Modeling perceived collision risk in port water navigation

Chin, Hoong Chor and Debnath, Ashim (2009) Modeling perceived collision risk in port water navigation. Safety Science, 47 (10). 1410 - 1416. ISSN 0925-7535

Modeling perceived collision risk in port water navigation

Hoong Chor Chin
Associate Professor,
Department of Civil Engineering,
National University of Singapore,
Engineering Drive 2,
E1A #07-03,
Singapore 117576
Email: cvechc@nus.edu.sg
Tel: +65 65162550

Ashim Kumar Debnath*
Research Scholar,
Department of Civil Engineering,
National University of Singapore,
Engineering Drive 2,
EW1 #04-02B,
Singapore 117576
Email: ashim@nus.edu.sg
Tel: +65 65162255

* Corresponding Author

Abstract

An increase in the likelihood of navigational collisions in port waters has put focus on the collision avoidance process in port traffic safety. The most widely used on-board collision avoidance system is the automatic radar plotting aid which is a passive warning system that triggers an alert based on the pilot's pre-defined indicators of distance and time proximities at the closest point of approaches in encounters with nearby vessels. To better help pilot in decision making in close quarter situations, collision risk should be considered as a continuous monotonic function of the proximities and risk perception should be considered probabilistically. This paper derives an ordered probit regression model to study perceived collision risks. To illustrate the procedure, the risks perceived by Singapore port pilots were obtained to calibrate the regression model. The results demonstrate that a framework based on the probabilistic risk assessment model can be used to give a better understanding of collision risk and to define a more appropriate level of evasive actions.

Keywords: Ordered regression model; Risk perception; Collision risk; Port navigation safety; Automatic Radar Plotting Aid; Harbor pilot.

Please cite this article as:
Chin, H.C. and Debnath, A.K. (2009) Modeling Perceived Collision Risk in Port Water Navigation. Safety Science, 47(10), pp. 1410-1416.

1. Introduction

Navigational collisions are a major safety concern in many seaports. The growth of shipping traffic over the past decades has intensified collision likelihood in busy and congested port waters (Darbra and Casal, 2004; Sato and Ishii, 1998; Yip, 2007). Consequently, the collision avoidance process has come into focus in port navigation safety. In general, harbor pilots assess and mitigate collision risk by combining data obtained from collision avoidance systems (CAS) with information obtained by visual watch-keeping. The most widely CAS used on most merchant vessels is the Automatic Radar Plotting Aid (ARPA) (Statheros et al., 2008). It allows pilots to track a number of target vessels within the radar detection range. Apart from providing a graphical display of the surrounding vessel traffic, ARPA provides forecasted values of two proximity measures for selected target vessels – Distance at Closest Point of Approach (DCPA) and Time to Closest Point of Approach (TCPA). The two indicators are respectively the probable distance and time required between the subject vessel and a target vessel at their Closest Point of Approach (CPA), given that the course and speed of both vessels remain unchanged. Pilots make use of these proximity indicators as a basis of risk assessment to determine their own necessary course of action to avoid a collision.

ARPA also possesses a warning system (e.g., aural alarm or flashing symbol) to alert the pilots of collision risk. Pilots may set some critical values ($DCPA_{limit}$ and $TCPA_{limit}$) to trigger the warning system. Since the critical values are defined by pilots, ARPA is a passive system based on the intuitive perceived risks of the pilots. This warning system is useful to draw attention of pilots who needed reminder when they have temporarily lost situational awareness.

Several researchers, such as Grech et al. (2002) and Wagenaar and Groeneweg (1987) have shown that the lack of situational awareness is responsible for about 70% of human errors in navigation. Further, Hetherington et al. (2006) and Rothblum (2000) have also shown that human errors contribute to more than 90% of collisions. Employing this arrangement of alertness, risk of collision is expressed as a unit step function involving two possible states: 'potential collision risk' and 'no risk', the former state when both the proximity indicators are below the critical limits while the latter for any other condition.

An improvement to the binary state of risk assessment is the three-level warning system proposed by Liu, Q. et al. (2006). Using preset critical values of DCPA and TCPA, they define the situation as "safe", "potential collision risk" and "direct collision risk". It should be noted that collision risk is strictly a continuous monotonic function of the proximity indicators based on the vessel interaction with influence from the performance capability and experience of the pilots in handling close quarter situations. Both the binary and three-state systems may not fully represent the range of risks involved and the appropriate actions needed of pilots.

Other researches on CAS have focused on different aspects of collision avoidance, such as improvement on plotting performance of ARPA (Sato and Ishii, 1998; Pedersen et al., 1999), development of cone-shaped danger regions (Leanrt, 1983), evaluation of display techniques (Pedersen et al., 2002a), and evaluation of anti-collision maneuvers in CAS (Pedersen and Jacobsen, 2002; Pedersen et al., 2002b; Pedersen et al., 2003). In all cases collision risk is treated as a discrete variable rather than a continuous variable. Furthermore, as the performance and judgment in close encounter vary from one pilot to another, it is also necessary to consider the probabilistic aspects of defining risk. Moreover, other factors such as vessel size and the environment play an important role in influencing navigational risk. These factors are not considered in the system of risk assessment and collision avoidance.

