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EVALUATING MARINE TRAFFIC SAFETY AT CHANNELS

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Abstract—An approach for measuring effects of policy schemes for improving marine traffic safety at channels is presented. Operational models involving traffic, channel, and ship characteristics are provided, and both collision and channel deviation risks of actual channels are quantified using them. Moreover, traffic control, speed regulation, and center line indication are considered as channel safety policies, and their effects are also measured using the models. The results suggest that the speed regulation scheme is effective in reducing accident risk in channels. It is concluded that methodology demonstrated and knowledge obtained in this study are useful for planning and safe operation of channels.

INTRODUCTION

The growth of marine traffic—in the number, size, and speed of ships that make up the traffic—has pointed to the necessity for some policy schemes for traffic safety in congested areas. Effects of such alternative schemes on marine traffic safety should be measured so that we can allocate the limited resources among them. This requires quantitative evaluation of marine traffic safety.

In many of the congested areas, channels are established as roads for ships. Because all the ships sailing in the area must pass through the channel, traffic is much congested in the channel and traffic accidents are likely to occur. Such being the case, marine traffic accidents at channels are selected as the subject of the study. Marine traffic accidents consist of collisions and groundings. But as to the latter, it can be considered that a ship would not ground within the channel unless she deviates from it. Therefore, we deal with channel deviation instead of grounding. Thus, this study aims at measuring traffic safety at channels from the viewpoint of preventing collisions and channel deviations, and at evaluating some policy schemes for improving channel traffic safety.

Because ship accidents are less common concerns than automobile accidents, there are not many preceding works that have systematically analyzed marine traffic safety. Hashimoto et al. (1985) analyzed human behavior causing ship accidents and demonstrated the latent factors involved in the occurrence of such behavior. This work provided data for long-range policies that would induce mariners to voluntarily change the behavior that could cause ship accidents.

On the other hand, shorter-range or more concrete policies that compulsorily reduce the causes are also important. This study centers on the short-range policies that produce an immediate effect on reducing ship accidents at channels. Previously published works measuring the effects of short-range policy schemes on channel traffic safety cannot be found. But some works have dealt with different aspects of accident risk at channels: Curtis (1979), Fujii et al. (1981), Lewison (1979), and Kuroda and Kita (1983) presented models obtaining the occurrence probabilities of specific collision categories, respectively. Inoue (1977) demonstrated an approximated distribution of ship track locations in the channel, and Hara et al. (1983) proposed a method to evaluate burdens of course change of ships. Each of these works gives us useful knowledge about each aspect of channel traffic safety. Based on the knowledge obtained from the preceding works, a set of models for measuring accident risk of a channel are presented in the second section of this paper. Using the models, the accident risk of actual channels are measured in the third section, and some policy schemes are evaluated in the fourth section.

MODELS

Accident risk of a channel is measured according to risk of collision and risk of channel deviation. Collisions are divided into head-on, overtaking, overtaken, and crossing categories according to the situation in which two ships meet. Collision risks of the first three categories are measured using the so-called linear collision model because these collisions occur between ships on the identical channel. Risk of crossing collision, which occurs at intersection of two channels, is measured using another one called crossing collision model. Risks of channel deviation are also divided into two categories: risk at straights of a channel and that at bends. Each of the two risks of channel deviation is measured using a different model. Hence, we deal with four kinds of model in this study.

Although accident risk of a channel is measured for every accident category using different models, the common concept throughout all these models is to measure risk of each category when an average ship sails through the channel once (i.e. per *channel trip*) in an average time period in a day. It is assumed that ships are classified into ship types according to their sizes and that ships of the identical type have the same length and breadth, and sail at the same speed. It is also assumed that the volume of through traffic of a channel is given for every ship type and every time period. Then letting $\Gamma^{cat}(i; t)$ be the accident risk of a certain category when ship i (a ship of type i) sails a channel trip in time period t and $\lambda_i(t)$ be the rate of traffic volume of ship type i in time period t, risk of the category Γ^{cat} is obtained as follows:

$$\Gamma^{cat} = \sum_t \sum_i \Gamma^{cat}(i; t) \cdot \lambda_i(t).$$

Therefore, the process up to getting $\Gamma^{cat}(i; t)$ is described in each of the following models.

Models measuring risk of collision

In this study, the probability of collision occurrence of each category is understood to be the collision risk of the category. Therefore, each of models in this subsection is for measuring the probability that an average ship meets with a collision of each category in a channel trip in an average time period.

In the model, ship i with length L_i, breadth B_i and speed V_i is considered and subscript j denotes the opposite ship in the collision. The channel is assumed to be uniform, in length L_c and width W_c and to have two-way traffic sailing on the right. It is also assumed that each ship sails parallel to the channel independently except when she gives way for collision avoidance and that she is expressed as a circle whose diameter is her breadth B. Then we define *collision* (C) as the situation in which the circles of ships intersect each other and *confrontation* (F) as the situation in which ships are on collision course, i.e. a collision will occur unless one of them gives way.

Linear collision model. This model deals with the head-on, overtaking, and overtaken categories of collision in the identical channel. Here, *head-on* (h) is the category in which a ship meets another ship coming from the opposite direction; *overtaking* (p) is the category in which she meets another slower ship travelling in the same direction; and *overtaken* (q) is, contrarily, the category in which she meets another, faster ship. We define these meetings to be *encounters* (E).

As for give-way for collision avoidance, the following is supposed: give-way is accomplished by means of a starboard turn. Any confrontation occurs on the identical course line of the two ships concerned, and a ship track of give-way is expressed as a line segment at an angle of θ. In the head-on confrontation, both of the two ships start to give way at the same time. On the other hand, in the overtaking and overtaken confrontations, only the ship that intends to overtake gives way. (See Figs. 3 and 4.)

To calculate collision risk for each of the three categories, the probability that ship i has a collision of each category in a channel trip in time period t, $P[C]$ $(i; t)$, must be obtained. For that, we calculate the probability that ship i collides with ship j in such a situation, $P[C]$ $(i, j; t)$. This probability is obtained from the collision probability under the condition of encounter, $P[C|E]$ $(\cdot)$, and the number of ships that a ship encounters within a channel, n. Moreover the probability $P[C|E]$ $(\cdot)$ is calculated as the product of two conditional probabilities $P[C|F]$ $(\cdot)$, the give-way failure probability, and $P[F|E]$ $(\cdot)$, the confrontation probability. That is an outline of the linear collision model. Following is the manner of obtaining the probability $P[C]$ $(i, j; t)$ based on the work of Kuroda and Kita (1983).

(i) The number of ships that a ship encounters. Let n_{ij}^h be the number of ships j (ships of type j) that ship i encounters in the head-on situation within a channel. Seeing Fig. 1, it is considered that ship i would encounter, within the channel, ships j in the opposite direction existing within the range between lines ρ_1 and ρ_3 (apart by ΔL^h from line ρ_2) at the time when she has just reached on line ρ_1. Here ΔL^h should satisfy

$$L_c/V_i = \Delta L^h/V_j.$$

Supposing that ships j appear at line ρ_3 following Poisson distribution, n_{ij}^h is considered to be the number of ships j generated during the time the first-generated ship j has sailed from line ρ_3 to ρ_1. Let τ_{ij}^h be the elapsed time above, then

$$\tau_{ij}^h = (L_c + \Delta L^h)/V_j = L_c(1/V_j + 1/V_i).$$

The mean of the Poisson distribution is considered to be $Q_j^o(t)\tau_{ij}^h$, where $Q_j^o(t)$ is the through traffic volume per unit time of ships j in time period t. Therefore, the probability that ship i encounters n_{ij}^h of ships j in the head-on situation is

$$P(n_{ij}^h; t) = \frac{[Q_j^o(t)\tau_{ij}^h]^{n_{ij}^h}}{n_{ij}^h!} \exp[-Q_j^o(t)\tau_{ij}^h].$$

