found for the collisions involving no fishing boats. The distribution of navigational status, strong wind/waves, visibility, judgement error, operation error, lookout failure, and machinery failure are also similar between two collision types. However, other variables like collision location and collision time vary substantially between the two collision types. For example, a minority of fishing boat collisions occurred during the nighttime period (48·4%) whereas 53·2% of collisions involving no fishing boats occurred at night. In addition, a larger proportion of fishing boat collisions (71·2%) occurred within the strait/sea area while only one-third of collisions involving fishing boats occurred within this water area. According to Table 1, it can also be seen that lookout failure (72·8%) and operation error (79·9%) are the major two human errors in fishing boat collision accidents.

Figure 7 graphically compares the average economic loss caused by the two collision types under various circumstances. It can be found from the figure that the average value of economic loss in fishing boat collisions is significantly greater than that from collisions involving no fishing boat under the following situations: (i) the collision occurs at night or under poor visibility conditions; (ii) the collision occurs when the ships are underway; and (iii) the collision involves human error like operation error and judgement error. However, fishing boat collisions are found to cause less economic loss than collisions involving no fishing boats in conditions of strong wind/waves.

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5. RESULTS AND DISCUSSION.

5.1. *Model results.* The results of spatial-temporal interaction models for both collision types (i.e., fishing boat collisions and collisions involving no fishing boats) are presented in Table 2, with a Bayesian credible interval (95% BCI). According to the model results, the majority of explanatory variables have positive coefficients, except for strong wind/waves and machinery failure in fishing boat collisions. The positive sign of a coefficient implies a higher economic loss as the value of this influencing factor increases and vice versa. This implies that the presence of machinery failure and lookout failure could result in higher economic loss in boat collision accidents. In addition, it can be found from Table 2 that the sign for strong wind/waves is negative for the fishing boat collisions while there is a positive coefficient of this variable for the collisions involving no fishing boats. This important finding implies that the strong wind/waves condition exhibits opposing effects on the economic loss resulting from the two collision types, respectively.

Table 2 also presents the heterogeneity effects including the unstructured spatial heterogeneity effect (σ_u), the spatial correlation effect (σ_s), the spatial-temporal interaction effect (σ_η), and the time trend effect (φ). The significant coefficient σ_η confirms the necessity of considering the spatial-temporal interaction effects in modelling the economic loss caused by ship collisions. The coefficients for the unstructured spatial heterogeneity effect (σ_u) and spatial correlation effect (σ_s) are both statistically significant for both collision types. Moreover, the unstructured spatial heterogeneity effect is much greater than the spatial correlation effect for both collision types (i.e., $\sigma_u = 1{\cdot}673$ and $\sigma_s = 0{\cdot}397$ for the fishing boat collisions). The negative sign of the time trend effect (φ) indicates that the economic loss resulting from ship collisions gradually decreases with the time trend in Fujian water areas.

5.2. *Comparison of the marginal effects of influencing factors in two collision types.* The estimated coefficients shown in Table 2 allow us to know whether a specific influencing factor presents a negative or positive impact on economic loss, however, the extent of the impact on economic loss is still unknown. In order to quantify this impact, we could take the exponent of the estimated coefficient for each influencing factor as the corresponding marginal effect in both collision types. Figure 8 shows the marginal effects of these factors on the economic loss in two collision types.

5.2.1. *Collision characteristics.* According to Figure 8, it can be found that three influencing factors: collision location, ship tonnage and the involvement of oil tanker, exhibit almost the same effects on the economic loss in both collision types. More specifically, consistent with previous studies (e.g., Jin, 2014), collision location is found to be closely associated with the economic loss for both collision types in this study. For example, Figure 8 indicates that the average economic loss caused by fishing boat collisions occurring in strait/sea areas (i.e., far away from the shore) is 63·23% larger than for fishing boat collisions occurring in the coastal/harbour/port areas. A similar effect of the collision location (51·44%) is found in collisions involving no fishing boat. In addition, increased ship tonnage is found to be associated with larger economic loss in both collision types. Consistent with our expectation, the involvement of ships carrying dangerous goods, like LNG, LPG or chemicals, could increase the economic loss for both collision types. This might be because collisions involving these dangerous ships are usually serious accidents that cause significant economic loss.

As expected, the involvement of passenger ships and cargo ships is found to increase the economic loss in both collision types. Nevertheless, note that the increment of economic loss caused by fishing boat collisions is much larger than that in collisions involving no

Table 2. The estimation results of spatial-temporal interaction model for ship collision.

