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EVALUATING MARINE TRAFFIC
SAFETY AT CHANNELS

by

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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 on reducing accident risk of channels. It is concluded that methodology demonstrated and knowledges 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 the traffic consists of -- has pointed to needs of 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 liable 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 evaluating some policy schemes for improving channel traffic safety.

Since ship accidents are less common concerns than automobile ones, there are not so many preceding works that systematically analyzed marine traffic safety. Hashimoto *et al.* (1985) analyzed human behaviors causing ship accidents and demonstrated the latent factors concerned in the occurrence of such behaviors. This work provided data for long-range policies which would make mariners reduce the behaviors causing ship accidents voluntarily.

On the other hand, shorter-range or more concrete policies which 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. The preceding works measuring effects of the short-range policy schemes on channel traffic safety are not found. But some works dealt with different faces 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 knowledges as to each face of channel traffic safety. Based on the knowledges obtained from the preceding works, a set of models for measuring accident risk of a channel are built in the second section. Using the models, 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 through risk of collision and that 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 model called linear collision model because these collisions occur between ships on the identical channel. Risk of crossing collision that occurs at intersections 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 the different model. Hence we deal with four kinds of models 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 supposed 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 supposed 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:

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

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 taken up as 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 of collision. The channel is supposed to be a uniform one with length L_c and width W_c and to be one for both-way traffic sailing on the right. It is also supposed 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 in collision course, i. e., a collision would occur unless one of them gives way.

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

As for give-way for collision avoidance, the following is supposed: A give-way is done through 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 meets with 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. Here the manner of obtaining the probability $P[C](i, j; t)$ is based on 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

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

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

where

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

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

(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

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

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

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

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

(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 deterministic part according to the ship type and probabilistic one. Let d_{ij}^h , d_{ij}^p and d_{ij}^q 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_{ij}^h 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,

$$m_{ij}^h = D_{ij} / \sin \theta.$$

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

$$m_{ij}^p = D_{ij} / \sin \alpha,$$

$$V_i / \sin(\pi - \alpha) = V_r / \sin \theta,$$

$$V_r^2 = V_i^2 + V_j^2 - 2V_i V_j \cos \theta,$$

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

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

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

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

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

$$P[C|F]^h(i, j) = \text{Prob}[d_{ij}^h \leq m_{ij}^h | F],$$

$$P[C|F]^p(i, j) = \text{Prob}[d_{ij}^p \leq m_{ij}^p | F],$$

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

(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

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

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

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

Likewise as to the overtaking and overtaken situations,

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

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

Since $\Pi_j P[\bar{C}]^h(i, j; t)$ 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

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

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

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

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

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

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

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: one, *starboard crossing* (r), is the category that ship i meets ship j approaching from the starboard side and another, *port crossing* (l), is one that 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 $N_{i,j}^r(t)$ 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

$$N_{ij}^{\gamma}(t) = \phi_j^{\gamma}(t) \cdot 2D'_{ij} \cdot V_{\gamma} \cdot \mu,$$

where $\phi_j^{\gamma}(t)$ 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 crossing collision; V_{γ} is the relative speed of ship j as seen by ship i ; μ is the time that ship i passes through the intersection. These are obtained as follows:

$$\phi_j^{\gamma}(t) = Q_j^{\gamma}(t) / V_j W_{\gamma} \quad (Q_j^{\gamma}(t) = \text{the volume of traffic per unit time}),$$

$$D'_{ij} = (L_i + L_j) / 4 \quad (\text{Fujii } et \text{ al. } 1981),$$

$$V_{\gamma} = (V_i^2 + V_j^2)^{1/2},$$

$$\mu = W_{\gamma} / V_i.$$

As for the port crossing confrontation,

$$N_{ij}^{\lambda}(t) = \phi_j^{\lambda}(t) \cdot 2D'_{ij} \cdot V_{\gamma} \cdot \mu,$$

where

$$\phi_j^{\lambda}(t) = Q_j^{\lambda}(t) / V_j W_{\gamma}.$$

(ii) Failure of give-way. The critical distance of give-way start in the starboard crossing confrontation, m_{ij}^{γ} , can be obtained geometrically assuming that courses of ships i and j cross at right angles and that 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,

$$D'_{ij} / m_{ij}^{\gamma} = \cos(\alpha + \beta),$$

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

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

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

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

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

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

The critical distance of give-way start in the port crossing confrontation, m_{ij}^{λ} ,

can be obtained exchanging i and j in expression m_{ij}^y :