Likewise the probabilities that ship i encounters n_{ij}^p of ships j in the overtaking situation and that she does n_{ij}^q of those in the overtaken one are respectively

$$P(n_{ij}^p; t) = \frac{[Q_j^s(t)\tau_{ij}^p]^{n_{ij}^p}}{n_{ij}^p!} \exp[-Q_j^s(t)\tau_{ij}^p],$$

$$P(n_{ij}^q; t) = \frac{[Q_j^s(t)\tau_{ij}^q]^{n_{ij}^q}}{n_{ij}^q!} \exp[-Q_j^s(t)\tau_{ij}^q],$$

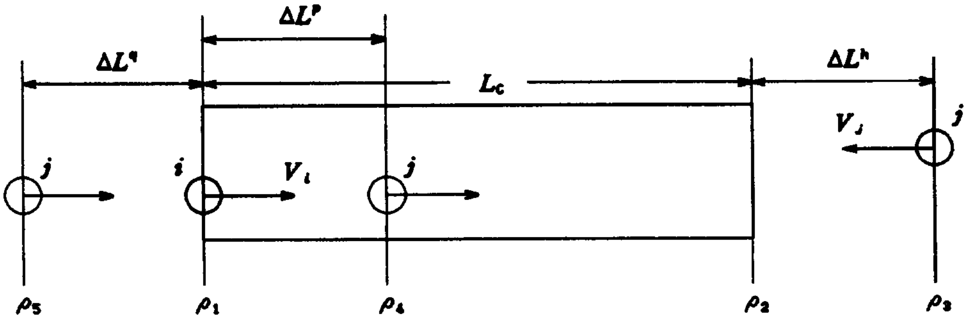

Fig. 1. Ships that a ship encounters within a channel.

where

$$\tau^{p}_{ij} = L_c(1/V_j - 1/V_i),$$

$$\tau^{q}_{ij} = L_c(1/V_i - 1/V_j).$$

(See Fig. 1 and note that superscripts *s* and *o* denote the same direction and the opposite one, respectively.)

(ii) Confrontation. As shown in Fig. 2, considering the x-coordinate axis perpendicular to channel and selecting the center of channel as the origin, track locations of ships i and j can be expressed as x_i and x_j, respectively and the relative distance between them is

$$R_{ij} = x_i - x_j.$$

Then the condition that ship i confronts ship j is

$$-D_{ij} \leqq R_{ij} \leqq D_{ij},$$

where

$$D_{ij} = (B_i + B_j)/2.$$

Since the situation that distance between centers of two ships is less than D_{ij} means a collision, D_{ij} is called *collision diameter.*

Inoue (1977) has shown that track locations of ships can be approximated to follow normal distribution with mean $\bar{x}$ and variance $[\sigma(t)]^2$, $N(\bar{x}, [\sigma(t)]^2)$, where $\bar{x}$ is a function of channel width and $\sigma(t)$ is that of channel width and through traffic volume. According to the Inoue approximation, the following can be derived: supposing that the tracks of ships in the same direction of ship i follow $N(\bar{x}, [\sigma^s(t)]^2)$, those in the opposite one follow $N(-\bar{x}, [\sigma^o(t)]^2)$. Hence, the distribution of relative distance R_{ij} follows $f^s(R_{ij}; t)$ when ships i and j are in the same direction or does $f^o(R_{ij}; t)$ when they are in the opposite one, where

$$f^s(R_{ij}; t) = N(0, 2[\sigma^s(t)]^2),$$

$$f^o(R_{ij}; t) = N(2\bar{x}, [\sigma^s(t)]^2 + [\sigma^o(t)]^2).$$

Therefore, the probabilities that ship i confronts ship j, given that they encounter in time period t, are for respective collision categories

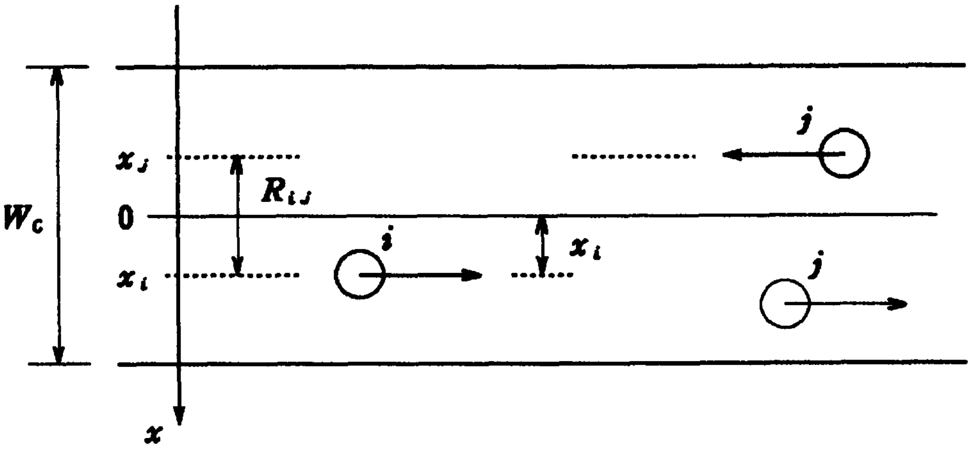

Fig. 2. Relative distance between two ships.

$$P[F|E]^h(i, j; t) = \int_{-D_{ij}}^{D_{ij}} f^o(R_{ij}; t)\, dR_{ij},$$

$$P[F|E]^p(i, j; t) = P[F|E]^q(i, j; t) = \int_{-D_{ij}}^{D_{ij}} f^s(R_{ij}; t)\, dR_{ij}.$$

(iii) Failure of give-way. Distances between two ships at the time when ships confronted with collision make starts on give-way are different one by one. In the model, the distance is supposed to be a random variable consisting of a deterministic part according to the ship type and a probabilistic part. Let d^h_{ij}, d^p_{ij} and d^q_{ij} be the distances of give-way start in the three categories of confrontations between ships i and j.

On the other hand, define *critical distance of give-way start* as the longest distance between two ships that collision can not be avoided even though give-way at an angle of θ is made a start on at the point. Moreover let m^h_{ij} be the critical distance of give-way start in the head-on confrontation between ships i and j, then it can be derived geometrically noting that the confrontation is assumed to occur on the identical course line of the two ships. That is, as shown in Fig. 3,

$$m^h_{ij} = D_{ij}/\sin\theta.$$

Likewise the critical distance of give-way start in the overtaking confrontation, m^p_{ij}, is derived as follows: As shown in Fig. 4,

$$\begin{aligned} m^p_{ij} &= D_{ij}/\sin\alpha, \\ V_i/\sin(\pi - \alpha) &= V_r/\sin\theta, \\ V_r^2 &= V_i^2 + V_j^2 - 2V_iV_j\cos\theta, \end{aligned}$$

where V_r is the relative speed of ship j as seen by ship i. Therefore,

$$m^p_{ij} = D_{ij}\frac{(V_i^2 + V_j^2 - 2V_iV_j\cos\theta)^{1/2}}{V_i\sin\theta}.$$

The critical distance of give-way start in the overtaken one, m^q_{ij}, can be obtained exchanging i and j in expression m^p_{ij}:

$$m^q_{ij} = D_{ij}\frac{(V_i^2 + V_j^2 - 2V_iV_j\cos\theta)^{1/2}}{V_j\sin\theta}.$$

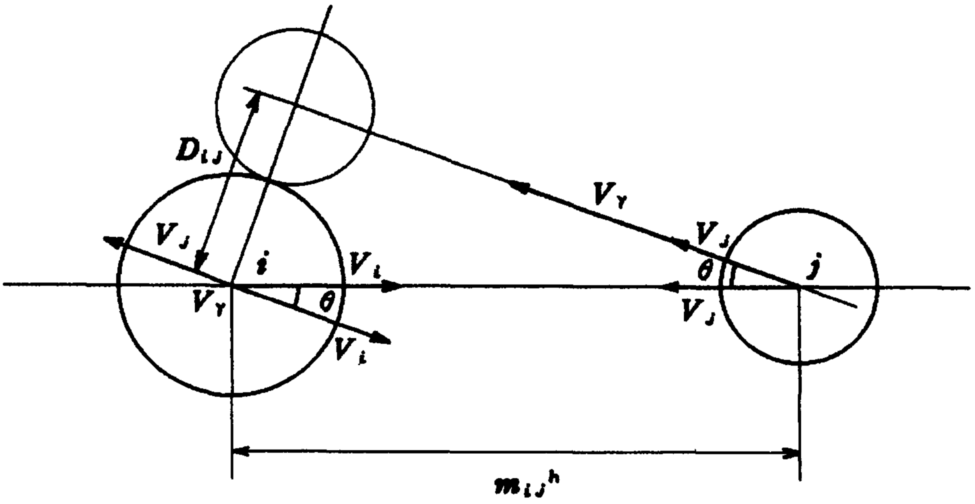

Fig. 3. Critical distance of give-way start in the head-on confrontation.

