# Determination of Optimal Route Based on AIS and Planned Route Information

Hitoi TAMARU*, Hideki HAGIWARA*, Kohei OHTSU*, Ruri SHOJI*,
Hironao TAKAHASHI** and Akira NAKABA***

* Tokyo University of Marine Science and Technology
2-1-6 Etchujima, Koto-ku, Tokyo 135-8533 Japan
tamaru@e.kaiyodai.ac.jp
** National Institute for Land and Infrastructure Management
3-1-1 Nagase, Yokosuka City, Kanagawa Prefecture, Japan
*** Japan Radio Co.,Ltd., 5-1-1 Shimorenjaku, Mitaka City, Tokyo, Japan

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**Abstract**

The authors have newly developed the "Port Traffic Management System(PTMS)". The PTMS provides each ship with the detailed planned routes of all the ships entering/leaving the port. This system also has a function to predict the encounter situations between own ship and other ships in the future.

Based on information of the present positions, speeds and planned routes of the own ship and other ships, it is possible to predict when and where the own ship will have dangerous encounters with other ships in the future.

The software of PTMS was developed from 2001. Then onboard experiments using small training ships equipped with actual AIS were performed in June 2003. From the results of these onboard experiments, the usefulness of PTMS was clarified. In addition to these onboard experiments, the effectiveness of PTMS was confirmed by comprehensive simulator experiments. In the simulator experiments, captains/pilot maneuvered a training ship/container ship in congested waters using PTMS. It was assumed that all ships have PTMS and send their planned routes.

After the simulator experiments, captains/pilot suggested that it is very beneficial if the optimal route of own ship can be automatically calculated. In response to this suggestion, software to calculate the optimal route of own ship using Dynamic Programming was developed. This software calculates the minimum time route from the present position to the destination keeping the danger of collision against other ships under predetermined level.

From the result of calculations for multi-encounter situations, it was confirmed that the developed software can provide safe and time-saving route.

## 1 Introduction

In order to drastically improve the safety and efficiency of ship operations, several projects to build up the "Marine ITS (Intelligent Transport System)" have been promoted since 2000 by the Ministry of Land, Infrastructure and Transport in Japan. As one of these projects, the support system for safe navigation in port area and berthing maneuver has been developed based on navigational information by AIS (Automatic Identification System), hydrographic information by ENC (Electronic Navigational Chart), marine environmental information, etc..

As a sub-system of this support system, the authors have developed the system which collects information on the detailed planned route of each ship equipped with AIS in port and its approach area. The system manages the planned routes of all the ships and distributes these planned routes to each ship. On board a ship, all planned routes of the ships joining the system can be displayed on a portable terminal and based on these planned routes as well as navigational information by AIS, it is possible to predict when and where the own ship will have dangerous encounters with other ships in the future.

This system is called "Port Traffic Management System (PTMS)" (1) (2). In this paper, a basic concept and operation procedure of PTMS are described and the results of onboard experiments of PTMS using small training ships of the Tokyo University of Marine Science and Technology (TUMST) are shown.

Then method to calculate the optimal route using Dynamic Programming is described. This software calculates the minimum time route keeping the danger of collision against other ships under predetermined level.

## 2 Basic Concept and Operation of Port Traffic Management System

After 1st July 2002, the vessels of 300 G/T or more engaged in international voyages and the vessels of 500 G/T or more engaged in domestic voyages are required to be equipped with AIS. The AIS transponder transmits static information (MMSI (Maritime Mobile Service Identity) number, call sign, ship's name, IMO number, length and beam of ship, type of ship, location of position-fixing antenna on the ship), dynamic information (latitude, longitude, position accuracy indication and integrity status, coordinated universal time, course over the ground, speed over the ground, ship's heading, rate of turn, navigation status) and voyage related information (ship's draft, hazardous cargo, destination, estimated time of arrival) and short safety-related messages.

In coastal waters and big bay areas like Tokyo Bay, this AIS will be powerful tool to prevent ship's collision and to improve marine traffic management by VTS (Vessel Traffic Services) center.

In a port and its approach area, however, each ship navigates along the planned route making many course changes. Since information on the detailed planned route can not be easily transmitted by AIS, it is difficult to achieve an effective collision avoidance and traffic management in such areas by using only AIS.