This paper develops a probabilistic model of collision risk derived from perception of the pilots. Ordered Probit Regression modeling is employed to examine risk for navigation in different vessel classes under both day and night conditions. To illustrate the derivation of the model, perceived risks are obtained from a risk perception survey on Singapore port pilots.

The following sections describe the methodology of the study consisting of the formulation, assessment and modeling considerations of the ordered probit regression model, followed by development of safety margins and description of a risk perception survey. Estimation results and model fitness are then discussed along with the interpretations of the perceived safety margins. A framework of probabilistic risk assessment in CAS is finally proposed.

2. Methodology

2.1 Ordered Probit Regression Model

To develop a probabilistic model of collision risk an ordered probit regression model is formulated, which is calibrated by using perceived risk data. Intensity of the risk can be expressed by a scale categorizing risk into five levels (see Table 1). The regression model is formulated to suit the categorical response variable.

2.1.1 Model formulation

Since the risk levels used in the scale are subjective but ordered in nature, an ordered categorical analysis will be most appropriate to treat such data. Two possible regression models may be employed: the ordered probit or ordered logit models. The models differ in the assumption of the distributions of regression errors. The probit model assumes a normal distribution of errors with mean 0 and variance 1, whereas the logit model assumes a standard logistic distribution with mean 0 and variance $\pi^2/3$. The ordered probit model is selected for this study though the choice matters little as both models produce very similar results.

The ordered probit model is usually formulated as a latent (i.e., unobserved) variable framework. The structural model specification is:

$$y_i^* = \boldsymbol{\beta}\mathbf{X}_i + \varepsilon_i \qquad (1)$$

where y_i^* is a continuous latent variable measuring perceived collision risk for the i^{th} set of $\mathbf{X}$; $\mathbf{X}_i$ is the vector of independent variables; $\boldsymbol{\beta}$ is the vector of regression coefficients; ε_i is the random error term $\sim N(0,1)$.

The measurement model, in which the latent variable y_i^* is mapped on to an observed ordinal variable y, is specified as:

$$y_i = m \quad \text{if} \quad \tau_{m-1} \le y_i^* < \tau_m \text{; for } m = 1 \text{ to J} \qquad (2)$$

where J is number of ordinal categories in y and the threshold values (τ) are unknown parameters describing the boundaries of risk levels.

Therefore, the observed discrete risk levels are tied to the continuous latent variable as follows:

$$y_i = \begin{cases} 1 & \text{if} \quad -\infty \le y^* < \tau_1 \quad [\text{Very High Risk (VHR)}] \\ 2 & \text{if} \quad \tau_1 \le y^* < \tau_2 \quad [\text{High Risk (HR)}] \\ 3 & \text{if} \quad \tau_2 \le y^* < \tau_3 \quad [\text{Moderate Risk (MR)}] \\ 4 & \text{if} \quad \tau_3 \le y^* < \tau_4 \quad [\text{Low Risk (LR)}] \\ 5 & \text{if} \quad \tau_4 \le y^* < \infty \quad [\text{Safe}] \end{cases} \tag{3}$$

where the threshold values τ_1, τ_2, τ_3, and τ_4 are unknown parameters to be estimated.

Based on the normality assumption of the error term, the probability of risk level m for given $\mathbf{X}_i$ can be predicted as:

$$\hat{\Pr}(y = m|\mathbf{X}_i) = F(\hat{\tau}_m - \hat{\boldsymbol{\beta}}\mathbf{X}_i) - F(\hat{\tau}_{m-1} - \hat{\boldsymbol{\beta}}\mathbf{X}_i) \; ; \; \sum_{m=1}^{J} \hat{\Pr}(y = m|\mathbf{X}_i) = 1 \tag{4}$$

where F is the cumulative distribution function for ε.

Once the probabilities of each risk level are predicted from the model estimates, associated collision risks can be computed. To do so, risk scores (RS_m) are assigned to each risk level based on the thresholds, as shown in Figure 1. The RS_m represents the probability of collision for risk level *m*. Using the proposed risk scale as shown in Table 1, risk scores for VHR and Safe levels are assigned values of 1 and 0 respectively. The VHR level refers to vessel interactions where collision cannot be avoided, which represents the probability of collision as 1. On the other hand where no action is required under the Safe level, the probability of collision is zero. As seen from equation (3), the Safe level exists if $y^* \ge \tau_4$. The τ values may be normalized to a probability value with the range [0,1].

