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Investigation of Occurrence Likelihood of Human Errors in Shipping Operations

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Abstract

Human errors are one of the most significant contributory factors in ship accidents. This study aims to explore the quantitative relationship between the occurrence likelihood of human errors and external factors including the environmental characteristics, accident characteristics and ship characteristics. A multinomial logistic regression model has been developed to reflect the relationship between these factors and the occurrence likelihood of human errors using 14 years' ship accident records from Fujian water areas. Model results show that the season of spring, poor visibility and night are more likely to be associated with high occurrence likelihood of negligence and judgment/operation errors. One important finding is that mooring and no strong-wind condition are two circumstances that would highly increase occurrence likelihood of all kinds of human errors. Fishing boats and engineering ships/sand dredgers are the primary ship types which have relatively higher occurrence likelihood of negligence errors than other ship types.

Key words: Human errors, shipping accidents, shipping operation, accident risk.

1. Introduction

Shipping, as a major international transportation mode, is increasingly crucial to trade and economy development around the world. With the continuous increase of shipping activities, it is an important and hot topic to prevent the occurrence of ship accidents. Previous studies (e.g., Wang and Dai, 2012) revealed that the majority of ship accidents are associated with human errors, e.g., 70-80% for collision accidents, 65-70% for grounding accidents and 85-90% for fire/explosion accidents. Considering the significant effects of human errors, the International Maritime Organization (IMO) put efforts in avoiding the occurrence of human errors. To achieve this objective, there is a critical need to analyze, under what circumstances, human errors could occur in shipping operations.

To date, a number of studies have been conducted for the analysis of human errors in ship accidents. Wang et al. (2005) found that negligence/carelessness of the crew accounts for the largest proportion of fishing vessel accidents. Nishizaki et al. (2012) identified "judgment" as the bottleneck task for preventing ship collisions and made it possible to analyze and predict crew's behavior as well as to indicate the cause of accident by modeling judgment patterns. Pazouki et al. (2018) investigated the impact of human-automation interaction in maritime operations.

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A number of models and methods have been used in maritime accident analysis to evaluate probability occurrence of accidents (e.g., Ma et al., 2016; Mullai and Paulsson, 2011; Ugurlu, 2016), including many systemic and organizational models (e.g., Reason, 1997; Xi et al., 2017; Uğurlu et al., 2018; Wu et al., 2018). For example, Chen et al. (2013) proposed a Human Factors Analysis and Classification System for Maritime Accidents (HFACS-MA). Chauvin et al. (2013) and Ugurlu et al. (2018) proposed a modified version of the Human Factor Analysis and Classification System (HFACS) for the analysis of human and organizational factors in ship collisions, fire and grounding and passenger vessel accidents, respectively. Although HFACS is appropriate for the human factor analysis in maritime accidents, it mainly allows for the qualitative analysis that could not be directly applied for the quantitative analysis.

The fault tree analysis (FTA) (e.g., Antão and Soares, 2006) is another broadly used methods for modeling accident scenarios, it use "AND" and "OR" gates to find root causes of accident. For example, Ugurlu et al. (2015) used the FTA method for collision and grounding accident analysis in oil tanker. Zhou et al. (2017) employed a fault tree analysis (FTA) to assess the safety of LNG (Liquid Natural Gas) carriers. In our case, the available data doesn't easily support the construction of a fault tree.

Bayesian networks (BN) is a start-of-art method widely used for the analysis of maritime accident occurrence likelihood (Akhtar and Utne, 2014; Wang et al., 2013) and accident consequence (Wang and Yang, 2018). BN is good at modeling risk factors of strong interdependency, the experimental evidence relating to our case doesn't show strong independence among the factors.

Analytic Hierarchy Process (AHP) (e.g., Arslan and Osman, 2009; Ugurlu et al., 2016; Kececi and Arslan, 2017) is often combined with fuzzy logic (Balmat et al., 2009) for identifying the contributory factors for maritime accidents from expert judgments (Ugurlu, 2015). However, these methods are more applicable under the circumstance when it lacks of adequate observation data for the analysis.

In this paper, we apply multinomial logistic regression to investigate the occurrence likelihood of human errors in shipping operations, which can reasonably interpret the marginal effects of influencing factors. In reality, the occurrence likelihood of human error may be simultaneously affected by various influencing factors (i.e. environmental characteristics, ship characteristics, etc.) in ship accidents. Considering the fact that the occurrence likelihood of human errors may be affected by multiple influencing factors at the same time, it is of utmost importance to model the quantitative relationship between human errors and influencing factors once we are given adequate number of historical records (Weng et al., 2018).

In general, human error can occur in many forms (e.g., Rasmussen, 1983; Reason, 1990; Harati-Mokhtari et al., 2007; Schager, 2008; Chauvin, 2011; Graziano et al., 2016). Reason (1990) divided human error into four types from a perspective of unsafe acts, including slip, lapse, mistake and violation. Rasmussen (1983) categorized human errors into three levels including the skill-based, rule-based and knowledge-based error levels. They indicated that there is no significant difference between the skill-based error and the rule-based error. In both studies, the rule-based error is referred as the application of wrong rules, or as the application of right rules but in wrong contexts (e.g., judgment/operation error). The knowledge-based error is referred as the inadequate knowledge to perform a task (e.g., negligence). In ship accidents, a negligence may occur when the crew receive wrong or inadequate information while a judgment/operation error may occur when crew falsely proceed the information or make a wrong decision. The negligence is actually regarded as a knowledge-based error, while the judgment/operation error belongs to the skill-based and rule-based errors. More details on this human error classification are shown in Figure 1. It should be pointed out that the negligence and judgment/operation errors may occur simultaneously in shipping operations. Hence, human errors possibly occurred in shipping operations can be categorized into three groups: the occurrence of negligence error only, the occurrence of judgment/operation error only, and the simultaneous occurrence of negligence and judgment/operation errors. Hereafter, negligence errors include the lack of lookout and inadequate watch-keeping, while incorrect situation assessment, the use of unsafe sailing speed, inappropriate collision avoidance action and non-compliance with navigation rules are considered as judgment/operation errors.