	Fishing boat collisions			Collisions involving no fishing boats		
Variables	Mean	S.D.	95% BCI	Mean	S.D.	95% BCI
Constant	1·368	0·865	(−0·012, 2·812)	1·365	0·477	(0·581, 2·152)
Collision location	0·490	0·323	(−0·034, 1·019)	0·415	0·196	(0·098, 0·741)
Involved_cargo_ship	0·386	0·330	(−0·151, 0·934)	0·994	0·328	(0·450, 1·535)
Involved_passenger_ship	1·937	1·009	(0·270, 3·612)	0·810	0·491	(0·009, 1·599)
Involved_oil_ship	0·043	0·422	(−0·631, 0·749)	0·123	0·277	(−0·338, 0·580)
Involved_big_ship	0·043	1·308	(−2·089, 2·219)	0·695	0·469	(−0·098, 1·462)
Ship tonnage	0·323	0·097	(0·163, 0·482)	0·222	0·080	(0·095, 0·356)
Navigational status	1·430	0·716	(0·225, 2·592)	0·566	0·282	(0·108, 1·034)
Visibility	0·210	0·273	(−0·228, 0·667)	0·179	0·189	(−0·135, 0·492)
Strong wind/waves	−0·176	0·367	(−0·785, 0·434)	0·315	0·271	(−0·127, 0·765)
Collision time	0·301	0·865	(−0·122, 0·731)	0·224	0·174	(−0·067, 0·504)
Judgement error	0·668	0·904	(0·015, 0·677)	0·106	0·303	(−0·386, 0·598)
Lookout failure	0·494	0·293	(0·022, 0·981)	0·472	0·185	(0·164, 0·781)
Machinery failure	−0·439	1·271	(−2·543, 1·677)	−1·006	0·600	(-1·980, 1·009)
Operation error	0·099	0·338	(−0·463, 0·656)	−0·616	0·255	(−1·042, −0·202)
σ_s	0·397	0·361	(0·092, 1·040)	0·383	0·318	(0·096, 0·950)
σ_u	1·673	0·093	(1·525, 1·831)	1·533	0·061	(1·435, 1·636)
φ	−0·045	0·035	(−0·103, 0·012)	0·011	0·024	(−0·030, 0·051)
σ_η	0·112	0·054	(0·056, 0·207)	0·094	0·043	(0·050, 0·172)
DIC	730·989			1,243·930		

fishing boats. The higher increment caused by the involvement of fishing boats could be probably because small fishing boats are not compulsorily equipped with the AIS that could make ships visible to each other (Weng et al., 2019). For those fishing boats equipped with AIS devices, they sometimes may shut down the AIS in order to avoid maritime supervision. In addition, fishing boats are less likely to comply with collision avoidance rules than commercial ships (cargo ships). Apparently, the irresponsible navigation behaviour of unseen fishing boats may result in greater economic loss when they are involved in ship collisions. Note that fishing boats are also more likely to display irresponsible navigation behaviour when they are underway in reality. This could fully explain another finding from Figure 8 that the increment of economic loss in underway collision accidents is also much bigger for fishing boat collisions (317·87%) compared with the collisions involving no fishing boats (76·12%).

In order to decrease the likelihood of collisions occurring, it sould be compulsory for fishing boats to comply with the collision avoidance rules. In addition, fishing boats should not impede the passage of other ships, especially larger commercial ships. It should also be mandatory for fishing boats, in case of danger, to use sound or light signals in order to warn approaching ships. In addition, small fishing boats should be encouraged to be equipped with AIS devices and maritime authorities should propose effective countermeasures to forbid fishing boats shutting down their AIS, especially when they are underway.

5.2.2. *Environmental characteristics.* Figure 8 shows that nighttime collisions could cause slightly greater economic loss for both collision types, which is close to findings from past studies (e.g., Talley et al., 2006; Debnath and Chin, 2009). More specifically, the nighttime period could result in a 35·12% increment of the economic loss in fishing boat collisions and 25·11% in collisions involving no fishing boats, respectively. The greater