(Insert Table 1 here)

(Insert Figure 1 here)

The collision risk for given $\mathbf{X}_i$ can then be computed as:

$$P_c|\mathbf{X}_i = \sum_{m=1}^{J} RS_m \times \hat{\Pr}(y = m|\mathbf{X}_i); \; 0 \le P_c \le 1 \tag{5}$$

2.1.2 Model assessment

In order to examine the significance of **X**s included in model the z-test is employed and to evaluate if the model have sufficient explanatory and predictive power several goodness-of-fit (gof) measures found in Long and Freese (2006) are used. The likelihood ratio statistics, $G^2 = 2(LL(\beta) - LL(0))$, is used to examine the overall gof of the model by testing the global null hypothesis that all coefficients except the intercept are zero, where $LL(\beta)$ and $LL(0)$ are the log-likelihoods of the fitted model and the null model respectively. The McKelvey and Zavoina's R^2, $\text{M \& Z R}^2 = Var(y^*)/(Var(y^*)+Var(\varepsilon))$, is also used to measure the predictive power of the model.

2.1.3 Modeling considerations

The risk of collision in any vessel interaction may vary with the size of vessels involved. Perez and Clemente (2007) have shown that maneuverability and ease in speed adjustments diminishes as vessel size increases and for this reason, vessels of different sizes would produce different levels of risk in an interaction. Consequently, the perceived risks by the pilots may also vary. In order to consider the effects of vessel sizes in the study of perceived risks, vessels may be clustered into four vessel classes (VC) according to the vessel gross tonnage (GT). The classification based on the Singapore port regulations is used in this study (see Table 2).

(Insert TABLE 2 here)

As the perceived risk is influenced by the pilot's experience in a particular vessel class, both experience and VC need to be considered together in the perception survey. In general, pilots with more experience are authorized to operate VC with higher GT, a positive association between experience and VC will exist. Hence, modeling perceived risks separately for each VC is necessary.

Furthermore, navigation is affected by the environment, and in particular, in day and night settings. Therefore, perceived risks would also be different for day and night conditions. Hence, perceived risks need to be modeled separately for day and night conditions.

2.2 Development of safety margins

The ordered probit model distinguishes different risk levels by generating a set of thresholds, which represent the boundaries of the risk levels on the latent variable scale, as shown in equation (3). Since the values of τ are on the scale of y^*, the structural model (equation 1) can be modified as:

$$\hat{\tau}_m = \hat{\beta}_1 \times DCPA + \hat{\beta}_2 \times TCPA\text{; for m = 1 to J-1} \qquad (6)$$

where $\hat{\tau}_m$, $\hat{\beta}_1$ and $\hat{\beta}_2$ are known parameters from regression estimates. Therefore, for each risk level two boundary points on DCPA and TCPA scale, i.e., $(DCPA_{TCPA=0})$ and $(TCPA_{DCPA=0})$ respectively, can be obtained by setting $\text{TCPA} = 0$ and $\text{DCPA} = 0$ respectively in equation (6). $DCPA_{TCPA=0}$ is the 'distance safety margin' (DSM) that pilots accept for the respective risk levels. For a given risk level, this would be the maximum passing distance between two ships that the pilots would allow. $TCPA_{DCPA=0}$ is the 'time safety margin' (TSM) which represents the marginal time remaining before a collision.

To examine the adequacy of the perceived safety margins in navigation, the margins can be compared against some existing standards. The margins are examined at two levels in a collision process; firstly, at the level requiring immediate evasive actions to prevent a collision and secondly, at ship domain level where pilots start to perceive that a collision risk exists. The standards used for comparison are those related to ship maneuverability (IMO, 2002) and ship domain (Fujii and Tanaka, 1971).

2.2.1 Safety margins at immediate evasive action level

The margins are compared against the IMO standards for ship maneuverability (IMO, 2002). The standards are used to evaluate maneuvering performance of ships in design, construction, repair and operation of vessels. According to the standards, a vessel's initial turning ability (ITA) is measured by a $10^{\circ}/10^{\circ}$ zigzag test. The execution of the test includes application of a 10° rudder angle to an initially straight approach, which is termed as 'first execute'. When the heading changes to 10° off the original heading, another 10° rudder angle is applied in the direction opposite to previous rudder angle application, which is termed as 'second execute' (SE). The standard of ITA is that a vessel should not travel more than 2.5 times of her length by the time of SE application from the original heading.

The ITA standard can be employed to examine if the perceived safety margins at HR level are adequate enough for safe navigation. As seen from Table 1, the HR level refers to vessel interactions where immediate actions are necessary to avoid a potential collision. It means that if any actions are not taken immediately (i.e., TCPA = 0) the risk level will rise to the VHR level, which refers to interactions resulting in certain collision. Safety margins higher than the ITA standard imply that a pilot is "ahead of the vessel" (Bowditch, 1976), i.e., there is a sufficient safety margin to avoid a collision.