Hence, the objective of this study is to explore the quantitative relationship between human errors and their influencing factors including environment, accident and ship characteristics using the multinomial logistic regression approach, which has been rarely addressed by the previous literature. This study is a pioneering work to quantify the effects of influencing factors on the occurrence likelihood of human errors using statistical regression techniques. With such useful information, the shipping companies and maritime authorities can review the efficiency of their current navigation management strategies and further propose some effective strategies to reduce the occurrence likelihood of human errors. Hence, the results of this study are beneficial for shipping companies and government policies.

2. Methodology

Multinomial logistic regression is one of the most applied econometric models that generalize logistic regression to multiclass problems, i.e., with more than two possible discrete outcomes. More specifically, it is a model that is used to predict the probabilities of different possible outcomes for a categorically distributed dependent variable, given a set of independent variables. The multinomial logistic regression model also can be used to estimate the marginal effect of each independent variable. Since this study concentrates on human errors in shipping operations, the human error outcome is considered as the target variable that can take one of the four values: 0, 1, 2 and 3. For example, it can be assumed that the human error outcome satisfies the following relationship

$$Y = \begin{cases} 0, \text{ if the ship incurs non-human errors} \\ 1, \text{ if the ship incurss Type I human errors: negligence errors only} \\ 2, \text{ if the ship incurs Type II human errors: judgement and operation errors only} \\ 3, \text{ if the ship incurs Type III human errors: Types I and II human errors} \end{cases} \quad (1)$$

The following multinomial logistic regression technique is employed to model the human errors in shipping operations as

$$Y_{in} = \boldsymbol{\beta}_i \boldsymbol{X}_{in} + \varepsilon_{in} \tag{2}$$

where Y_{in} is a linear predictor function to determine the i^{th} human error type for the ship n. $\boldsymbol{X}_{in}$ is the vector of independent variables (i.e. season, ship type and so on) influencing the occurrence probability of human error in shipping operations, $\boldsymbol{\beta}_i$ is the vector of coefficient to be estimated.

The probability of ship n suffering the i^{th} type of human errors, denoted by $P_n(i)$, can be calculated by

$$P_n(i) = \frac{\exp(\boldsymbol{\beta}_i \boldsymbol{X}_{in})}{\sum_{\forall I} \exp(\boldsymbol{\beta}_i \boldsymbol{X}_{in})} \tag{3}$$

Since this study concentrates on the human errors in shipping operations, the type of non-human errors (i.e. $Y=0$) is chosen as the reference category in the regression analysis.

3. Data

To analyze the human errors involved in shipping accidents, we collected 1248 records from a historical accident database managed by the Fujian Maritime Safety Administration covering the period from 2000 and 2014. This database has a detailed record for each ship accident in the southeast water area of China. Each record contains the information regarding environmental characteristics, ship characteristics and accident characteristics. More detailed information with regard to these influencing factors is listed below.

(a) Environmental characteristics: this type of information includes detailed information with regard to the season (spring, summer, autumn and winter), the visibility (poor visibility condition; good visibility condition), winds/waves (strong winds/waves; no strong winds/waves), and time of the day (night; day).

(b) Accident characteristics: accident type and accident location (near port water areas; far away from port water areas) are taken into account as accident characteristics. Six accident types are considered in this study, including sinking, contact, grounding, collision, fire and explosion, and others (e.g., hull damage/machinery failure).

(c) Ship characteristics: this type of information includes the navigational status (moored/docked; underway) and ship type (cargo/container ship; fishing boat; LNG/LPG(Liquefied petroleum gas)/Oil tanker; other ship types). It should be pointed out that towing vessels, engineering ships and sand dredgers belong to the category of other ship types.

It should be pointed out that some factors may be closely linked to other factors in shipping accidents. Therefore, both Pearson correlation and covariance tests will be applied to check which factor may covariate with other factors. One factor that is closely linked to other factors will be combined into one group in order to avoid variable covariance problems.

Table 1 provides more details of the 11 independent variables mentioned above. In total, 1248 records were collected from 2000 to 2014. Both Pearson correlation and covariance test results show that the season of summer is linked to the accident location. After several trials, it is found that there exists no variable covariance problem if three seasons including summer, autumn and winter are categorized into one group (other seasons). Among these records, 247 records involve non-human errors while there are 94 records involving Type I human errors (i.e., negligence errors only) and 539 records involving Type II human errors (i.e., judgment/operation errors only). It should be pointed out that 368 ships suffer Type III human errors, namely, the simultaneous occurrence of Types I and II human errors. Table 1 also shows that the overall distribution of shipping accidents based on the selected independent variables. It can be clearly seen that there is a large proportion of shipping accidents occurring under the circumstances with good visibility conditions, no strong winds/waves and the situation when ships are underway. In addition, cargo and container ships are the major types of ships involved in shipping accidents. From the table, it can be also seen that the majority of shipping accidents are collisions.

Figure 2 graphically compares the human error distributions of different types under various circumstances associated with the environment, accident and ship characteristics. It can be observed from Figure 2(b) that there is a bigger proportion of shipping accidents involving negligence, judgment/operation errors under poor visibility conditions than good visibility conditions. In addition, the proportion of shipping accidents involving human errors is bigger for the conditions characterized by the season of spring and no strong winds/waves, as shown in Figures 2(a) and (c). Interestingly, it can be clearly seen that the human error distribution varies substantially among ship types and accident types. More specifically, a bigger proportion of human errors are strongly associated with fishing boats and three accident types including contact, grounding and collision accidents.