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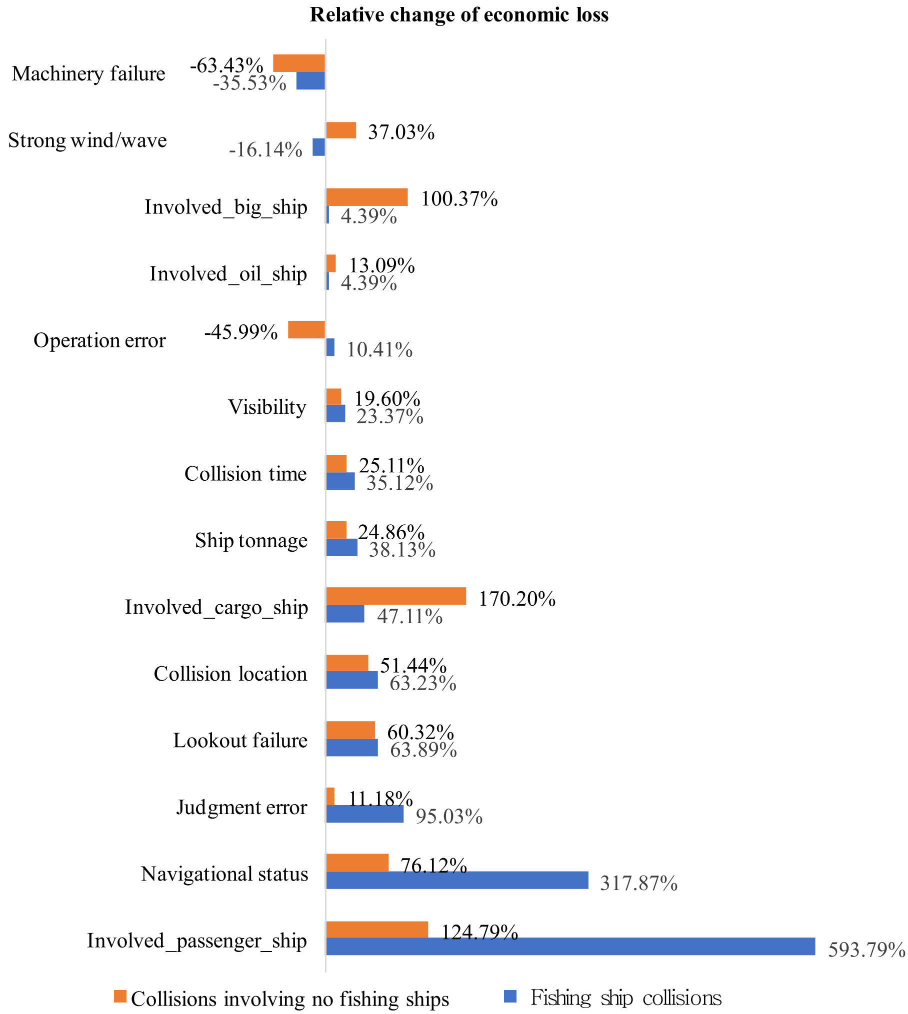

Figure 8. Comparison of marginal effects of economic loss between fishing boat collisions (blue) and collisions involving no fishing boat (orange).

economic loss during the nighttime period might be because search and rescue operations are less efficient at night than in daytime. Similarly, poor visibility could slightly increase economic loss from collisions. The average collision economic loss in poor visibility conditions is 23·37% greater for fishing boat collisions and 19·60% greater for collisions involving no fishing boats, compared with good visibility conditions. It is clear that the likelihood of human error is relatively higher in conditions of poor visibility. In addition, the efficiency of accident detection and emergency rescue operations is greatly reduced in poor visibility conditions.

In contrast with collision time and visibility, the strong wind/waves condition presents the opposite effects to the economic loss in two different collision types. More specifically, the presence of strong wind/waves increases the economic loss by 37·03% for collisions

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involving no fishing boats, as shown in Figure 8. However, the economic loss of fishing boat collisions is reduced by 16·14% in strong wind/waves conditions. It should be pointed out that this result is reasonable because many additional safety measures are adopted for fishing boats in such conditions. For example, almost all of the fishing boats are forewarned by Fujian maritime authorities to enter anchorages or sheltered harbours before the arrival of strong winds (e.g., typhoons), measures which could greatly decrease the probability of serious fishing boat collisions occurring in such conditions.

5.2.3. *Accident cause factors.* Human errors are reported to be the major causes of ship accidents (e.g., Martins and Maturana, 2010; Karahalios, 2014). As mentioned in the descriptive statistics, operation errors and lookout failure are the two major types of human error in fishing boat collisions. This is due to the fact that the bridge is often unattended when fishing boat crews focus on fishing. Figure 8 reveals that lookout failure could present a little more effect on economic loss in fishing boat collisions than that in collisions involving no fishing boats. The occurrence of lookout failure can increase the economic loss by 63·89% for fishing boat collisions and by 60·32% for collisions involving no fishing boats. However, the effect of judgement error on the economic loss in collisions is quite different for both collision types. There is a significant increment (95·03%) of economic loss in fishing boat collisions involving judgement errors while it only contributes to an 11·18% increase of economic loss in collisions involving no fishing boat. This result highlights that, for the purpose of mitigating the consequences of fishing boat collisions, there is a critical need to take countermeasures (e.g., enhancing navigation skills and education training for fishermen) to decrease the likelihood of judgement errors by fishing boat crews.