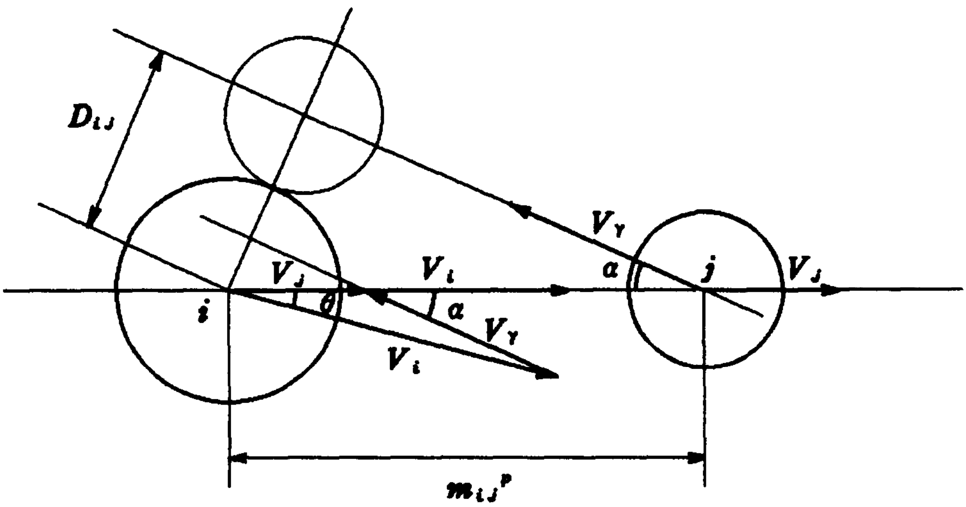

Fig. 4. Critical distance of give-way start in the overtaking confrontation.

Therefore, the probabilities of give-way failure, i.e. the probabilities of collision given that ships i and j confront each other are for respective collision categories

$$P[C|F]^h(i,j) = Prob[d_{ij}^h \leqq m_{ij}^h|F],$$
$$P[C|F]^p(i,j) = Prob[d_{ij}^p \leqq m_{ij}^p|F],$$
$$P[C|F]^q(i,j) = Prob[d_{ij}^q \leqq m_{ij}^q|F].$$

(iv) Risk of collision. The probability of collision given that ships i and j encounter in the situation of each collision category is obtained as the product of confrontation probability and give-way failure one:

$$P[C|E]^h(i,j;t) = P[F|E]^h(i,j;t) \cdot P[C|F]^h(i,j),$$
$$P[C|E]^p(i,j;t) = P[F|E]^p(i,j;t) \cdot P[C|F]^p(i,j),$$
$$P[C|E]^q(i,j;t) = P[F|E]^q(i,j;t) \cdot P[C|F]^q(i,j).$$

Since $1 - P[C|E]^h(i,j;t)$ is the probability that ship i does not collide with ship j given that they encounter in the head-on situation, the probability that ship i does not collide with ships of type j in that situation during a channel trip is

$$P[\overline{C}]^h(i,j;t) = \sum_{n_{ij}^h=0}^{\infty} [1 - P[C|E]^h(i,j;t)]^{n_{ij}^h} \cdot P(n_{ij}^h;t).$$

Considering a Maclaurin series of the expression, the probability can be approximated as follows:

$$P[\overline{C}]^h(i,j;t) \cong \sum_{n_{ij}^h=0}^{\infty} [1 - n_{ij}^h P[C|E]^h(i,j;t)] \cdot P(n_{ij}^h;t)$$
$$= 1 - Q_j^o(t)\tau_{ij}^h P[C|E]^h(i,j;t).$$

Likewise as to the overtaking and overtaken situations,

$$P[\overline{C}]^p(i,j;t) \cong 1 - Q_j^s(t)\tau_{ij}^p P[C|E]^p(i,j;t),$$
$$P[\overline{C}]^q(i,j;t) \cong 1 - Q_j^s(t)\tau_{ij}^q P[C|E]^q(i,j;t).$$

Since $\Pi_j P[\overline{C}]^h(i, j; t)$ is the probability that ship i does not collide in the head-on situation during a channel trip, the probability that ship i collides in that situation, i.e. the collision risk of head-on category when ship i sails a channel trip in time period t is

$$\Gamma^h(i; t) = 1 - \Pi_j P[\overline{C}]^h(i, j; t).$$

The collision risks of overtaking and overtaken categories when ship i sails a channel trip in time period t are also given as

$$\Gamma^p(i; t) = 1 - \Pi_j P[\overline{C}]^p(i, j; t),$$

$$\Gamma^q(i; t) = 1 - \Pi_j P[\overline{C}]^q(i, j; t).$$

Furthermore considering the total of head-on, overtaking and overtaken to be *linear collision* category (u), the collision risk of that category when ship i sails a channel trip in time period t is

$$\Gamma^u(i; t) = 1 - \Pi_j P[\overline{C}]^h(i, j; t) \cdot P[\overline{C}]^p(i, j; t) \cdot P[\overline{C}]^q(i, j; t).$$

Crossing collision model. This model deals with crossing collisions at an intersection of two channels. That is, ship i goes into the intersection on the channel with width W_c and the opposite ship j comes from the other cross-channel with width W_r. According to the Collision Regulations, a crossing ship approaching from the starboard side is the stand-on ship and the other one is therefore expected to give way. In the model, it is, hence, supposed that only the ship that sees the opposite one in her starboard side intends to give way. Therefore we consider two categories: in one, *starboard crossing* (r), ship i meets ship j approaching from the starboard side, and in the other, *port crossing* (l), ship i meets ship j approaching from the port side.

(i) Confrontation. Fujii et al. (1981) have derived the number of latent collisions between a ship and the other ships approaching in the other cross-stream of traffic when no ships give way. This is considered to be the number of crossing confrontations.