4. Results and discussions

4.1 Univariate statistical analysis results

One of the univariate statistical techniques is the quasi-induced exposure technique, which is usually applied to measure the relative propensity of different groups. To extend the quasi-induced exposure technique into exploring the impacts of environment, accident and ship characteristics on human errors in shipping operations, we compare the proportion of records involving human errors with that involving non-human error. The relative human error ratio (*RHER*) is thus adopted to measure the relative effects of environment, accident and ship characteristics, which is defined as:

$$RHER_{k,i}^{m} = \frac{\text{Proportion of records involving the } m^{\text{th}} \text{ type of human errors under the } k^{\text{th}} \text{ condition of the } i^{\text{th}} \text{ variable}}{\text{Proportion of records involving non-human errors under the } k^{\text{th}} \text{ condition of the } i^{\text{th}} \text{ variable}}$$

$$= \frac{N_{k,i}^{m} \Big/ \sum_{j=1}^{n_i} N_{j,i}^{m}}{N_{k,i}^{0} \Big/ \sum_{j=1}^{n_i} N_{j,i}^{0}} \quad (4)$$

where $RHER_{k,i}^{m}$=relative ratio of the m^{th} type of human errors under the k^{th} condition for the variable *i*; n_i=the number of conditions associated with the variable *I*; $N_{k,i}^{m}$ =the number of records involving the m^{th} type of human errors under the k^{th} condition for the variable *i*; $N_{k,i}^{0}$=the number of records involving non-human errors under the k^{th} condition for the variable *i*. According to the above definition, the m^{th} type of human errors is more likely to occur as $RHER_{k,i}^{m}$>1.0 while a ship is less likely to be associated with the m^{th} type of human error if $RHER_{k,i}^{m}$<1.0.

Figure 3 depicts the relative human error ratios for different situations characterized by the environment, accident and ship characteristics. Figure 3 (a) shows that the *RHER* for the season of spring is larger than 1.0, suggesting that human errors are more likely to occur in the season of spring. Similarly, ships are more likely to incur human errors under one of the following situations: (i) visibility=poor visibility; (ii) time of the day=night; (iii) navigational status=moored/docked and (iv) ship type=fishing boat. This is because the *RHER* values for these situations are all larger than 1.0. Figure 3 (e) shows that the *RHERs* of contact, grounding and collision are larger than 1.0, indicating that these three accident types are more likely to be associated with human errors.

Nevertheless, the above quasi-induced exposure technique only allows the analysis of a single categorical factor at a time. This may give rise to biased or incorrect results due to the isolation of a single factor for analysis while other factors are held fixed. In reality, the occurrence likelihood of human errors may be affected by multiple factors at the same time.

4.2 Multinomial logistic regression model results

The logit procedure in the Statistical Product and Service Solutions (SPSS, 22.0) is applied to estimate the coefficients of independent variables for the multinomial logistic regression model. The Wald chi-squared statistic is used to check the variable significance in the model. Two statistics including the Akaike information criterion (AIC) statistic and -2 log-likelihood statistic are applied to access the goodness of fit for the model.

The variable coefficients and related statistical results of the multinomial logistic regression model with regard to different types of human errors are given in Table 2. From the table, it can be seen that poor visibility conditions, no strong winds/waves, accident types of contact, grounding and collision, the involvement of fishing boat and other ship types (e.g., engineering ships and sand dredgers) are statistically (at the significance level of 0.20) associated with an increased occurrence likelihood of three types of human errors. Moreover, Table 2 also shows that the occurrence likelihood of Type I human error (negligence errors only) is greatly affected by two factors including the season and time of the day at the significance level of 0.20. However, the coefficient associated with the sinking is negative for Type I human error but positive for Type II human error, indicating that opposing effects in sinking accidents are exhibited on the occurrence likelihood of different types of human errors, respectively.

It should be pointed out that Type I human error is not strongly affected by the accident location which has significant influences on the occurrence likelihood of Type II and Type III human errors, respectively. More specifically, the negative coefficient associated with the accident location for Type III human errors suggests that the simultaneous occurrence probability of negligence and judgment/operation errors is bigger for a ship sailing far away from port water area than that near port water area. Similar to fishing boats, cargo/container ships and LNG/LPG/Oil tankers are also found to be strongly associated with the increased occurrence likelihood of Type III human errors (i.e., simultaneous occurrence of negligence and judgment/operation errors).

4.3 Discussions

Although the signs of the estimated coefficients for the multinomial logistic regression model could provide information on whether changes in given variables increase or decrease the occurrence likelihood of human errors, they do not provide information on the extent to which the underlying human error probabilities change. For example, there is a critical need to examine the impact of changes in the influencing factors on the occurrence probability of Type I human error. In this study, the odds ratio (OR) is employed to represent the marginal effect for a given variable that is defined as the relative amount by which the odds of human errors increase or decrease when the corresponding variable's value increases by one unit. The marginal effects of influencing factors on the occurrence likelihood of human errors across different human error types are presented in Figure 4. For clarity, the marginal effect results are discussed according to the categories mentioned earlier.

4.3.1 Marginal effects of environmental characteristics

Figure 4 shows that the OR associated with the visibility is 2.45 for Type I human error, 1.48 for Type II human error and 1.44 for Type III human error. This result implies that a ship sailing under the poor visibility condition is 2.45 times more likely to incur negligence errors than that sailing under the good visibility condition. In addition, under the poor visibility condition, a ship has a 48% higher probability of incurring judgment/operation errors. The high occurrence likelihood of negligence and judgment/operation errors might be due to the fact that it is more frequent for the lookout to neglect the potential hazards under poor visibility conditions. For instance, it is found that the proportion of accidents involving lookout failures under the poor visibility condition is about twice of that under the good condition in Fujian water area from 2001 to 2014. As evidenced by Flohberger (2010), low visibility will impact the responding ability of the watch-keeper on the bridge and neighboring vessels. In addition, the detection range will be reduced under the poor visibility condition, which could further increase the occurrence probability of the master's wrong decisions and crew's operation errors. In order to reduce the occurrence probability of negligence and judgment/operation errors, the master must depend on electronic aids such as electronic charts, automatic identification system (AIS), radar and vessel traffic service (VTS) to improve the accurate detection rate and communication with passing vessels under the poor visibility conditions (Cockcroft and Lameijer, 2012).