Since the ITA standard includes the term, ship length, in its consideration, it is necessary to obtain representative lengths of all VCs. From observations of the vessels' GT and length-overall (LOA), the summary statistics of the LOAs of the VCs are presented in Table 3. The 50^{th} percentiles are used as representatives of the LOAs of VCs, because in the survey the pilots were asked to rate their perceived collision risk for an average vessel size that they operate frequently.

(Insert Table 3 here)

Although the ITA standard sets a requirement of maneuverability in terms of space, it does not set any direct requirement in terms of time. Therefore, a surrogate measure of maneuverability in terms of time requirement is derived. This is computed based on the limiting distance separation when the vessel is operating at the maximum regulated speed In this study, the maximum speed of navigation adopted is 12 knots according to the Singapore port regulations (MPA, 2006). This results in the surrogate measure, 'time to second execute' (TSE), which is the time to reach the SE in a $10^{\circ}/10^{\circ}$ zigzag test at a speed of 12 knots.

2.2.2 Safety margins at ship domain level

The perceived safety margins at LR level can be compared against the standard of ship domain (Fujii and Tanaka, 1971) in order to examine the adequacy of the margins. The ship domain is the surrounding effective waters around a vessel that a pilot requires to keep clear of other vessels. According to this standard, a pilot is required to maintain a distance of at least 4 times the ship length, from the center of his vessel to that of other vessels. If a vessel penetrates the circular domain circumference, pilots are required to monitor the vessel movement continuously to assess collision risk. Using this concept, this will coincide with the transition from the Safe level to LR level in the proposed risk scale. The standards for DSM and TSM at LR level would be the domain radius (DR) and the time to domain circumference (TDC) respectively.

2.3 Risk perception survey

To illustrate the method developed, perceptions of collision risks under different vessel interaction situations need to be obtained from the pilots. Perceived risk data can be collected by employing two experimental methods: simulation or survey. The former is an exercise which can be carried out using ship-handling simulators, where pilots are asked to navigate vessels in a specified navigational environment and to judge collision risks at various stages of the navigation. The difficulty in a simulation exercise is the amount of resources needed for a sufficiently large number of pilots to ensure a sound statistical analysis. On the other hand, the survey method involves conducting questionnaires among pilots by generating a suitable platform for them to judge collision risk. In this case, DCPA and TCPA values would be used to define the navigational conditions, and pilots would specify the level of their perceived risk under various conditions of DCPA and TCPA. The survey method allows a high amount of respondents to be obtained easily for a proper statistical analysis. The survey method is employed in this study.

2.3.1 Survey design

To collect perceived risk data, it is necessary to develop a two-way risk matrix, defined by different values of DCPA and TCPA. The appropriate values of DCPA and TCPA used in classifying the different navigational situation were determined based on the expert input of several experienced pilots in a preliminary survey. Based on the outcome of the preliminary survey, a 5x5 risk matrix is formulated, representing 5 threshold values of TCPA $\in (1,3,5,10,20)$ minutes and 5 values of DCPA $\in (1,2,5,7,10)$ cables length[1]. Pilots are asked to indicate their level of perceived risk of collision in terms of Safe, Low Risk, Moderate Risk, High Risk and Very High Risk, for each of the 25 combinations of DCPA and TCPA. The perceived risk were assessed separately for the day and night conditions.

2.3.2 Data collection

A total of 160 pilots were given the survey forms. Participation was voluntary and the response is anonymous. A total of 70 respondents completed the survey giving a return rate of 44%. The age of the respondents ranges from 28 to 61 years with a mean and standard deviation of 43.0 years and 9.8 years respectively. The experience of the respondents as harbor pilot exhibits a mean and standard deviation of 11.3 years and 10.9 years respectively, ranging from 3 months to 40 years. The wide range of age and experience in the sample gave quite a good representative picture of the population.

3. Results and discussion

3.1 Estimation results of the ordered probit model

The ordered probit models were calibrated using the maximum likelihood method for each of the vessel class and separately for day and night conditions. Table 4 shows the estimated parameters and goodness-of fit statistics of all models. The likelihood ratio statistics of all models (e.g., 243.4 and 187.8 for VC1-Day and VC1-Night models respectively) are well above the critical value for significance at 1% level of significance, which implies that the

[1] 1 cable length = 0.1 nautical mile

models have reasonable good fit. The McKelvey and Zavoina's R^2 values (e.g., 0.58 and 0.47 for VC1-Day and VC1-Night models respectively) also indicate sufficient predictive power for all models.

Both DCPA and TCPA show significant positive association with the latent variable in all models (e.g., for VC1-Day model: β_{DCPA} = 0.27, p < 0.001; β_{TCPA} = 0.12, p < 0.001). This indicates that collision risk decreases if DCPA and TCPA increase (see equation 3).