Let $N^r_{ij}(t)$ be the number of starboard crossing confrontations between ship i and ships j, i.e. the number of ships j that ship i confronts in the starboard crossing situation within an intersection in time period t. Then,

$$N^r_{ij}(t) = \phi^r_j(t) \cdot 2D'_{ij} \cdot V_r \cdot \mu,$$

where $\phi^r_j(t)$ is the traffic density of ships j approaching from the starboard cross-channel in time period t; D'_{ij} is the collision diameter in the case of a crossing collision; V_r is the relative speed of ship j as seen by ship i; μ is the time that ship i passes through the intersection. Given that ($Q^r_j(t)$ is the volume of traffic per unit time and based on Fujii et al. (1981), these are obtained as follows:

$$\phi^r_j(t) = Q^r_j(t)/V_j W_r,$$

$$D'_{ij} = (L_i + L_j)/4,$$

$$V_r = (V_i^2 + V_j^2)^{1/2},$$

$$\mu = W_r/V_i.$$

As for the port crossing confrontation,

$$N^l_{ij}(t) = \phi^l_j(t) \cdot 2D'_{ij} \cdot V_r \cdot \mu,$$

where

$$\phi_j^i(t) = Q_j^i(t)/V_jW_r.$$

(ii) Failure of give-way. The critical distance of give-way start in the starboard crossing confrontation, m_{ij}^r, can be obtained geometrically assuming that courses of ships i and j cross at right angles and that the centers of ships i and j would collide with each other at the intersecting point of their courses unless ship i gives way. As shown in Fig. 5,

$$D_{ij}'/m_{ij}^r = \cos(\alpha + \beta),$$

$$\cos(\alpha + \beta) = \cos\alpha\cos\beta - \sin\alpha\sin\beta$$

$$= \frac{V_i}{V_b}\cdot\frac{V_j + V_i\sin\theta}{V_a} - \frac{V_j}{V_b}\cdot\frac{V_i\cos\theta}{V_a},$$

$$V_b^2 = V_i^2 + V_j^2,$$

$$V_a^2 = V_i^2 + V_j^2 - 2V_iV_j\cos(\pi/2 + \theta),$$

where V_b and V_a are the relative speeds of ship j as seen by ship i before and after course change of ship i. Therefore,

$$m_{ij}^r = D_{ij}'\frac{(V_i^2 + V_j^2)^{1/2}\cdot(V_i^2 + V_j^2 + 2V_iV_j\sin\theta)^{1/2}}{V_i[V_i\sin\theta + V_j(1 - \cos\theta)]}.$$

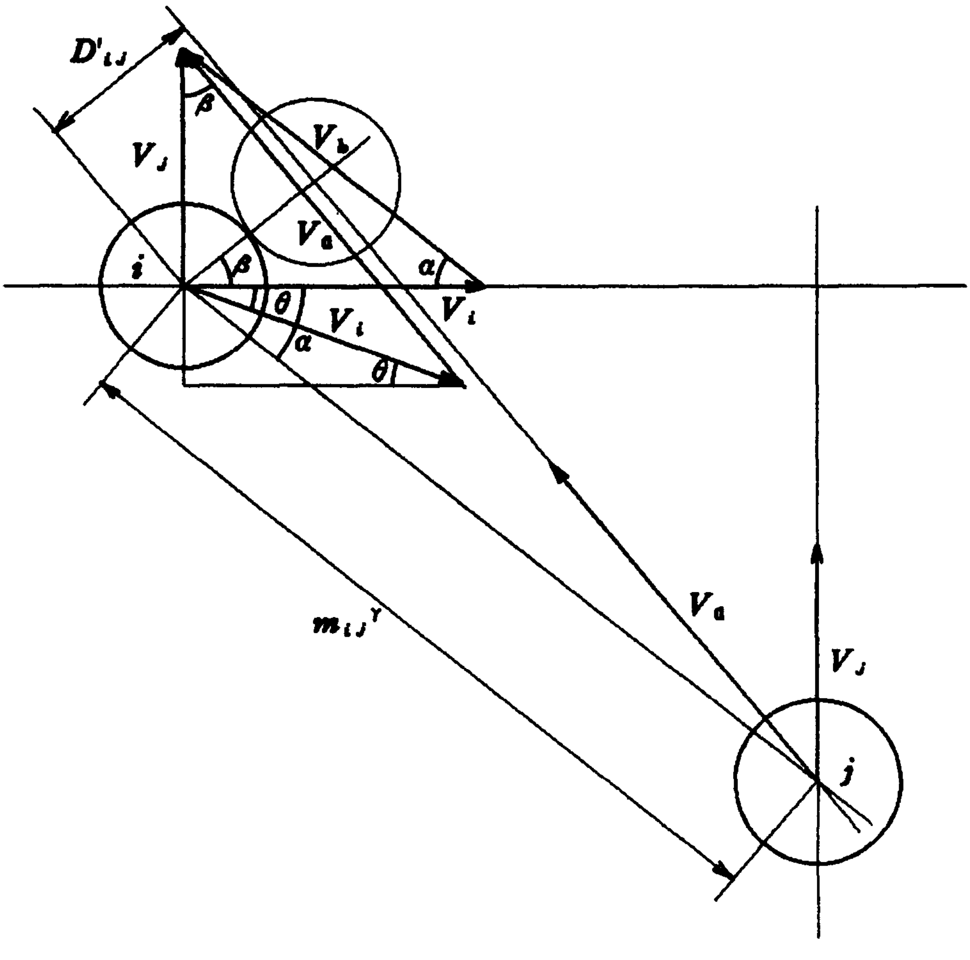

Fig. 5. Critical distance of give-way start in the starboard crossing confrontation.

The critical distance of give-way start in the port crossing confrontation, m^l_{ij}, can be obtained exchanging i and j in expression m^r_{ij}:

$$m^l_{ij} = D'_{ij}\,\frac{(V_i^2 + V_j^2)^{1/2}\cdot(V_i^2 + V_j^2 + 2V_iV_j\sin\theta)^{1/2}}{V_j[V_j\sin\theta + V_i(1 - \cos\theta)]}\,.$$

Considering the distances of give-way start in the two crossing confrontations, d^r_{ij} and d^l_{ij}, as random variables, the probabilities of give-way failure for respective crossing categories are:

$$P[C|F]^r(i, j) = Prob[d^r_{ij} \leqq m^{\gamma}_{ij}|F],$$

$$P[C|F]^l(i, j) = Prob[d^l_{ij} \leqq m^l_{ij}|F].$$

(iii) Risk of collision. Since $1 - P[C|F]^{\gamma}(i, j)$ is the probability that ship i does not collide with ship j given that they confront in the starboard crossing situation, the probability that ship i does not collide with ships of type j in that situation at the intersection is given as follows:

$$P[\overline{C}]^r(i, j; t) = [1 - P[C|F]^r(i, j)]^{N^r_{ij}(t)}.$$

Likewise as to the port crossing category,

$$P[\overline{C}]^l(i, j; t) = [1 - P[C|F]^l(i, j)]^{N^l_{ij}(t)}.$$

Since $\Pi_j P[\overline{C}]^r(i, j; t)$ is the probability that ship i does not collide in the starboard crossing situation at the intersection, the probability that ship i collides in that situation, i.e. the collision risk of starboard crossing category when ship i sails a channel trip in time period t is

$$\Gamma^r(i; t) = 1 - \Pi_j\Pi_{int}P[\overline{C}]^r(i, j; t),$$

where Π_{int} denotes multiplying values for respective intersections that ship i passes through. Likewise as to the port crossing category,

$$\Gamma^l(i; t) = 1 - \Pi_j\Pi_{int}P[\overline{C}]^l(i, j; t).$$

Moreover, the collision risk of *crossing* category (v) as the total of starboard and port crossings is

$$\Gamma^v(i; t) = 1 - \Pi_j\Pi_{int}P[\overline{C}]^r(i, j; t)\cdot P[\overline{C}]^l(i, j; t).$$

Furthermore considering *collision as a whole* (w) as the total of all collision categories, the risk of collision as a whole is

$$\Gamma^w(i; t) = 1 - \Pi_j[P[\overline{C}]^h(i, j; t)\cdot P[\overline{C}]^p(i, j; t)\cdot P[\overline{C}]^q(i, j; t) \times \Pi_{int}P[\overline{C}]^{\gamma}(i, j; t)\cdot P[\overline{C}]^l(i, j; t)].$$

Models measuring risk of channel deviation

Steering a ship in the channel is mainly course-keeping in addition to give-way maneuver in evading collision, but course-change must be added at the bends of the channel. Hence, we consider two categories of channel deviation: *channel deviation at straights* (a) and *channel deviation at bends* (b). The former is caused mainly by failure to stay on course and the latter is due to failure to alter course. Therefore, on the subject of risk of channel deviation, we consider both the probability of channel deviation and the burden of course-change.