Similar to the factor of visibility, the factor of season is also found to have significant effects on the occurrence likelihood of human errors. More specifically, a ship has a 102% higher probability of incurring negligence errors (OR=2.02 for Type I human error) and an 84% higher probability of incurring negligence and judgment/operation errors simultaneously (OR=1.84 for Type III human error) in the season of spring. According to port throughput statistics (China Port, 2017), the cargo transportation demands reach its top in spring. The possible heavy workload in this season could cause ship crew members making more mistakes like negligence.

Consistent with our expectation, the nighttime period is associated with the higher occurrence likelihood of human errors like negligence and judgment/operation errors. More specifically, the OR=1.55 for Type I human error in Figure 4 reveals that the occurrence likelihood of negligence error is 55% higher at nigh than during the daytime period. There is also a 10% increased occurrence probability for Type III human error (i.e., simultaneous occurrence of negligence and judgment/operation errors) at night. Apparently, fatigue may have contributed to the captain's perceptual error and the crew's unresponsiveness. Appropriate work schedules could provide the crew with sufficient sleep time and thus reduce fatigue at night (Lutzhoft, 2007; Williamson et al., 2011).

Interestingly, our results show that the presence of strong winds/waves could decrease the occurrence likelihood of human errors. For example, it is found that the occurrence probability will be reduced by 61% for Type I human error (i.e., negligence errors only), by 65% for Type II human error (i.e., judgment/operation errors only) and by 66% for Type III human error (i.e., the simultaneous occurrence of negligence and judgment/operation errors), respectively. This result is consistent with the reality because all ships are forewarned to enter sheltered harbours and/or anchorages before the onset of strong winds/waves (e.g., typhoons) in Fujian water areas. These safety measures could greatly reduce the occurrence likelihood of human errors. This result is also consistent with the previous finding that monotonous weather conditions with no strong winds/waves can lead to the increased number of human errors because of reduced vigilance (Williamson et al., 2011; Akhtar and Utne, 2015). Therefore, corresponding measures should be considered for preventing the occurrence of human errors under the weather condition with no strong winds/waves.

4.3.2 Marginal effects of accident characteristics

Figure 4 shows that the high occurrence likelihood of Type II human error is associated with the sinking accident (OR=2.78). Although the OR associated with the sinking accident is larger than 1.0 for Type III human error, it is not statistically associated with the increased occurrence likelihood of the negligence and judgment/operation errors.

Compared with other accident types like hull damage and machinery failure, three accident types including contact, grounding and collisions are strongly associated with the higher occurrence likelihood of human errors because their ORs are larger than 1.0, as shown in Figure 4. For example, collisions are 1.90 times more likely to be incurred by Type I human errors than hull damage/machinery failure accidents, 8.89 times more by Type II human errors and 15.74 times more by Type III human errors. The increased human error occurrence likelihood among these three accident types can possibly be explained by the previous finding that there are more inadequate watch-keeping, crew's fatigue, the master's reduced ability to discharge his duty, poor manning level and lack of lookout in ship collisions and groundings (MAIB, 2004). In addition, if there is a collision threat, the crew's mental workload will definitely increase and the performance on the secondary task (e.g., collision avoidance action) will be reduced subsequently, further leading to 70% more human errors (Hetherington et al., 2006). In order to reduce collisions caused by human errors, one important countermeasure is to require that crews should fully understand navigation regulations and be familiar with emergency collision avoidance procedures. In addition, better procedures and training should be designed to promote better communications between shipmates, masters, ship-to-ship and ship-to-VTS. In addition, a combination of better training, standardized equipment design and an overhaul of the present method of assigning crew to ships is also required.

Another finding from Figure 4 is that the ORs associated with the accident location are lower than 1.0 for Types II and III human errors, respectively. This suggests that ships sailing near port water area are less likely to incur negligence and judgement/operation errors, compared with those sailing far away from port water area. Note that this finding is supported by previous research results that the watch-keeper will be more vigilant in busy water areas where there a large number of vessels and platforms (Flohberger, 2010). On the other hand, more emphasis should be put on the careful navigation behaviour for the ship sailing far from port water area, which can greatly reduce the occurrence likelihood of negligence and judgement/operation errors within this area.

4.3.3 Marginal effects of ship characteristics

Many researchers (e.g., Talley et al., 2006) reported that the navigational status could influence ship accident consequence significantly. Actually, the occurrence likelihood of human errors is greatly affected by the navigational status. More specifically, the occurrence probability of negligence errors will be increased by 114% (OR=2.14 for Type I human error) for the ships when they are mooring/unmooring, compared with the ships which are underway. In general, the occurrence probability of judgement/operation errors for the mooring/unmooring ships is about four times of that for the ships which are underway, as shown in Figure 4. One possible reason for the higher occurrence probability of human errors for the mooring/unmooring ships is that mooring/unmooring tasks are usually more complex. Therefore, major efforts should be placed to force fishing ship crew to comply with mooring regulations. For example, the crew members involved with the mooring operation should be aware of the snap back zones and rope bight and try to avoid mixed mooring. In addition, the intelligent mooring monitoring system can also be applied to mitigate the occurrence likelihood of human errors because it could reduce the work intensity of officer on watch and improve work efficiency through calculating mooring safety alert radius automatically.