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

Considering the distances of give-way start in the two crossing confrontations, d_{ij}^y and d_{ij}^l , as random variables, the probabilities of give-way failure are for respective crossing categories

$$P[C|F]^y(i, j) = \text{Prob}[d_{ij}^y \leq m_{ij}^y | F],$$

$$P[C|F]^l(i, j) = \text{Prob}[d_{ij}^l \leq m_{ij}^l | F].$$

(iii) Risk of collision. Since $1 - P[C|F]^y(i, j)$ 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:

$$P[\bar{C}]^y(i, j; t) = [1 - P[C|F]^y(i, j)]^{N_{ij}^y(t)}.$$

Likewise as to the port crossing category,

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

Since $\Pi_j P[\bar{C}]^y(i, j; t)$ 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

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

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

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

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

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

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

$$\Gamma^{\text{II}}(i;t) = 1 - \prod_j [P[\bar{C}]^b(i,j;t) \cdot P[\bar{C}]^p(i,j;t) \cdot P[\bar{C}]^q(i,j;t) \\ \times \prod_{int} P[\bar{C}]^r(i,j;t) \cdot P[\bar{C}]^s(i,j;t)].$$

Models measuring risk of channel deviation

Steering a ship in the channel is mainly course keeping besides give-way maneuver in evading collision, but course change must be added at 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 due to failing to stand on the course and the latter is due to failing to alter the course. Therefore as risk of channel deviation, we consider the probability of channel deviation as to the former and the burden of course change as to the latter.

Channel deviation at straights. The probability that a ship deviates from 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 channel and through traffic volume.

Channel deviation at bends. A ship at bends must alter her course because she would deviate from the channel if she keeps 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) :

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

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 \sum_{ben} denotes 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 consist in 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 effects of policy schemes using them. For these objectives, it is considered that the assumptions are consistent and 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 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 existing 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 both-way traffic. And center lines are indicated by buoys and such like 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 ones given for every ship type and every time period of an hour.

Ships were, in the study, 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 start, 30 degs 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 distance of give-way start as 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 estimated using the data by The Third District Port

Construction Bureau (1974) :

$$d_{ij}^h = 109.6 + 3.22V_i + 2.51V_j + 381.5\varepsilon \quad (n=24, R=0.712),$$

$$d_{ij}^p = 184.5 + 4.22L_i - 0.929(V_i - V_j) + 117.3\varepsilon$$

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

$$(d_{ij}^q = 184.5 + 4.22L_i - 0.929(V_j - V_i) + 117.3\varepsilon),$$

$$d_{ij}^y = -648.8 + 5.81V_i + 9.43L_j + 519.4\varepsilon \quad (n=15, R=0.617),$$

$$(d_{ij}^t = -648.8 + 5.81V_j + 9.43L_i + 519.4\varepsilon),$$

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 not any 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 degs 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 that westbound comes after. That is, Bisan-East is the most dangerous channel in the sense that a ship is most liable to meet with a collision 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, which is 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 more dangerous 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 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 footnote of 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 least dangerous in Bisan-East channel besides 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 Akashi channel is severest for mariners to steer ships.

Table 4 also shows that overtaking, overtaken and crossing collisions have about the same occurrence probabilities, but head-on collision has the extremely small one. This is mainly due to the small probability of give-way failure of 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. It is considered to be because 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 center line is not indicated, so that ship track distribution locates to the middle of channel. The former is because Uraga channel has traffic in which the rate of large-sized ships is high. 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 has greater risk than Akashi channel though Uraga has the bend with smaller curvature that brings on larger room for course change than Akashi. This is because Uraga has the traffic with high rate 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 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 gross traffic volume of channel might be considered as 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 of rush hours and ships excluded from the 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 twenty-four time periods to an average was supposed.

Accident risk of channels under the traffic averaging scheme and 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 due to 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 limit of maximum speed was

supposed. 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 that have traffics with high rate of large-sized ships. Considering ships over 3,000 gross tons (i. e. , ship types 5, 6 and 7) as large-sized ones, the speed regulation scheme influences only large-sized ships. That is, speed reduction of large-sized ships would bring on the effect on collision risk reduction.