Channel deviation at straights. The probability that a ship deviates from the channel at straights can be considered using distribution of ship track locations. Suppose that the track locations of ships follow the normal distribution, $N(\bar{x}, [\sigma(t)]^2)$, as mentioned before, then deviation from channel is the event that a track is located outside of the channel. Therefore, we can obtain the risk of channel deviation at straights when ship i sails a channel trip in time period t as follows (see Fig. 2):

$$\Gamma^a(i; t) = \int_{-\infty}^{-W_c/2} N(\bar{x}, [\sigma(t)]^2)\, dx + \int_{W_c/2}^{\infty} N(\bar{x}, [\sigma(t)]^2)\, dx.$$

It is shown that the risk of this category does not depend on the ship type but depends on the characteristics of the channel and the through-traffic volume.

Channel deviation at bends. A ship at bends must alter her course because she would deviate from the channel if she kept straight on. As shown in Fig. 6, even though ship i intends to alter her course, she must go straight a certain distance S_i. This is called *distance required for new course* and is obtained as follows (Hara et al. 1983):

$$S_i = V_i[T_i + t_s/2 + \tan(\psi/2)/K_i\delta],$$

where T_i and K_i are steering indexes of ship of type i; t_s is steering time; δ is steering angle; ϕ is angle of course change.

On the other hand, there is room z for ship i to alter her course, so that the ratio of S_i to z is considered to be the burden of course change. Let Σ_{ben} denote summing up values for respective bends that ship i passes through, then the risk of channel deviation at bends when ship i sails a channel trip in time period t is

$$\Gamma^b(i; t) = \sum_{ben} S_i/z.$$

This does not depend on time period t.

In this way, the models described in this section contain many assumptions and errors due to simplification. However, this study would not call values of accident risk derived by the models themselves in question, but would compare the risks among channels and measure the effects of policy schemes using them. For these objectives, it is considered that the assumptions are consistent and that the precision of the models is sufficient. Moreover, the following advantages of the models should rather be noted: accident risks of channels can be measured for both collision and channel deviation using

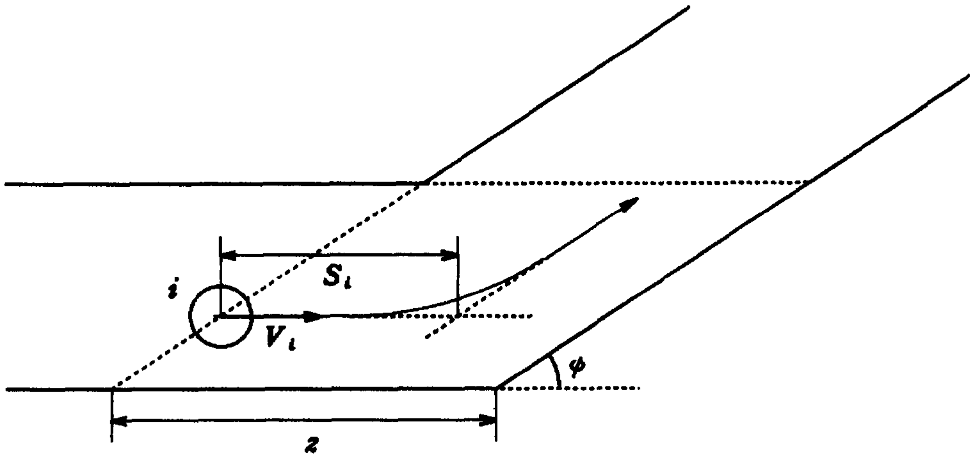

Fig. 6. Distance required for new course.

the models. Furthermore, the models are operational enough to estimate the channel risks under some policy schemes, because they are connected with traffic, channel, and ship characteristics.

MEASURING RISK OF CHANNELS

In this section, accident risks of the actual channels are measured using the models described in the preceding section and the present states of the channels are evaluated.

Applying models

The four channels that have characteristics shown in Table 1 were selected for the study. All the channels are for two-way traffic. And center lines are indicated by buoys and suchlike except for Irako channel. Bisan-East channel has four bends and two intersections. Moreover, the values of through-traffic volume shown are averages during the latest three years (1983-1985) and are the totals of averages given for every ship type and every time period of an hour.

In the study, ships were classified into seven types as shown in Table 2. The values of length, breadth, and speed of each ship type were derived from the Ship Statistics and the Through Traffic Investigations. Additionally, as the angle of course-change needed in getting critical distances of give-way starts, 30° was employed.

As for the normal distribution $N(\bar{x}, [\sigma(t)]^2)$ that approximates ship track distribution, the following $\bar{x}$ and $\sigma(t)$ derived by Inoue (1977) were employed:

$$\bar{x} = aW_c,$$

$$\sigma(t) = -7.170 + 0.105W_c + 2.168QL(t),$$

where $a = 0.2$ in the case that center line is indicated or $a = 0.1$ otherwise; $QL(t)$ is called L converted traffic volume, i.e. converted traffic volume per hour using ship length as the conversion coefficient.

Considering the distance of give-way start as a random variable consisting of deterministic and probabilistic parts, as mentioned before, regression analyses were done using various independent variables. Assuming that the probabilistic part follows normal distribution, the following regression equations for respective collision categories were

Table 1. Channel data

Channel	Length L_c (m)	Width W_c (m)	Center Line Indication	Intersections	Bends (Curvature ψ degs)	Traffic volume (ships/day)	
Uraga	14900	1400	Yes	—	1 (35)	Northbound Southbound	269 271
Akashi	6850	1500	Yes	—	1 (38)	Eastbound Westbound	245 340
Irako	3880	1180	No	—	—	Northbound Southbound	112 130
Bisan-East	37350	1400	Yes	2*	4 (14, 38, 15, 8)	Eastbound Westbound	238 221

*The intersection with Ukoh-West channel and one with Ukoh-East channel. These cross-channels are respectively for one-way traffic and have the following characteristics:

Cross-channel	Width W_c (m)	Traffic volume (ships/day)	
Ukoh-West	700	Southbound	186
Ukoh-East	700	Northbound	139

Table 2. Ship data

Ship type i	Size (gross tons)	Length L_i (m)	Breadth B_i (m)	Speed V_i (m/min)
1	less than 100	20.0	5.0	242.0
2	100–500	36.1	7.9	286.9
3	500–1,000	53.1	10.5	320.6
4	1,000–3,000	74.6	13.6	353.6
5	3,000–10,000	114.2	18.7	399.7
6	10,000–20,000	159.0	23.9	439.7
7	20,000 and over	200.0	28.4	469.7

estimated using the data by The Third District Port Construction Bureau (1974):

$$d^h_{ij} = 109.6 + 3.22V_i + 2.51V_j + 381.5\epsilon \quad (n = 24, R = 0.712),$$

$$d^p_{ij} = 184.5 + 4.22L_j - 0.929\,(V_i - V_j) + 117.3\epsilon$$

$$(n = 10, R = 0.770),$$

$$(d^q_{ij} = 184.5 + 4.22L_i - 0.929\,(V_j - V_i) + 117.3\epsilon),$$

$$d^r_{ij} = -648.8 + 5.81V_i + 9.43L_j + 519.4\epsilon \quad (n = 15, R = 0.617),$$

$$(d^l_{ij} = -648.8 + 5.81V_j + 9.43L_i + 519.4\epsilon),$$

where ϵ is the random variable following $N(0, 1)$; n is the number of cases; R is the correlation coefficient of regression. Although it can not necessarily be said that these regression equations adequately explain the distance of give-way start, they must be employed because there are no other data about give-way.

As the data needed in computing risk of channel deviation at bends, the following values and expressions by Hara (1973) were employed: the steering angle δ is 15° and the steering indexes T_i and K_i and the steering time t_s are given as follows:

$$T_i = T' \cdot L_i/V_i,$$

$$K_i = K' \cdot V_i/L_i,$$

$$t_s = \delta/V_s,$$

where $T' = 2.5$; $K' = 1.8$; V_s, steering speed, is 2.33 degs/sec.