In addition to the navigational status, the ship type also has a significant effect on the occurrence likelihood of human errors. Moreover, Figure 4 reveals that Type III human errors are most likely to be associated with fishing boats (OR=4.27), followed by cargo/container ships (OR=3.18) and then other ship types like engineering ships and sand dredgers (OR=2.72). Fishing boats and engineering ships/sand dredgers are the primary ship types which have relatively higher occurrence likelihood of negligence errors because their corresponding ORs are larger than other ship types. This result may be due to the fact that crew members of fishing boats, engineering ships and sand dredgers are not compulsory to have a license or other mariner credential. In addition, fishing boats had more reports of alcohol use and fatigue than merchant ships (Loughran et al., 2012; Hovdanum et al., 2014).

From Figure 4, it can also been seen that LNG/LPG/oil tankers are less likely to incur negligence errors as the OR for Type I human error is smaller than 1.0. This result is consistent with our expectation because these ships carry oils or other hazardous/dangerous liquid goods and crew members have to be more vigilant in shipping operations. However, it should be also pointed out that LNG/LPG/oil tankers also have slightly higher occurrence likelihood of judgment/operation errors though these ships implement the safety management system to the fullest extent. One possible reason might be that there is high fault tolerance for LNG/LPG/oil tankers (e.g., a small mistake or inappropriate judgment could be easily corrected for these ships in reality).

5. Conclusions

The main objective of this study is to explore the relationship between the occurrence likelihood of human errors and external factors including environmental characteristics, accident characteristics and ship characteristics in shipping operations. Based on the literature review and investigation, we found that human errors involved in shipping operations were classified into four groups: non-human errors, negligence errors only (Type I human error), judgment/operation errors only (Type II human error) and the simultaneous occurrence of negligence and judgment/operation errors (Type

III human error). A multinomial logistic regression model has thus been developed to examine the relationship between these influencing factors and the occurrence likelihood of human errors based on the historical shipping accident records from 2000 to 2014 in Fujian water areas. The marginal effects of influencing factors on the occurrence likelihood of human errors were also examined and compared in this study.

Models results reveal that poor visibility conditions, no strong winds/waves, accident types of contact, grounding and collision, the involvement of fishing boats and other types of ships like engineering ships/sand dredgers are statistically (at a significance level of 0.20) associated with an increased occurrence likelihood of human errors. In addition, the occurrence likelihood of Type I human error (i.e., negligence errors) is greatly affected by another two factors including the season and time of the day at the significance level of 0.20. However, these two factors (i.e., season and time of the day) have no significant effects on the occurrence likelihood of Type II human errors (i.e., judgment/operation errors).

Furthermore, the marginal effect results indicate that ships are more likely to incur human errors including negligence and judgment/operation errors under one of the following situations: (i) visibility=poor visibility condition; (ii) season=spring; (iii) time of the day=night; (iv) weather condition=no strong winds/waves and (v) navigational status=moored/docked. Compared with accident types like hull damage and machinery failure, contact, grounding and collisions are the three accident types strongly associated with the higher occurrence likelihood of human errors. One finding from this study is that ships sailing near Fujian port water area are less likely to incur negligence and judgement/operation errors, compared with those sailing far away from Fujian port water area. The marginal effect results also show that fishing boats and engineering ships/sand dredgers are the primary ship types which have relatively higher occurrence likelihood of negligence errors than other ship types in Fujian water areas. Due to data limits, the organizational factors (e.g., resource management, organizational process) on the human errors were not considered in this study. In the future, we will take into account these factors after collecting more data from different water areas characterized by various navigation management strategies. In addition, our future study will also model human errors separately according to accidents types.

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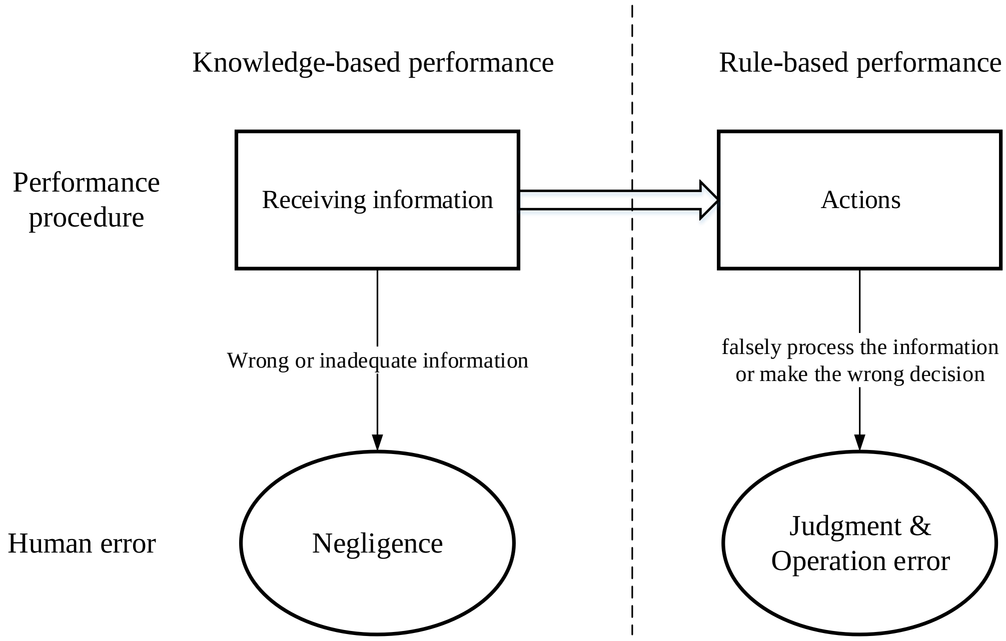