The method for estimating collision risk from the regression estimates is illustrated for DCPA = 1 cable length and TCPA = 2 minutes, as shown in Table 5. A comparison of the risks with the scores of the risk levels (presented in Table 6) of all models shows that the risks fall in the HR range (e.g., for VC1-Day model: risk = 0.86 < RS_{HR} = 0.91), which is expected for such small values of DCPA and TCPA. Risks in night conditions are also found to be higher than those in the day, e.g., the risk in night increases by 1.3% for VC1. The trends observed in perceptions of the pilots are discussed in the following section.

(Insert TABLE 5 here)

(Insert TABLE 6 here)

3.2 Distance and time safety margins

3.2.1 Safety margins at immediate evasive action level

Ratios of safety margins to the maneuverability standards are employed to examine adequacy of the margins. Ratios greater than or equal to unity indicate that the margins are adequate. The higher the ratios are from unity, the higher the safety buffers beyond the standards. The computed ratios (presented in Table 7) show that the margins are adequate (i.e., greater than one) for all vessel classes in both day and night conditions.

(Insert Table 7 here)

A comparison of the results with the ratios of DSM to ITA standard shows that pilots of VC1 hold highest ratios (3.6 and 5.4 in day and night respectively). It means that this pilot group maintains higher space buffer beyond the standard, compared to other pilots. For all pilots, the ratios in night conditions are found to be higher than those in the day. Among all, the highest increment in the ratios in night from those in the day (equals 1.8) is observed for the pilots of VC1. It means that these pilots maintain higher safety margins in night, thus are more careful than the other pilots in night conditions.

Similar results are found in comparing the results with the ratios of TSM to TSE. Pilots of VC1 attribute highest ratios in both day and night navigation (16.4 and 26.3 respectively). Among all, this pilot group is found to be influenced mostly by a change from day to night condition, so that the ratio in night increases by 9.9. Interestingly, it is noted that the ratios of TSM to TSE are higher than those of DSM to ITA standard for all pilots. It indicates that pilots are keen to maintain higher safety margins in time than in space.

3.2.2 Safety margins at ship domain level

Ratios of DSM to DR and TSM to TDC (shown in Table 8) are also found greater than unity for all vessel classes, which imply that the margins are adequate. The findings at ship domain level are similar to those in the immediate evasive action level.

(Insert Table 8 here)

A comparison of results with the ratios of DSM to DR show that pilots of VC1 hold the highest ratios in both day and night conditions and the highest increment in ratios from day to night. This pilot group maintains DSM of 6.8 times the DR in day condition, whereas in night it increases to 7.9 times the DR. While all pilots maintain higher margins in night conditions, the highest increment in this (equals 1.1) is observed for the pilots of VC1.

The ratios of TSM to TDC also show that the pilots of VC1 maintain the highest safety buffers (ratios of 30.9 and 38.2 in day and night conditions respectively) and are most sensitive to a change from day to night condition (the ratio in night increases by 7.3). The other pilots are also found to maintain higher margins in night conditions.

3.2.3 Discussion on results

Analyses of the safety margins have identified several findings. Firstly, the margins in night conditions are higher than those in the day. This finding is consistent with that in Debnath and Chin (2009) who reported that pilots perceive higher collision risks at night, i.e., higher margins are necessary to mitigate the risks. Maintaining higher margins at night is logical because during the day the speeds and distances between vessels and even any change of courses can be judged readily because of better visibility. At night pilots need to rely on navigational aids (e.g., radar, navigational lights etc.). This may imply that in assessing risks, pilots place a higher value on their own visual judgment than on instruments. Furthermore, effectiveness of navigational lights can be reduced in night due to bright background lights on shore and from nearby islands (see Akten, 2004; Liu, C. et al., 2006). Naturally visibility deteriorates at night which could further hinder the watchkeeping process leading to possible confusion in navigation.

Secondly, there is a clear trend of perceiving higher time safety margins than the distance margins. This could be because the pilots are more able to perceive risk based on the visual image of a vessel and hence the distance between vessels. Since the pilots are less sensitive to time change when vessels are in relative motion, they will become more careful and hence provide a higher safety margin.

Finally, pilots of low GT vessels (i.e., VC1) maintain higher safety buffers and are more sensitive to a change from day to night conditions than the pilots of larger vessels. The pilots of VC1 are generally less experienced with less knowledge of the port water characteristics and traffic environment. Lutzhoft and Nyce (2006) have argued that new pilots prepare a database in memory by combining static information from course books and navigational experiences, and use the database for future navigation. Therefore, these less experienced pilots remain in a learning stage and are more conservative in risk perception. Also such pilots may require more reaction time to decide and take evasive actions in a close encounter.

4. Proposed framework of probabilistic risk assessment in CAS

The foregoing shows that the proposed models have reasonable predictive power and that the perceived safety margins are adequate. This implies that the regression estimates can be used effectively to develop a CAS. A framework of risk assessment in CAS that utilizes the estimates to predict collision risk is now proposed. A block diagram showing configurations of the CAS is presented in Figure 2.