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 on 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. Center line indication scheme was considered at Irako channel where center line is not indicated in the existing state. 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 have great effect on reducing risk of head-on collision, but, on the other hand, it would increase risk of channel deviation at straights extremely. No effects are shown on 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 brought on as Irako channel southbound (see 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 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 do because ships of the same type are supposed to sail at the same speed. That would result in zero risk of collision besides crossing collision. Although it goes without saying that this scheme is also not realistic, it suggests that traffic control 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, in the existing state, under an obligation to inform of time when they would pass through the channel and the number of them is comparatively few, so that it is considered to be possible to control the traffic of them 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 supposed. To put it concretely, in the most crowded (as to the total traffic of both ways in

the existing state) twelve time periods out of twenty-four, the channel is closed to large-sized ship traffic (ship types 5, 6 and 7) and they are evenly assigned to the remaining twelve time periods.

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 deal of encounters in the overtaking and overtaken situations in the case of this channel. However effects of this scheme are different in respective channels. This is because the large-sized traffic control scheme does not always bring on great decrease of encounters according to traffic characteristics of channels (i. e. , traffic volume rate of each ship type, that of each time period, etc.). That is, effect of this scheme depends on 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 grasp traffic characteristics peculiar to each channel precisely. But it is considered to be difficult to do so perfectly. In this sense, traffic control must be said to be unsteady.

Effect on reducing risk of head-on collision. Here we consider effect of the policy schemes on reducing risk of head-on collision that brings on severe damage though it has the small occurrence probability. Irako is the channel that has the greatest risk per kilometer of head-on collision (see Table 4), but 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 category. In consequence, Irako would be the channel

that has the smallest risk of head-on collision of the four channels after the center line indication scheme.

The traffic control would not have great effect on reducing risk of head-on collision (see Tables 5 and 8). But traffic control has possibility to 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 increase of the probability of give-way failure through speed reduction of large-sized ships.

Hence, for reducing head-on collision risk, center line indication should firstly 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 it great and steady, we might have to consider a scheme separating traffics of both ways 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). Since channel deviation does not directly cause accidents unlike collision, its risk should be considered together with outside environment close to the channel.

Irako channel has the smallest risk of channel deviation at straights in the existing state, and the risk would not be greater than the other three channels even if center line is indicated (see Tables 3 and 7). But there exist 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 so costly and effective on 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 due to traffic control might have to be considered.

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

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

CONCLUSIONS

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

The models consist in 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. The models are rather 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 actual 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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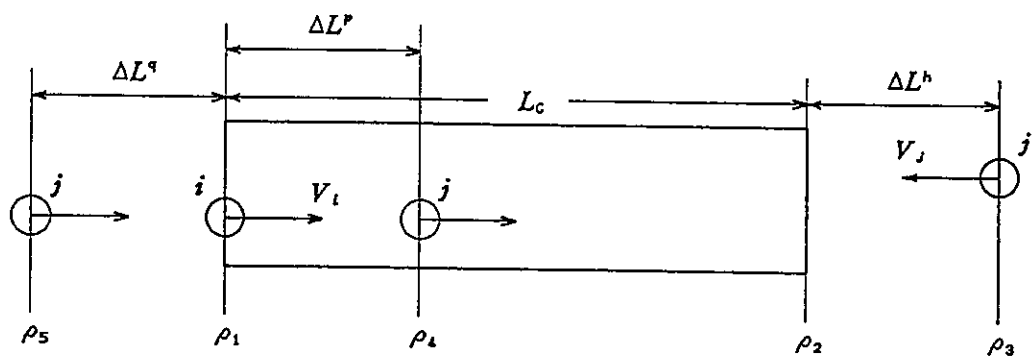


Fig. 1. Ships that a ship encounters within a channel.

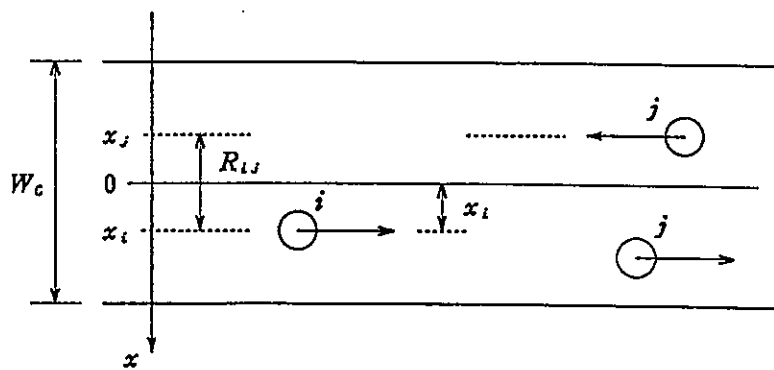


Fig. 2. Relative distance between two ships.