Figure 1 Human error classification

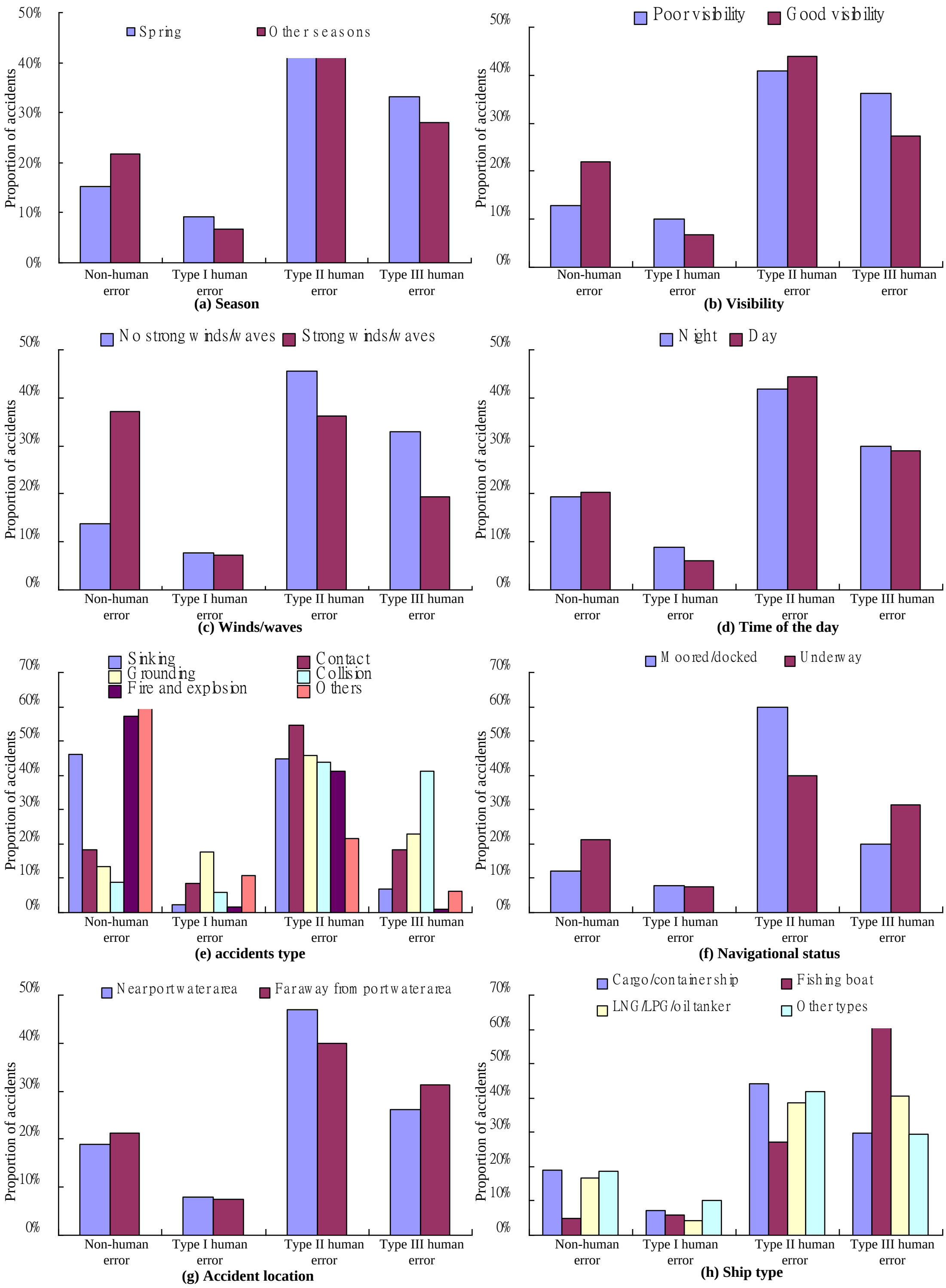

Figure 2 Accident distributions among four human error types

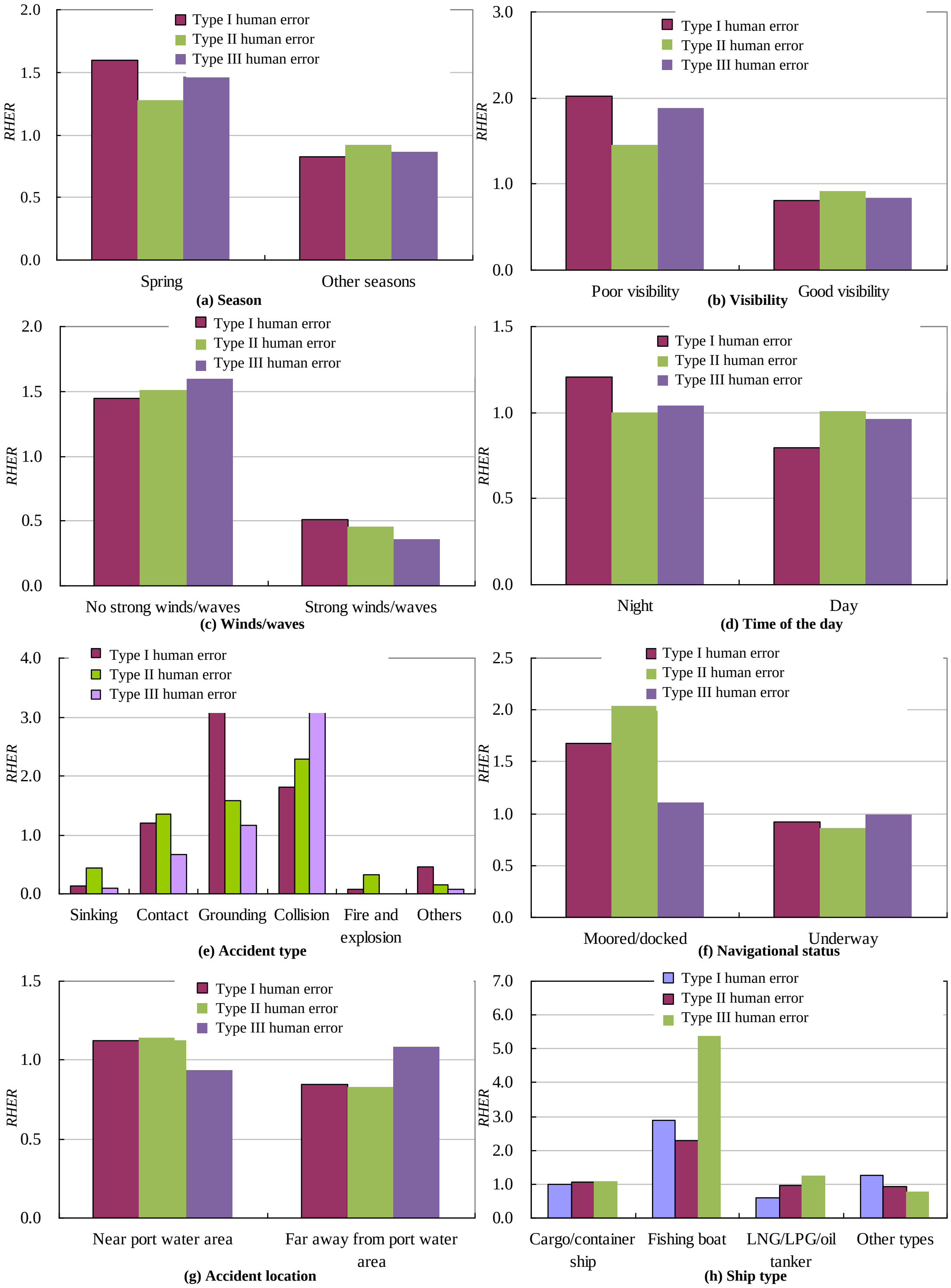