(Insert Figure 2 here)

The CAS requires the courses and speeds of own vessel and target vessels as input information and these can be obtained from on-board radar, global positioning system (GPS) and automatic identification system (AIS) of own vessel. By utilizing the input data, DCPA and TCPA are calculated to assess the risk of collision in vessel interactions. Interactions with non-negative TCPA values imply there is a risk of collision. For such interactions, it is necessary to predict and assess the risk and this is accomplished by employing the probabilistic model developed in this paper. Taking in consideration the vessel classes and navigation time (i.e., day or night), the model predicts the level of collision risk based on the values of DCPA and TCPA. From the level of risk present, the associated alarm to alert the pilots can be incorporated.

By assessing the collision risk with all interacting vessels within the of detection range of the radar of own vessel, it is possible to rank the interacting vessels in descending order of collision risk and the associated level of alarm. With continuous tracking of other vessels, a real-time system with multi-level alarm alerts can be developed that will enable pilots to make appropriate corrective actions, prioritized according to the level of risk involved. This is particularly important when there are more than one nearby vessels that contribute to the existing risk in navigation. Pilots will be able to better manage the risk in a more systematic manner under such complex navigational environment.

Even under less complex environment where interaction is only with one nearby vessel, the multi-tier system allows earlier warning with less serious evasive action compared to the two-state system. This should alert pilots who have temporarily lost situational awareness and help them to avoid entering unknowingly into a close encounter situation.

Furthermore, the multi-level system will allow pilots with different experience and capability to better adapt their own judgment and courses of action to match the different levels of danger and alert produced by the system. This adaptation arising from the different perceived interpretation of danger and customized level of action is particularly important for the system to gain greater credibility.

5. Conclusion

An ordered probit regression model was derived for probabilistic modeling of perceived collision risk in port water navigation. To illustrate the method, perceived risks were obtained from a risk perception survey on Singapore port pilots and are used to calibrate the models for different vessel classes under both day and night conditions. Estimation results show all the calibrated modules have reasonable goodness-of fit and predictive powers.

Perceived distance and time safety margins were analyzed to examine their adequacy with standards of ship maneuverability and ship domain. Results indicate that the judgment of the pilots is reasonably reflective of the various safety margins. Several interesting findings were derived from the analyses. Firstly, pilots give a larger safety margins at night than in the day. Secondly, pilots tend to give a higher allowance of safety for time separation and this is largely because they judge time separation less precisely. Finally, pilots of low GT vessels, representing the less experienced ones, maintain higher safety buffers and are more careful than their more experienced counterparts in night conditions.

A framework to develop a collision avoidance system based on probabilistic risk assessment using the regression estimates to predict collision risk is proposed. It is possible to introduce an interaction component with multi-level alarm system to alerts pilots of the different levels of navigational risk. There are several important benefits of a multi-level system. It will help pilots to make an earlier evasive action. In more complex situations involving more than one interacting vessel, a more systematic and prioritized plan of action can be produced. Finally a more customized and adaptable system is possible based on the individual pilot experience and capability.

While Singapore port pilots have been surveyed to develop the model in this paper, the modeling technique should be generally applicable. This research provides valuable insights into modeling perception of collision risk of pilots in navigation. The use of a probabilistic model to predict risks perceived by pilots is unique and robust. The developed models can be readily applied in developing a multi-level alert collision avoidance system.

Acknowledgements

The authors would like to thank Mr. William Seow, Mr. Er Chor Meng and Mr. Tan Teck Kheng of PSA Marine (Pte) Ltd Singapore for their invaluable help in conducting this survey. Special thanks also go to all the harbor pilots of PSA Marine (Pte) Ltd who participated in this survey.

References

Akten, N., 2004. Analysis of shipping casualties in the Bosphorus. Journal of Navigation 57, 345-356.

Bowditch, N., 1976. Bowditch for Yachtsmen: Piloting. David McKay Company, Inc., NY.

Darbra, R.M., Casal, J., 2004. Historical analysis of accidents in seaports. Safety Science 42, 85-98.

Debnath, A.K., Chin, H.C., 2009. Hierarchical modeling of perceived collision risks in port fairways. Transportation Research Record, *in press*.

Fujii, Y., Tanaka, K., 1971. Traffic capacity. Journal of Navigation 24, 543-552.

Grech, M., Horberry, T., Smith, A., 2002. Human error in maritime operations: Analyses of accident reports using the leximancer tool. In: Proceedings of the 4th Annual Meeting of the Human Factors and Ergonomics Society, September 30-October 4, Baltimore, U.S.

Hetherington, C., Flin, R., Mearns, K., 2006. Safety in shipping: The human element. Journal of Safety Research 37, 401-411.

IMO, 2002. Standards for ship maneuverability. Resolution MSC.137(76), Annex 6, International Maritime Organization.

Lenart, A.S., 1983. Collision threat parameters for a new radar display and plot technique. Journal of Navigation 36, 404-410.