Accident risk of channels

Accident risk of the four channels were measured as shown in Table 3.

Risk of collision. As shown in the column for collision as a whole in Table 3, Bisan-East channel eastbound has the greatest collision risk per channel trip and westbound has the next greatest risk. That is, Bisan-East is the most dangerous channel in the sense that a ship is more likely to meet with a collision here, compared with other channels when she sails a channel trip. This is because only Bisan-East channel has crossing collisions and because the length of channel is longest, so that a ship encounters a lot of ships within the channel. Bisan-East channel is followed by Uraga, Akashi, and Irako channels in order of channel length. The collision risk per channel trip is important from the viewpoint of grasping the risk of a channel as a whole objectively.

Next, let us consider collision risk per unit distance normalized by channel length. Mariners would feel least safe in the channel with greater collision risk per unit distance, even if collision risks per channel trip of two channels are the same. Hence, the collision risk per unit distance is considered to be mariners' subjective evaluation of channel collision risk. The linear collision risk per kilometer is shown in Table 4. These values

Table 3. Accident risk of channels

Channel		Collision								Channel Deviation	
		Linear Collision				Crossing Collision					
		Head-on (h) [$\times 10^{-7}$]	Overtaking (p) [$\times 10^{-3}$]	Overtaken (q) [$\times 10^{-3}$]	Total (u) [$\times 10^{-3}$]	Starboard (r) [$\times 10^{-5}$]	Port (l) [$\times 10^{-5}$]	Total (v) [$\times 10^{-5}$]	Collision as a whole (w) [$\times 10^{-3}$]	At straights (a) [$\times 10^{-2}$]	At bends (b) [$\times 10^{-1}$]
Uraga	Northbound	0.474	1.01	1.01	2.02	—	—	—	2.02	1.85	1.55
	Southbound	0.471	1.43	1.42	2.85	—	—	—	2.85	3.44	1.53
Akashi	Eastbound	0.709	0.814	0.814	1.63	—	—	—	1.63	1.06	1.29
	Westbound	0.514	0.742	0.742	1.48	—	—	—	1.48	1.80	1.17
Irako	Northbound	0.625	0.221	0.221	0.442	—	—	—	0.442	0.0560	—
	Southbound	0.698	0.228	0.228	0.456	—	—	—	0.456	0.251	—
Bisan-East	Eastbound	2.16	1.98	1.98	3.95	2.41	3.08	5.48	4.01	1.04	2.58*
	Westbound	2.25	1.85	1.85	3.70	3.38	1.87	5.26	3.75	1.03	2.57*

*Summation of values for four bends. The values for respective bends are:

Eastbound [$\times 10^{-1}$] 0.497, 1.27, 0.531, 0.285,
Westbound [$\times 10^{-1}$] 0.495, 1.26, 0.530, 0.285.

Table 4. Collision risk per kilometer

Channel		Linear Collision Head-on (h) [$\times 10^{-8}$]	Overtaking (p) [$\times 10^{-4}$]	Overtaken (q) [$\times 10^{-4}$]	Total (u) [$\times 10^{-4}$]
Uraga	Northbound	0.318	0.680	0.679	1.36
	Southbound	0.316	0.957	0.956	1.91
Akashi	Eastbound	1.04	1.19	1.19	2.38
	Westbound	0.750	1.08	1.08	2.17
Irako	Northbound	1.61	0.569	0.569	1.14
	Southbound	1.80	0.587	0.587	1.17
Bisan-East*	Eastbound	0.578	0.529	0.529	1.06
	Westbound	0.602	0.495	0.496	0.991

*

Channel		Crossing Collision Starboard (r) [$\times 10^{-4}$]	Port (l) [$\times 10^{-4}$]	Total (v) [$\times 10^{-4}$]
Bisan-East	Eastbound	0.344	0.440	0.783
	Westbound	0.483	0.267	0.751

are the occurrence probabilities of respective collisions. Since crossing collisions occur only at intersections, the occurrence probabilities of these categories should be normalized by the width of cross-channel. Such values per kilometer are also shown in the footnote to Table 4.

Seeing the column for linear collision total in Table 4, Bisan-East channel takes the smallest values. This shows that mariners would feel safest in Bisan-East channel, excluding intersections. Akashi channel has the greatest collision risk per kilometer, that is, a little over twice as much as Bisan-East. Hence, it might be said that mariners have the most difficulty steering ships in Akashi channel.

Table 4 also shows that overtaking, overtaken, and crossing collisions have about the same occurrence probabilities, but head-on collision probability is extremely small. This is mainly due to the small probability of give-way failure of the head-on category. Although head-on collision is, thus, the stochastically rare event, it must not be slighted, because it is considered to cause more serious damage than the others once the collision has occurred. Irako channel has the greatest occurrence probability per kilometer of head-on collision, that is five or six times as much as Uraga. The reason for this is assumed to be that the center line is not indicated at Irako channel. The effect of center line indication is measured in the next section.

Risk of channel deviation. As for channel deviation at straights, Uraga channel has the greatest risk, and Irako channel has the smallest (see Table 3). The latter is because the center line is not indicated, so that ship track distribution locates to the middle of channel. The former is because Uraga channel traffic has a high proportion of large-sized ships. This brings on great value of L converted traffic volume, which brings on great value of standard deviation of ship track distribution. Since there are obstacles close by Uraga channel, the greatest risk of channel deviation at straights of Uraga channel should be noted.

Bisan-East channel has the greatest risk of channel deviation at bends. This is because Bisan-East channel has four bends. What we should note here is that Uraga channel presents greater risk than Akashi channel, though Uraga has the bend with smaller curvature providing more room for course change than Akashi. This is because Uraga has traffic with a high proportion of large-sized ships as mentioned before, which brings on greater value of distance required for new course. Thus, this index can measure the risk of channel deviation at bends considering not only bend curvature but also traffic characteristics of the respective channels.

EVALUATING POLICY SCHEMES

As policy schemes for improving channel traffic safety, traffic control, speed regulation, and center line indication were considered in this study. Accident risk of channels in the case that each policy scheme is in operation is calculated using models demonstrated in the second section, and effects of the policies are measured comparing with the existing risk shown in the third section.

Effects of policy schemes

Traffic control. Reducing the gross traffic volume of channel might be considered one of traffic control schemes. But it can not be approved because it means shutout of ships in the marine traffic case where no alternative passages exist. Therefore, we consider a scheme that does not reduce gross traffic volume, but reduces traffic volume at rush hours, and ships excluded from the channel at these hours are forced to pass through the channel in another time period. As an ultimate of such a scheme, *traffic averaging* scheme, i.e. a scheme that reduces all the traffic volume of the 24 time periods to an average was supposed.

Accident risk of channels under the traffic averaging scheme and the effect of the scheme are shown in Table 5. It is shown that this scheme would not have great effect on reducing collision risk. Collision risk would rather be increased by this scheme, i.e. there exist negative effects for Irako channel southbound and Uraga channel northbound. As for risk of channel deviation at straights, we find the greatest effect for Irako channel southbound. It is followed by Uraga channel southbound and Irako channel northbound.

Speed regulation. Maximum speed regulation like one for automobile traffic is considered. Such a scheme has been enforced at some actual channels and 12 knots (370.4 m/min) has been employed as the speed limit. Hence, a speed regulation scheme that employs 12 knots as the maximum speed limit was assumed. Effect of the scheme can be calculated by reducing speeds of ship types whose speeds are over 12 knots (i.e. ship types 5, 6, and 7) to 12 knots. Of course, it is based on the assumption that all the ships observe the regulation. The results are shown in Table 6.

Effect of the scheme on reducing collision risk would be great for Uraga and Irako channels having traffic with a high proportion of large-sized ships. Considering ships over 3,000 gross tons (i.e. ship types 5, 6, and 7) as large, the speed regulation scheme influences only large-sized ships. That is, speed reduction of large-sized ships would reduce collision risk.