Figure 3 Relative human error ratios for different human error types

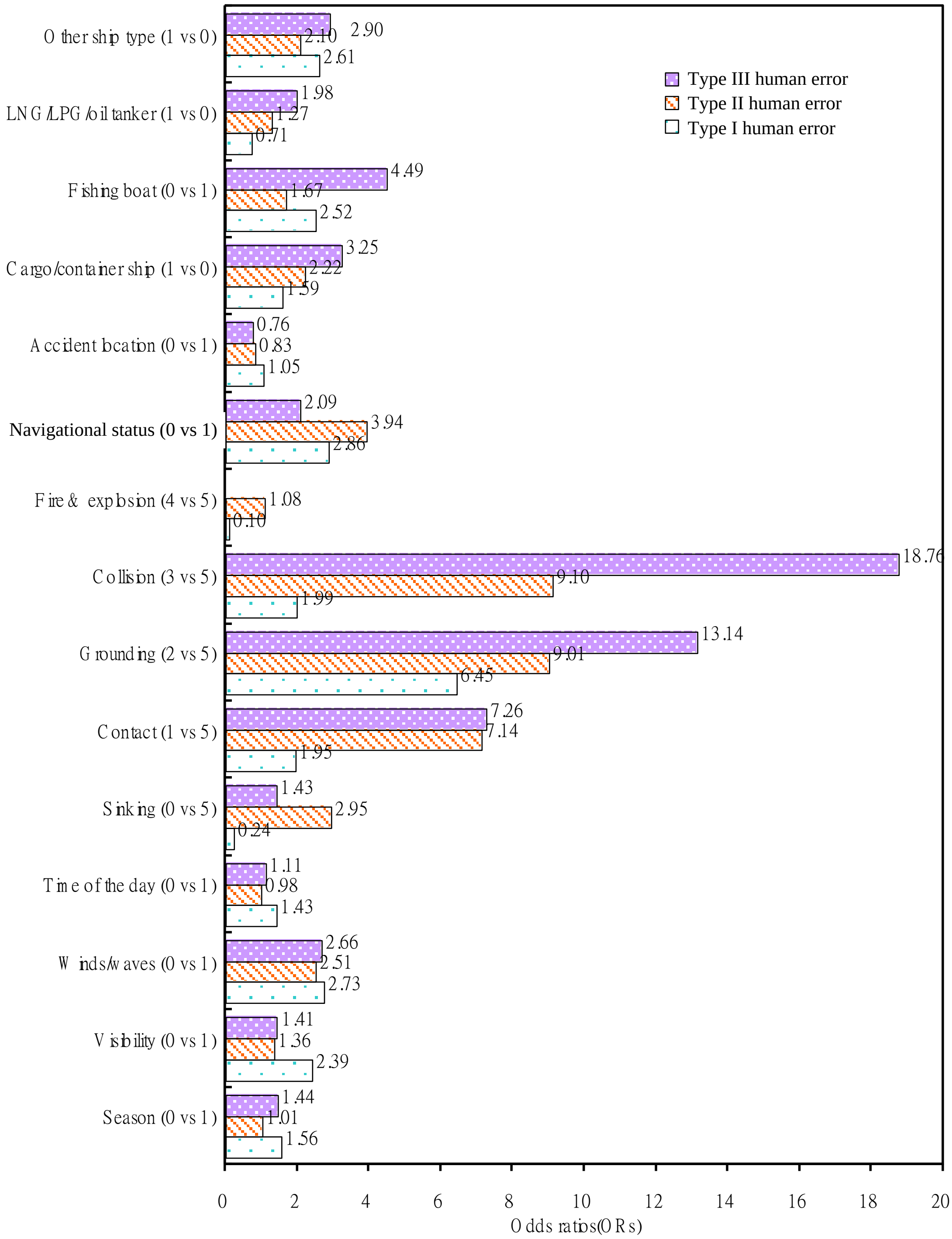

Figure 4 Marginal effects of influencing factors on the occurrence likelihood of different types of human errors