Liu, Q., Pedersen, E., Okazaki, T., Fukuto, J., Tanaka, K. 2006. Direct perception interface for ship-ship collision avoidance. In: Proceedings of the 2006 IEEE international conference on systems, man and cybernetics, October 8-11, Taipei, Taiwan.

Liu, C.-P., Liang, G-S., Su, Y., Chu, C-W., 2006. Navigation safety analysis in Taiwanese ports. Journal of Navigation 59, 201-211.

Long, J.S., Freese, J., 2006. Regression models for categorical dependent variables using Stata. Second Edition, Stata Press, Texas, USA.

Lutzhoft, M.H., Nyce, J.M., 2006. Piloting by heart and by chart. Journal of Navigation 59, 221-237.

MPA, 2006. Singapore port information. The 2006/2007 edition, Maritime and Port Authority of Singapore.

Pedersen, E., Arai, Y., Sato, N., 1999. On the effect of plotting performance by the errors of pointing targets in the ARPA system. Journal of Navigation 52, 119-125.

Pedersen, E., Inoue, K., Tsugane, M., 2002a. Evaluation of a radar plot and display technique for anti-collision assessment of multiple targets in true vector presentation by application of a environmental stress model. Journal of Japan Institute of Navigation 106, 1-12.

Pedersen, E., Inoue, K., Tsugane, M., 2002b. On decision making in connection with optimal anti-collision maneuvers by high speed craft in waters congested by conventional speed vessels. Journal of Japan Institute of Navigation 107, 177-183.

Pedersen, E., Inoue, K., Tsugane, M., 2003. Simulator studies on a collision avoidance display that facilitates efficient and precise assessment of evasive maneuvers in congested waterways. Journal of Navigation 56, 411-427.

Pedersen, E., Jacobsen, A., 2002. On a radar plot and display technique for judging anti-collision manoeuvers from the viewpoint of acquired targets. Singapore Maritime and Port Journal 2002, 67-73.

Perez, F.L., Clemente, J.A., 2007. The influence of some ship parameters on manoeuvrability studied at the design stage. Ocean Engineering 34(3-4), 518-525.

Rothblum, A.R., 2000. Human error and maritime safety. Paper presented at the National Safety Council Congress and Expo, October 13-20, Orlando, FL.

Sato, Y., Ishii, H., 1998. Study of a collision-avoidance system for ships. Control Engineering Practice 6, 1141-1149.

Statheros, T., Howells, G., McDonald-Maier, K., 2008. Autonomous ship collision avoidance navigation concepts, technologies and techniques. Journal of Navigation 61, 129-142.

Wagenaar, W.A., Groeneweg, J., 1987. Accidents at sea: Multiple causes and impossible consequences. International Journal of Man-Machine Studies 27, 587-598.

Yip, T.L., 2007. Port traffic risks – A study of accidents in Hong Kong waters. Transportation Research Part E, doi: 10.1016/j.tre.2006.09.002.

Table 1
Navigational collision risk scale

Risk level	Level of actions necessary to avoid collision
Safe	No actions necessary
Low	Keep safe navigational watch
Moderate	Take precautionary actions, communicate with other ship
High	Immediate actions needed
Very high	Collision imminent, cannot be avoided

Table 2
Vessel categories according to gross tonnage

Vessel class	Description
VC 1	If $300 \leq GT \leq 12000$
VC 2	If $12000 < GT \leq 20000$
VC 3	If $20000 < GT \leq 75000$
VC 4	If $GT > 75000$

Table 3
Summary statistics of vessel lengths in meters

Vessel class	No of Observations	Median	Min	Max
VC1	383	81	26	164
VC2	61	168	140	197
VC3	137	209	164	305
VC4	32	322.5	250	352