It is shown that there would exist negative effects of this scheme on risk reduction of head-on and crossing collisions. This is because speed reduction of large-sized ships increases the probability of give-way failure, but quantities of the negative effects are small. Moreover, the speed regulation scheme would have the effect of reducing risk of channel deviation at bends due to decrease of the distance required for new course, but the quantity of the effect is also very small.

Center line indication. A center line indication scheme was considered at Irako channel where the center line is not indicated at present. Accident risk under the scheme can be calculated by converting the coefficient value of mean of ship track distribution from 0.1 to 0.2. The results are shown in Table 7.

It is shown that center line indication would greatly reduce the risk of head-on collision, but, on the other hand, it would greatly increase risk of channel deviation at straights. No effects are shown for reducing risk of collision as a whole because the occurrence probabilities of overtaking and overtaken collisions are not influenced by this scheme and that of head-on collision takes very small value.

Discussions

Effect of traffic control on reducing collision risk. As mentioned before, the traffic averaging scheme is not so effective on reducing collision risk, and there are some cases where great negative effect is caused, as in Irako channel southbound (see Table 5).

Table 5. Effect of traffic averaging scheme*

Channel		Collision								Channel Deviation	
		Linear Collision				Crossing Collision			Collision as a whole (*w*) $[\times 10^{-3}]$	At straights (*a*) $[\times 10^{-2}]$	At bends (*b*) $[\times 10^{-1}]$
		Head-on (*h*) $[\times 10^{-7}]$	Overtaking (*p*) $[\times 10^{-3}]$	Overtaken (*q*) $[\times 10^{-3}]$	Total (*u*) $[\times 10^{-3}]$	Starboard (*r*) $[\times 10^{-5}]$	Port (*l*) $[\times 10^{-5}]$	Total (*v*) $[\times 10^{-5}]$			
Uraga	Northbound	0.430 (0.907)	1.09 (1.08)	1.09 (1.08)	2.18 (1.08)	—	—	—	2.18 (1.08)	1.32 (0.717)	1.55 ([1])
	Southbound	0.437 (0.928)	1.22 (0.853)	1.22 (0.859)	2.44 (0.856)	—	—	—	2.44 (0.856)	1.32 (0.383)	1.53 ([1])
Akashi	Eastbound	0.639 (0.901)	0.700 (0.860)	0.701 (0.861)	1.40 (0.859)	—	—	—	1.40 (0.859)	0.776 (0.732)	1.29 ([1])
	Westbound	0.457 (0.889)	0.718 (0.968)	0.719 (0.969)	1.44 (0.973)	—	—	—	1.44 (0.973)	1.04 (0.578)	1.17 ([1])
Irako	Northbound	0.689 (1.10)	0.196 (0.887)	0.196 (0.887)	0.392 (0.887)	—	—	—	0.392 (0.887)	0.0260 (0.464)	—
	Southbound	0.687 (0.984)	0.366 (1.61)	0.366 (1.61)	0.732 (1.61)	—	—	—	0.732 (1.61)	0.0280 (0.112)	—
Bisan-East	Eastbound	1.49 (0.690)	1.89 (0.955)	1.89 (0.955)	3.78 (0.957)	2.41 ([1])	3.08 ([1])	5.48 ([1])	3.83 (0.955)	0.755 (0.726)	2.58 ([1])
	Westbound	1.56 (0.693)	1.61 (0.870)	1.62 (0.876)	3.23 (0.873)	3.38 ([1])	1.87 ([1])	5.26 ([1])	3.28 (0.875)	0.695 (0.675)	2.57 ([1])

*Each value in the parentheses is the ratio of accident risk of each category to that in the existing state shown in Table 3. The brackets show that it is obvious due to structure of the model that the policy scheme has no effects on reduction of the accident risk.

Table 6. Effect of speed regulation scheme*

Channel		Collision								Channel Deviation	
		Linear Collision				Crossing Collision			Collision as a whole		
		Head-on (h) [$\times 10^{-7}$]	Overtaking (p) [$\times 10^{-3}$]	Overtaken (q) [$\times 10^{-3}$]	Total (u) [$\times 10^{-3}$]	Starboard (r) [$\times 10^{-5}$]	Port (l) [$\times 10^{-5}$]	Total (v) [$\times 10^{-5}$]	(w) [$\times 10^{-3}$]	At straights (a) [$\times 10^{-2}$]	At bends (b) [$\times 10^{-1}$]
Uraga	Northbound	0.507	0.275	0.275	0.550	—	—	—	0.550	1.85	1.54
		(1.07)	(0.272)	(0.272)	(0.272)				(0.272)	([1])	(0.994)
	Southbound	0.504	0.391	0.391	0.782	—	—	—	0.782	3.44	1.52
		(1.07)	(0.273)	(0.275)	(0.274)				(0.274)	([1])	(0.993)
Akashi	Eastbound	0.725	0.365	0.365	0.731	—	—	—	0.731	1.06	1.28
		(1.02)	(0.448)	(0.448)	(0.448)				(0.448)	([1])	(0.992)
	Westbound	0.526	0.343	0.343	0.685	—	—	—	0.685	1.80	1.17
		(1.02)	(0.462)	(0.462)	(0.463)				(0.463)	([1])	(1.00)
Irako	Northbound	0.649	0.0782	0.0782	0.156	—	—	—	0.156	0.0560	—
		(1.04)	(0.354)	(0.354)	(0.353)				(0.353)	([1])	
	Southbound	0.740	0.0718	0.0718	0.144	—	—	—	0.144	0.251	—
		(1.06)	(0.315)	(0.315)	(0.316)				(0.316)	([1])	
Bisan-East	Eastbound	2.20	0.904	0.902	1.81	2.44	3.12	5.56	1.86	1.04	2.58
		(1.02)	(0.457)	(0.456)	(0.458)	(1.01)	(1.01)	(1.01)	(0.464)	([1])	(1.00)
	Westbound	2.29	0.744	0.743	1.49	3.44	1.91	5.35	1.54	1.03	2.57
		(1.02)	(0.402)	(0.402)	(0.403)	(1.02)	(1.02)	(1.02)	(0.411)	([1])	(1.00)

*See the footnote to Table 5.

Table 7. Effect of center line indication*

Channel		Collision								Channel Deviation	
		Linear Collision				Crossing Collision			Collision as a whole		
		Head-on (h) [$\times 10^{-7}$]	Overtaking (p) [$\times 10^{-3}$]	Overtaken (q) [$\times 10^{-3}$]	Total (u) [$\times 10^{-3}$]	Starboard (r) [$\times 10^{-5}$]	Port (l) [$\times 10^{-5}$]	Total (v) [$\times 10^{-5}$]	(w) [$\times 10^{-3}$]	At straights (a) [$\times 10^{-2}$]	At bends (b) [$\times 10^{-1}$]
Irako	Northbound	0.0807 (0.129)	0.221 ([1])	0.221 ([1])	0.442 (1.00)	—	—	—	0.442 (1.00)	0.653 (11.7)	—
	Southbound	0.0908 (0.130)	0.228 ([1])	0.228 ([1])	0.456 (1.00)	—	—	—	0.456 (1.00)	1.39 (5.54)	—

*See the footnote to Table 5.

This is because the traffic averaging scheme is a policy that has influence on the number of encounters of ships. As for Irako channel southbound, it is considered that averaging traffic volume brings on increases of encounters in the overtaking and overtaken situations, which increases collision risk. Thus, the traffic averaging scheme is not necessarily the best policy. Moreover, it is not realistic because of the assumption that all the traffic that passes through a channel can be controlled.