Table 1 Variable descriptions

Variables	Observations	Values	Non-human error	Type I: negligence errors only	Type II: judgment/operation errors only	Type III: Simultaneous occurrence of negligence, judgment/operation errors	Total
Environmental characteristics							
Season	Spring	0	56[b]	34	156	122	368
	Other seasons	1[a]	191	60	383	246	880
Visibility	Poor visibility conditions[c]	0	39	30	123	109	301
	Good visibility conditions	1[a]	208	64	416	259	947
Winds/waves	No strong winds/waves	0	129	71	424	306	930
	Strong winds/waves	1[a]	118	23	115	62	318
Time of the day	Night	0	122	56	265	189	632
	Day	1[a]	125	38	274	179	616
Accident characteristics							
Accident type	Sinking	0	40	2	39	6	87
	Contact	1	24	11	71	24	130
	Grounding	2	18	24	62	31	135
	Collision	3	64	44	320	300	728
	Fire and explosion	4	32	1	23	0	56
	Others	5[a]	69	12	24	7	112
Accident location	Near port water area	0	138	59	343	192	732
	Far away from port water area	1[a]	109	35	196	176	516
Ship characteristics							
Navigational status	Moored/docked	0	25	16	123	41	205
	Underway	1[a]	222	78	416	327	1043
Cargo/container ship	Not involved	0	49	19	79	56	203
	Involved	1[a]	198	75	460	312	1045
Fishing boat	Not involved	0	238	83	489	253	1063
	Involved	1[a]	9	11	50	115	185
LNG/LPG/Oil tanker	Not involved	0	231	90	502	329	1152
	Involved	1[a]	16	4	37	39	96
Other ship type	Not involved	0	208	73	452	307	1040
	Involved	1[a]	39	21	87	61	208

Note: [a]The reference category for the categorical variable; [b]The number of records based upon the selected variable; [c]poor visibility is accepted as lower than 1nm.

Table 2 Multinomial logistic regression model results for human errors in shipping operations

Variables	Human error type[a]	Coefficients	Standard error	Wald chi-squared	*p*-value
Intercept	Type I human error	-1.764	0.987	3.195	0.068
	Type II human error	-1.368	0.756	3.276	0.065
	Type III human error	-2.569	0.699	13.51	<0.001
Season (Spring vs Other seasons)	Type I human error	0.702	0.264	7.071	0.010
	Type II human error	0.330	0.194	2.873	0.090
	Type III human error	0.608	0.217	7.857	0.005
Visibility (Poor visibility conditions vs Good visibility conditions)	Type I human error	0.897	0.301	8.874	0.003
	Type II human error	0.392	0.224	3.045	0.081
	Type III human error	0.368	0.245	2.256	0.119
Winds/waves (No strong winds/waves vs Strong winds/waves)	Type I human error	0.946	0.288	10.73	<0.001
	Type II human error	1.053	0.181	99.99	<0.001
	Type III human error	1.075	0.219	24.20	<0.001
Time of the day (Night vs day)	Type I human error	0.436	0.255	2.934	0.086
	Type II human error	-0.023	0.167	0.019	0.892
	Type III human error	0.095	0.171	0.308	0.579
Sinking	Type I human error	-1.350	0.760	3.158	0.071
	Type II human error	1.022	0.348	8.628	0.005
	Type III human error	0.316	0.539	0.343	0.553
Contact	Type I human error	0.673	0.510	1.742	0.172
	Type II human error	1.997	0.371	28.97	<0.001
	Type III human error	2.013	0.529	14.48	<0.001
Grounding	Type I human error	1.834	0.435	17.77	<0.001
	Type II human error	2.112	0.368	32.93	<0.001
	Type III human error	2.343	0.501	21.87	<0.001
Collision	Type I human error	0.641	0.384	2.786	0.094
	Type II human error	2.185	0.312	49.04	<0.001
	Type III human error	2.756	0.435	40.14	<0.001
Fire and explosion	Type I human error	-2.155	1.079	3.988	0.049
	Type II human error	0.075	0.404	0.034	0.841
	Type III human error	N.A.	N.A.	N.A.	N.A.
Navigational status (Moored/docked vs Underway)	Type I human error	0.759	0.371	4.190	0.040
	Type II human error	1.126	0.256	19.34	<0.001
	Type III human error	0.573	0.302	3.595	0.065
Accident location (Near port water area vs Far away from port water area)	Type I human error	0.088	0.139	0.399	0.507
	Type II human error	-0.191	0.183	1.089	0.309
	Type III human error	-0.275	0.203	1.835	0.164
Cargo/container ship (Involved vs Not involved)	Type I human error	0.475	0.679	0.489	0.443
	Type II human error	0.789	0.511	2.384	0.113
	Type III human error	1.156	0.525	4.848	0.021
Fishing boat (Involved vs Not involved)	Type I human error	0.845	0.511	2.734	0.096
	Type II human error	0.583	0.392	2.211	0.139
	Type III human error	1.451	0.346	17.59	<0.001
LNG/LPG/Oil tanker (Involved vs Not involved)	Type I human error	-0.346	0.795	0.189	0.603
	Type II human error	0.235	0.536	0.192	0.600
	Type III human error	0.785	0.559	1.972	0.205
Other ship type (Involved vs Not involved)	Type I human error	0.932	0.635	2.154	0.147
	Type II human error	0.756	0.514	2.163	0.146
	Type III human error	1.001	0.498	4.045	0.036
	Intercept only		Intercept and covariates		
AIC	1965.078		1578.856		
-2 log-likelihood	1959.078		1482.856		

Note: [a] The reference category is non-human errors.