Table 4
Ordered probit estimates for perceived collision risk

		Ordered probit regression models							
		VC 1		VC 2		VC 3		VC 4	
		Day	Night	Day	Night	Day	Night	Day	Night
Regression estimates of covariates									
DCPA (cables length)									
	Coef.	0.2660	0.2179	0.5611	0.6502	0.2641	0.2710	0.2431	0.2088
	Std. Err.	0.0221	0.0202	0.0487	0.0523	0.0248	0.0248	0.0123	0.0117
	Z-stat	12.01*	10.77*	11.51*	12.44*	10.65*	10.93*	19.82*	17.85*
TCPA (minutes)									
	Coef.	0.1168	0.0902	0.3278	0.2637	0.1151	0.1181	0.1013	0.0892
	Std. Err.	0.0108	0.0096	0.0288	0.0230	0.0119	0.0117	0.0058	0.0056
	Z-stat	10.80*	9.35*	11.39*	11.48*	9.70*	10.07*	17.42*	16.02*
Thresholds									
τ_1	$\hat{\tau}_1$	0.2716	0.3271	0.7505	1.3021	0.3212	0.5363	0.3732	0.4457
	Std. Err.	0.1489	0.1402	0.2578	0.2364	0.1674	0.1659	0.0833	0.0808
τ_2	$\hat{\tau}_2$	1.0468	1.2946	2.5342	3.3943	1.5432	1.8126	1.4135	1.5219
	Std. Err.	0.1504	0.1486	0.2743	0.3088	0.1805	0.1857	0.0891	0.0898
τ_3	$\hat{\tau}_3$	2.1088	1.9947	4.6098	5.9758	2.3581	2.7565	2.3464	2.4159
	Std. Err.	0.1738	0.1627	0.4031	0.4776	0.2039	0.2147	0.1029	0.1027
τ_4	$\hat{\tau}_4$	3.1519	3.0112	6.9348	8.5806	3.4408	3.9437	3.3680	3.2375
	Std. Err.	0.2058	0.1912	0.5655	0.6476	0.2390	0.2602	0.1200	0.1154
Summary statistics									
# of Obs		325	325	225	225	250	250	950	950
$LL(0)$		-500.5	-518.4	-334.0	-343.3	-395.0	-395.0	-1510.9	-1505.6
$LL(\beta)$		-378.8	-424.5	-153.9	-150.7	-300.0	-294.4	-1193.9	-1242.7
G^2 (2 dof)		243.4	187.8	360.2	385.0	190.1	201.1	634.0	525.7
M&Z R^2		0.583	0.471	0.894	0.887	0.578	0.591	0.527	0.456

* significant at 99% significance level; $LL(0)$: log-likelihood at zero; $LL(\beta)$: log-likelihood at convergence; G^2 : likelihood ratio statistics; M&Z R^2 : McKelvey and Zavoina's R^2.

Table 5
Estimated risk level probabilities and collision risks (at DCPA = 1 cable length, TCPA = 2 minutes)

Vessel class	Day Time						Night Time					
	Predicted probability from model estimates					Collision risk	Predicted probability from model estimates					Collision risk
	VHR	HR	MR	LR	SAFE		VHR	HR	MR	LR	SAFE	
VC1	0.4099	0.2981	0.2383	0.0498	0.0040	0.858	0.4716	0.3433	0.1298	0.0507	0.0045	0.869
VC2	0.3205	0.5857	0.0935	0.0003	0.0000	0.902	0.5495	0.4372	0.0133	0.0000	0.0000	0.928
VC3	0.4313	0.4216	0.1159	0.0296	0.0016	0.887	0.5116	0.3925	0.0836	0.0120	0.0003	0.900
VC4	0.4711	0.3623	0.1379	0.0269	0.0017	0.881	0.5233	0.3484	0.1070	0.0191	0.0022	0.901

Table 6
Risk scores for risk levels

Vessel class	Day			Night		
	RS_{HR}	RS_{MR}	RS_{LR}	RS_{HR}	RS_{MR}	RS_{LR}
VC1	0.9138	0.6679	0.3309	0.8914	0.5701	0.3376
VC2	0.8918	0.6346	0.3353	0.8483	0.6044	0.3036
VC3	0.9066	0.5515	0.3147	0.8640	0.5404	0.3010
VC4	0.8892	0.5803	0.3033	0.8623	0.5299	0.2538

Table 7
Safety margins and maneuverability standards at immediate action level

Vessel class	Ratio of DSM to ITA			Ratio of TSM to TSE		
	Day	Night	Increase at night	Day	Night	Increase at night
VC1	3.60	5.43	1.83	16.40	26.27	9.87
VC2	1.99	2.30	0.31	6.82	11.35	4.53
VC3	2.07	2.37	0.30	9.51	10.88	1.37
VC4	1.34	1.67	0.34	6.41	7.84	1.43

Table 8
Safety margins and maneuverability standards at ship domain level

Vessel class	Ratio of DSM to DR			Ratio of TSM to TDC		
	Day	Night	Increase at night	Day	Night	Increase at night
VC1	6.77	7.90	1.12	30.86	38.18	7.33
VC2	3.41	3.64	0.23	11.66	17.93	6.27
VC3	2.89	3.22	0.34	13.25	14.79	1.54
VC4	1.99	2.23	0.24	9.54	10.42	0.87

Figure 1
Risk scores for subjective risk levels

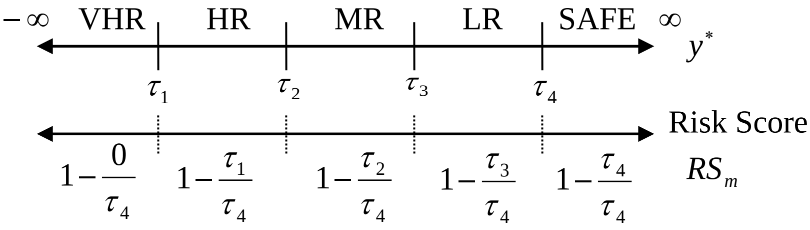

Figure 2
Block diagram of collision avoidance system