Interestingly, the occurrence of machinery failure is associated with lower economic loss in both collision types. Moreover, the economic loss will be reduced by 35·53% in fishing ship collisions suffering machinery failure, as shown in Figure 8. The reduction in economic loss for the event of machinery failure is readily explained by the fact that ships suffering a machinery failure usually have adequate time to reduce their sailing speed gradually before a collision occurs, as compared with a sudden collision where two ships quickly collide at relatively higher sailing speeds. Obviously, the reduced sailing speeds could mitigate the consequence of ship collision. In addition, there is often more time for rescue operations in the event of machinery failure, which could further reduce the consequences of a ship collision.

6. CONCLUSIONS.

Considering the unobserved spatial effects and time effects in shipping collision accidents, we propose a Bayesian spatial-temporal interaction model for predicting the economic loss in fishing boat collisions. Considering the difference in navigation behaviour between fishing boats and commercial boats, collisions involving no fishing ships are also investigated for the purpose of comparison. With 10 years of records of ship collisions occurring across six different water areas in Fujian waters, the model parameters are determined for fishing boat collisions and collisions involving no fishing boats, respectively. In addition, the marginal effects of influencing factors are compared between both collision types in this study.

The geographical locations of fishing boat collisions show that the majority of collision accidents happened near the coastline closed to Mindong fishing ground, Minzhong fishing ground, and Minnan fishing ground. Water areas around Mintai central fishing port and Daao central fishing port show greater frequency of fishing boat collisions than other water areas. Narrow waterways and commercial routes are highly dangerous places for fishing ships. For both fishing boat collisions and collisions involving no fishing boat, the total economic loss greatly varies with water areas managed by different fishing cities. Zhangzhou water area is found to be associated with the least economic loss for both collision types. The model results show that the economic loss is generally greater for both types of collisions when they occurred: (i) in the straits/seas; (ii) during the nighttime period; (iii) in poor visibility conditions; (iv) when LNG/LPG/chemical-carrying ships are involved. The economic loss is slightly higher for fishing boat collisions caused by lookout failure. In addition, in both types of collisions, machinery failure was associated with reduced economic loss because ships suffering machinery failure usually have adequate time to reduce their sailing speed before the occurrence of a collision.

Three factors – navigational status and the involvement of passenger ships and cargo ships – are found to exhibit varying effects on the economic loss between both collision types. For example, the increment of economic loss caused by the involvement of cargo ships in fishing boat collisions is much larger than that in collisions involving no fishing ships. In addition, the increment of economic loss under the status of underway is substantially larger for fishing boat collisions, as compared with the collisions involving no fishing boats. The higher increment of economic loss in fishing boat collisions could be attributed to the fact that fishing boat are not compulsorily equipped with AIS devices so that they are not easily detected by other ships. Some fishing boats equipped with AIS devices may even shut down the AIS service in order to avoid maritime supervision. In addition, fishing boats are less likely to comply with collision avoidance rules. Obviously, the irresponsible navigation u of unseen fishing boats could result in larger economic loss when they are involved in ship collisions. Another important finding is that the presence of strong wind/waves could increase the economic loss in collisions involving no fishing boats while the economic loss in fishing boat collisions is generally reduced in strong wind/waves conditions. The opposing effects of strong winds/waves are readily explained by the fact that many additional safety measures are adopted for fishing boats in such conditions (i.e., fishing boats are forewarned to enter anchorages or sheltered harbours before the arrival of strong winds).

The results of this study are useful for maritime authorities and shipping companies in prioritising various navigation safety-enhancing measures and strategies. For example, it is recommended that maritime authorities should strengthen the supervision of the water areas of Mintai central fishing port and Daao central fishing port, where there is higher likelihood of fishing boat collisions than other waters. More focus should be also placed on narrow waterways and the intersections of commercial routes. Since collisions between fishing boats and passenger ships may cause disastrous consequences, small fishing boats are encouraged to be equipped with AIS devices so that their positions could be monitored in these water areas accurately. In addition, policymakers should propose effective countermeasures to forbid fishing boats shutting down their AIS service, especially when they are underway. Insurance companies can also adopt the developed model to help determine the appropriate ship insurance rates. The spatial-temporal interaction effects have been considered for the model formulation in this study. However, the effects of some influencing factors might vary with different water areas. Therefore, our future study will attempt to build a geographically weighted regression model to account for the spatially varying coefficients.

DISCLAIMER

The views expressed in this study only reflect the opinion of the author and must not be considered as official opinions from any national or international maritime authorities.

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