However, assuming the controllability of all the traffic, there exists a scheme that can make collision risk zero in computation. It is a scheme fixing traffic direction and ship type that can pass through the channel in every time period. That is, in each time period under that scheme, the channel is offered for exclusive use of ships of a certain type travelling in a certain direction. Then, encounters in the head-on situation would not occur because there is no traffic from the opposite direction and those in the overtaking and overtaken ones would not occur because ships of the same type are supposed to sail at the same speed. That would result in zero risk of collision (excluding crossing collision). Although it goes without saying that this scheme is also not realistic, it suggests that traffic control by decreasing the number of encounters should be considered.

Then let us consider a scheme controlling only the traffic of large-sized ships as a more realistic one. Large-sized ships are, at present, under an obligation to inform of time when they would pass through the channel and there are comparatively few of them, so that it is considered to be possible to control this kind of traffic to some extent. Hence, as another traffic control scheme, *large-sized traffic control* that excludes large-sized ships from rush hours and makes them sail evenly in less crowded time periods was considered. To put it concretely, in the most crowded (as to the total of two-way traffic at present) 12 time periods out of 24, the channel is closed to large-sized ship traffic (ship types 5, 6, and 7), and they are evenly assigned to the remaining 12 time periods. The effect of the large-sized traffic control scheme is shown in Table 8.

It shows that this scheme is more effective, on the whole, than the traffic averaging scheme. As for Irako channel southbound, in particular, great effect is shown in contrast to Table 5. It is considered that this scheme would have reduced a good number of encounters in the overtaking and overtaken situations in the case of this channel. However, the effects of this scheme are different in the respective channels. This is because the large-sized traffic control scheme does not always bring on great decrease of encounters because of traffic characteristics of the channels (i.e. traffic volume rate of each ship type, that of each time period, etc.). That is, the effect of this scheme depends on the traffic characteristics of channels.

In this way, since traffic control influences encounters of ships, a traffic control scheme that would surely decrease the number of encounters can be expected to have great effect on reducing collision risk. For decreasing the number of encounters, it is necessary to understand the traffic characteristics peculiar to each channel precisely. But it is considered difficult to do so perfectly. In this sense, traffic control must be said to be unreliable.

Effect on reducing risk of head-on collision. Here we consider effect of the policy schemes for reducing risk of head-on collision. As mentioned earlier, head-on collisions cause severe damage though they have small occurrence probability. Irako is the channel that has the greatest risk per kilometer of head-on collision (see Table 4), but the center line is not indicated there. Supposing center line indication at Irako channel, it would have great effect (i.e. 85% to 90% reduction) on head-on collision reduction (see Table 7). This is because center line indication reduces the confrontation probability of head-on collision. In consequence, Irako would be the channel that has the smallest risk of head-on collision of the four channels after implementation of the center line indication scheme.

The traffic control scheme would not have great effect on reducing risk of head-on collision (see Tables 5 and 8). But traffic control can reduce the risk drastically, because it influences encounters of ships as mentioned before. The speed regulation scheme would have negative effect (see Table 6). This is mainly due to the increase of the probability of give-way failure through speed reduction of large-sized ships.

Table 8. Effect of large-sized traffic control scheme*

Channel		Collision								Channel Deviation	
		Linear Collision				Crossing Collision			Collision as a whole (*w*) $[\times 10^{-3}]$	At straights (*a*) $[\times 10^{-2}]$	At bends (*b*) $[\times 10^{-1}]$
		Head-on (*h*) $[\times 10^{-7}]$	Overtaking (*p*) $[\times 10^{-3}]$	Overtaken (*q*) $[\times 10^{-3}]$	Total (*u*) $[\times 10^{-3}]$	Starboard (*r*) $[\times 10^{-5}]$	Port (*l*) $[\times 10^{-5}]$	Total (*v*) $[\times 10^{-5}]$			
Uraga	Northbound	0.365 (0.770)	0.964 (0.954)	0.963 (0.953)	1.93 (0.955)	—	—	—	1.93 (0.955)	1.95 (1.05)	1.55 ([1])
	Southbound	0.366 (0.777)	0.574 (0.401)	0.573 (0.404)	1.15 (0.404)	—	—	—	1.15 (0.404)	1.62 (0.471)	1.53 ([1])
Akashi	Eastbound	0.584 (0.824)	0.503 (0.618)	0.503 (0.618)	1.01 (0.620)	—	—	—	1.01 (0.620)	0.939 (0.886)	1.29 ([1])
	Westbound	0.432 (0.840)	0.548 (0.739)	0.548 (0.739)	1.10 (0.743)	—	—	—	1.10 (0.743)	1.34 (0.744)	1.17 ([1])
Irako	Northbound	0.613 (0.981)	0.208 (0.941)	0.208 (0.941)	0.416 (0.941)	—	—	—	0.416 (0.941)	0.0427 (0.763)	—
	Southbound	0.673 (0.964)	0.0798 (0.350)	0.0798 (0.350)	0.160 (0.351)	—	—	—	0.160 (0.351)	0.0435 (0.173)	—
Bisan-East	Eastbound	1.78 (0.824)	1.39 (0.702)	1.39 (0.702)	2.78 (0.704)	2.41 ([1])	3.08 ([1])	5.48 ([1])	2.83 (0.706)	0.815 (0.784)	2.58 ([1])
	Westbound	1.84 (0.818)	0.940 (0.508)	0.939 (0.508)	1.88 (0.508)	3.38 ([1])	1.87 ([1])	5.26 ([1])	1.93 (0.515)	0.768 (0.746)	2.57 ([1])

*See the footnote to Table 5.

Hence, for reducing head-on collision risk, center-line indication should first be considered. It can be expected to have great effect. But further reduction of the risk at channels where center lines have already been indicated is not easy. For making the reduction great and reliable, we might have to consider a scheme separating two-way traffic perfectly, such as one offering the channel for one-way traffic by the hour.

Effect of center-line indication. Although center-line indication decreases risk of head-on collision, it drastically increases that of channel deviation at straights (see Table 7). Because, unlike collision, channel deviation does not directly cause accidents, its risk should be considered together with outside environment close to the channel.

At present, Irako channel has the smallest risk of channel deviation at straights, and the risk would not be greater than the other three channels even if the center line were indicated (see Tables 3 and 7). But there are a lot of sunken rocks around this channel, so that channel deviation is more liable to cause groundings at this channel than at the others. This is the reason why center-line indication can not immediately approved at Irako channel.

Generally speaking, center-line indication by buoys is not very costly and is effective in reducing risk of head-on collision. But there exists a trade-off—increasing risk of channel deviation at straights—which requires a thorough consideration of natural characteristics of the channel when the scheme is enforced.

In this way, it is considered that the most effective scheme on the whole is the speed regulation. Although it would increase risks of head-on and crossing collisions a little, it would considerably decrease risk of collision as a whole. Moreover, it would also decrease risk of channel deviation at bends a little.

The speed regulation scheme does not affect risk of channel deviation at straights. As for the channel having little room outside, reduction of channel deviation risk by means of traffic control might have to be considered.

Traffic control schemes must depend on traffic characteristics of the channel and, thus, involve uncertainties, so that their effects are unpredictable though there might be some cases where they are great.

As for reducing risk of head-on collision, center-line indication has great effect. But it is necessary to consider its negative effect of greatly increasing risk of channel deviation at straights.

CONCLUSIONS

This paper presented an approach for evaluating channel traffic safety using models measuring risks of collision and channel deviation. Because the models cover all the accident categories at channels, they can be applied to any channel.

The models include points of issue such as simplifications of ship movements and errors of values used. But it is considered to be sufficient for evaluation taking a large view, such as comparing accident risks among channels and measuring effects of alternative policy schemes. Rather, the models are useful by reason of their operational structures. That is, since they are connected with traffic, channel, and ship characteristics, they are suitable to measure effects of policy schemes.

Using the models, accident risks of the four channels were measured and the policy schemes for improving channel traffic safety were evaluated. Here we found that Akashi channel has the greatest collision risk per kilometer and that the speed regulation scheme has the greatest effect on reducing accident risk on the whole. It is considered that knowledges obtained and methodology demonstrated in this study would make contributions to planning and safe operation of channels.

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