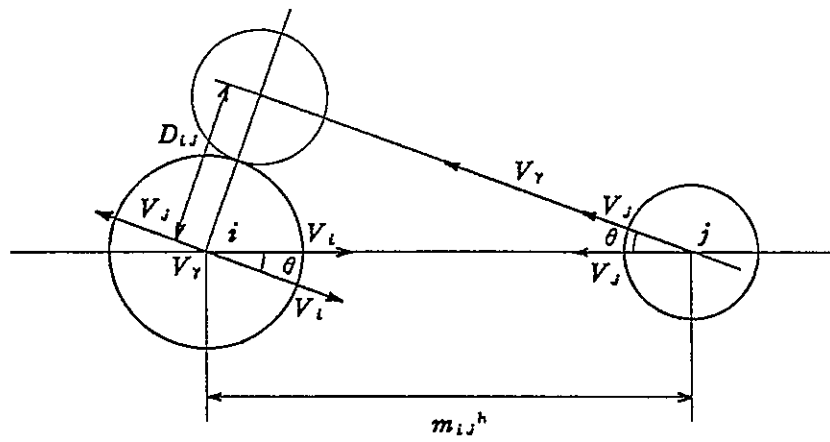


Fig. 3. Critical distance of give-way start in the head-on confrontation.

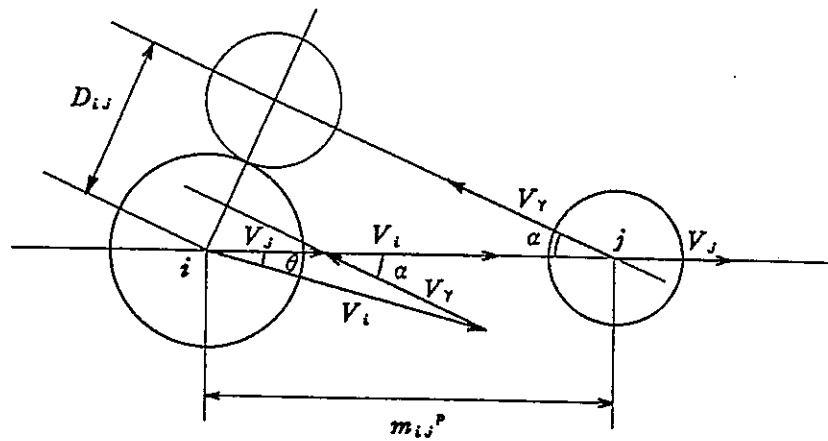


Fig. 4. Critical distance of give-way start in the overtaking confrontation.

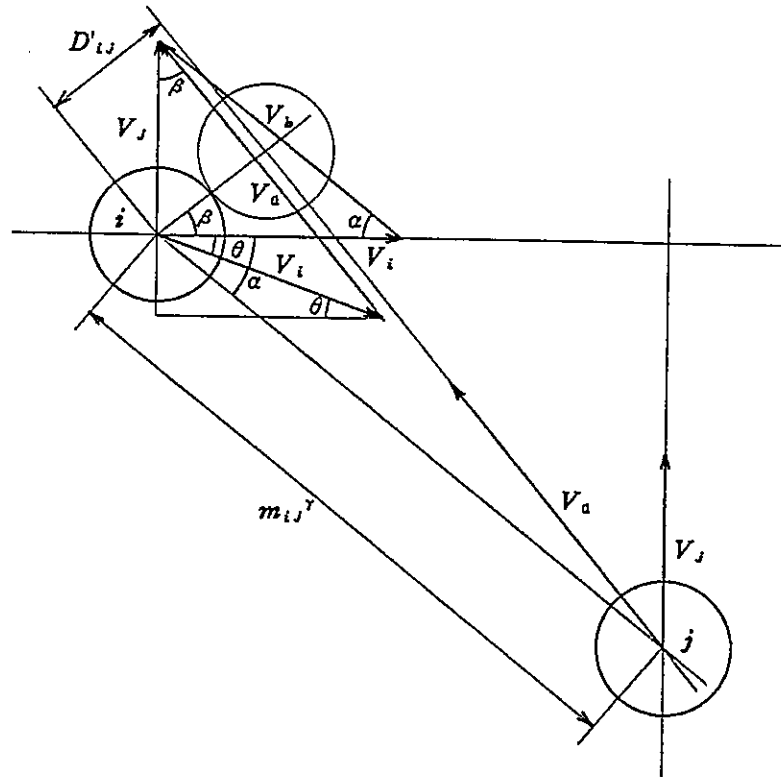


Fig. 5. Critical distance of give-way start in the starboard crossing confrontation.

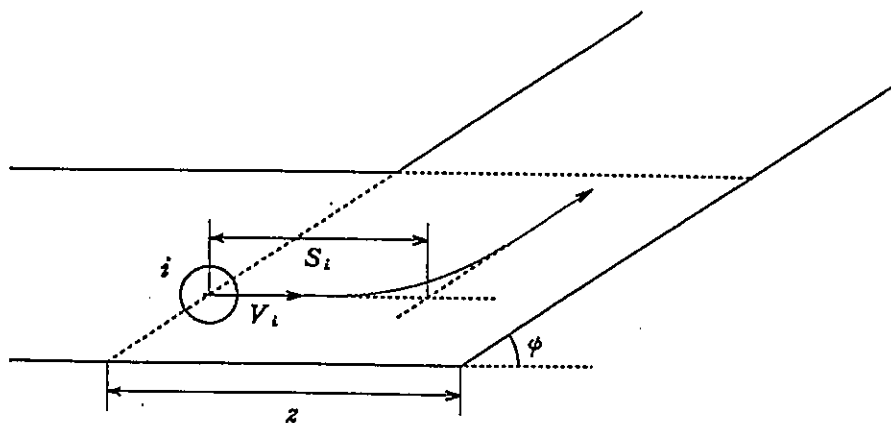


Fig. 6. Distance required for new course.

Table 1. Channel data.

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

Table 3. Accident risk of channels.

Channel		Collision							Channel Deviation		
		Linear Collision				Crossing Collision			Collision as a Whole (w) [$\times 10^{-2}$]	At Str-aights (a) [$\times 10^{-2}$]	At Bends (b) [$\times 10^{-1}$]
		Head-on (h) [$\times 10^{-7}$]	Over-taking (p) [$\times 10^{-3}$]	Over-taken (q) [$\times 10^{-3}$]	Total (u) [$\times 10^{-3}$]	Star-board (r) [$\times 10^{-5}$]	Port (l) [$\times 10^{-5}$]	Total (v) [$\times 10^{-5}$]			
Uraga	North-bound	0.474	1.01	1.01	2.02	-	-	-	2.02	1.85	1.55
	South-bound	0.471	1.43	1.42	2.85	-	-	-	2.85	3.44	1.53
Akashi	East-bound	0.709	0.814	0.814	1.63	-	-	-	1.63	1.06	1.29
	West-bound	0.514	0.742	0.742	1.48	-	-	-	1.48	1.80	1.17
Irako	North-bound	0.625	0.221	0.221	0.442	-	-	-	0.442	0.0560	-
	South-bound	0.698	0.228	0.228	0.456	-	-	-	0.456	0.251	-
Bisan-East	East-bound	2.16	1.98	1.98	3.95	2.41	3.08	5.48	4.01	1.04	2.58*
	West-bound	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)[$\times 10^{-3}$]	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

Table 5. Effect of traffic averaging scheme*.

Channel		Collision							Channel Deviation		
		Linear Collision				Crossing Collision			Collision as a Whole	At Str-aights	At Bends
		Head-on (h) [$\times 10^{-7}$]	Over-taking (p) [$\times 10^{-3}$]	Over-taken (q) [$\times 10^{-3}$]	Total (u) [$\times 10^{-3}$]	Star-board (r) [$\times 10^{-5}$]	Port (l) [$\times 10^{-5}$]	Total (v) [$\times 10^{-5}$]			
		(w) [$\times 10^{-3}$]	(a) [$\times 10^{-2}$]	(b) [$\times 10^{-1}$]							
Uraga	North-bound	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 (1.1)
	South-bound	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 (1.1)
Akashi	East-bound	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 (1.1)
	West-bound	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 (1.1)
Irako	North-bound	0.689 (1.10)	0.196 (0.887)	0.196 (0.887)	0.392 (0.887)	-	-	-	0.392 (0.887)	0.0260 (0.464)	-
	South-bound	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-bound	East-bound	1.49 (0.690)	1.89 (0.955)	1.89 (0.955)	3.78 (0.957)	2.41 (1.1)	3.08 (1.1)	5.48 (1.1)	3.83 (0.955)	0.755 (0.726)	2.58 (1.1)
East	West-bound	1.56 (0.693)	1.61 (0.870)	1.62 (0.876)	3.23 (0.873)	3.38 (1.1)	1.87 (1.1)	5.26 (1.1)	3.28 (0.875)	0.695 (0.675)	2.57 (1.1)

*Lower 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	At Str-aights	At Bends
		Head-on	Over-taking	Over-taken	Total	Star-board	Port	Total			
		(h) [$\times 10^{-7}$]	(p) [$\times 10^{-3}$]	(q) [$\times 10^{-3}$]	(u) [$\times 10^{-3}$]	(r) [$\times 10^{-5}$]	(l) [$\times 10^{-5}$]	(v) [$\times 10^{-5}$]	(w) [$\times 10^{-3}$]	(a) [$\times 10^{-2}$]	(b) [$\times 10^{-1}$]
Uraga	North-bound	0.507 (1.07)	0.275 (0.272)	0.275 (0.272)	0.550 (0.272)	-	-	-	0.550 (0.272)	1.85 (11)	1.54 (0.994)
	South-bound	0.504 (1.07)	0.391 (0.273)	0.391 (0.275)	0.782 (0.274)	-	-	-	0.782 (0.274)	3.44 (11)	1.52 (0.993)
Akashi	East-bound	0.725 (1.02)	0.365 (0.448)	0.365 (0.448)	0.731 (0.448)	-	-	-	0.731 (0.448)	1.06 (11)	1.28 (0.992)
	West-bound	0.526 (1.02)	0.343 (0.462)	0.343 (0.462)	0.685 (0.463)	-	-	-	0.685 (0.463)	1.80 (11)	1.17 (1.00)
Irako	North-bound	0.649 (1.04)	0.0782 (0.354)	0.0782 (0.354)	0.156 (0.353)	-	-	-	0.156 (0.353)	0.0560 (11)	-
	South-bound	0.740 (1.06)	0.0718 (0.315)	0.0718 (0.315)	0.144 (0.316)	-	-	-	0.144 (0.316)	0.251 (11)	-
Bisan-	East-bound	2.20 (1.02)	0.904 (0.457)	0.902 (0.456)	1.81 (0.458)	2.44 (1.01)	3.12 (1.01)	5.56 (1.01)	1.86 (0.464)	1.04 (11)	2.58 (1.00)
East	West-bound	2.29 (1.02)	0.744 (0.402)	0.743 (0.402)	1.49 (0.403)	3.44 (1.02)	1.91 (1.02)	5.35 (1.02)	1.54 (0.411)	1.03 (11)	2.57 (1.00)

*See the footnote of Table 5.

Table 7. Effect of center line indication*.

Channel		Collision							Channel Deviation		
		Linear Collision				Crossing Collision			Colli- sion as a Whole (w) [$\times 10^{-3}$]	At Str- aights (a) [$\times 10^{-2}$]	At Bends (b) [$\times 10^{-1}$]
		Head-on	Over- taking	Over- taken	Total	Star- board	Port	Total			
		(h) [$\times 10^{-7}$]	(p) [$\times 10^{-3}$]	(q) [$\times 10^{-3}$]	(u) [$\times 10^{-2}$]	(r) [$\times 10^{-5}$]	(l) [$\times 10^{-5}$]	(v) [$\times 10^{-5}$]			
Irako	North-bound	0.0807 (0.129)	0.221 ([1])	0.221 ([1])	0.442 (1.00)	-	-	-	0.442 (1.00)	0.653 (11.7)	-
	South-bound	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 of Table 5.

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

Channel		Collision							Channel Deviation		
		Linear Collision				Crossing Collision			Colli- sion as a Whole	At Str- aights	At Bends
		Head-on	Over- taking	Over- taken	Total	Star- board	Port	Total			
		(h) [$\times 10^{-7}$]	(p) [$\times 10^{-3}$]	(q) [$\times 10^{-3}$]	(u) [$\times 10^{-2}$]	(r) [$\times 10^{-5}$]	(l) [$\times 10^{-5}$]	(v) [$\times 10^{-5}$]	(w) [$\times 10^{-3}$]	(a) [$\times 10^{-2}$]	(b) [$\times 10^{-1}$]
Uraga	North-bound	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])
	South-bound	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	East-bound	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])
	West-bound	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	North-bound	0.613 (0.981)	0.208 (0.941)	0.208 (0.941)	0.416 (0.941)	-	-	-	0.416 (0.941)	0.0427 (0.763)	-
	South-bound	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-bound	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])
East	West-bound	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 of Table 5.