Thus the authors have developed PTMS in order to provide each ship with the detailed planned routes of all ships and to perform effective collision avoidance and traffic management in a port and its approach area. The hardware of the first-stage PTMS consists of a portable terminal (notebook PC), AIS and mobile phone on board each ship and a management server (PC) and mobile phone at the PTMS center on shore. (See Fig.1)

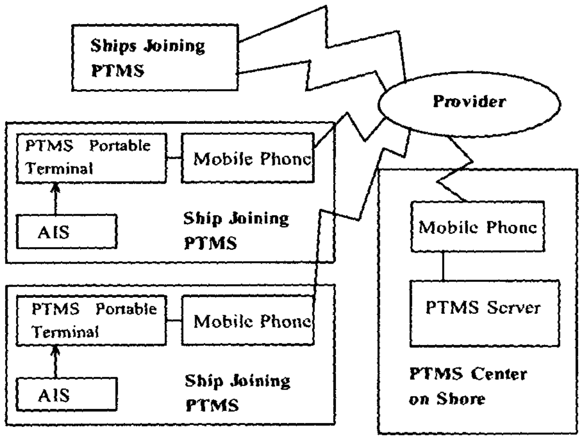


Fig.1 Configuration of the first-stage PTMS

The operation procedure of the first-stage PTMS is as follows:

(1) When a ship is approaching the port or leaving the berth, the waypoints of the planned route are determined on ENC display of PTMS portable terminal using mouse or pen, then transmitted to the PMTS server at the PTMS center with MMSI number via mobile phone.

(2) The AIS on board each ship transmits the present position, course/speed over the ground, ship's heading, MMSI number, ship's name, length of ship, etc. at intervals not longer than 10 seconds.

(3) The PTMS server manages the planned routes from all the ships joining the system, and transmits these planned routes to each ship with ship identification numbers via mobile phone. (The PTMS server transmits all planned routes when new planned route of a certain ship is received.)

(4) On ENC display of PTMS portable terminal on board each ship, the planned routes as well as the present positions, courses, speeds, ship's names, etc. of all the ships obtained from AIS can be shown.

(5) Based on information of the present positions, speeds over the ground and planned routes of the own ship and other ships, it is possible to predict when and where the own ship will have dangerous encounters with other ships in the future. This operation is called "Dangerous Ship Judgment (DSJ) mode".

In DSJ mode, the predicted positions of all ships can be shown on the planned routes using animation. When the own ship has a dangerous encounter with a certain ship, the color of both ships is changed (e.g. from green to red) to notify the shipmaster/pilot of the danger of collision. If a dangerous encounter is predicted, the shipmaster/pilot can communicate with the corresponding ship via VHF radiotelephone and talk about the change of planned route or present speed. (In case the planned route is changed, the waypoints of newly planned route are transmitted to the PTMS server.)

## 3 Judgment of Dangerous Ships

In DSJ mode of the developed PTMS, dangerous other ships are judged by the following two methods.

-Judgment by SJ (Subjective Judgment) value

-Judgment by Bumper Model

### 3.1 Judgment by SJ value

The SJ value means "subjective risk of collision felt by a watch officer against target ship" obtained by ship maneuvering simulator experiments, and is calculated by the following formulae (1).

Crossing encounter:

Own ship is give-way

$$SJ = 6.00\Omega + 0.09R' - 2.32 \tag{1}$$

Own ship is stand-on

$$SJ = 7.01\Omega + 0.08R' - 1.53 \tag{2}$$

Head-on encounter

$$SJ = 6.00\Omega + 0.09R' - 2.32 \tag{3}$$

Overtaking encounter

$$SJ = 54.43\Omega + 0.24R' + 2.77\, dR'/dt - 0.784 \tag{4}$$

where

$\Omega = |d\theta/dt| L_O/V_O$ : non-dimensional change rate of target ship direction

$R' = R/\{(L_O + L_T)/2\}$ : non-dimensional distance between own ship and target ship

$dR'/dt = V_R/V_O$ : non-dimensional relative speed between own ship and target ship

$d\theta/dt$ : change rate of target ship direction (rad/min)

$L_O$ : length of own ship (m)
$L_T$ : length of target ship (m)
$V_O$ : Speed of own ship (m/min)
$V_R$ : relative speed between own ship and target ship (m/min)
$R$ : distance between own ship and target ship (m)

In ship maneuvering simulator experiments, SJ value ranges from +3 (very safe) to -3 (very dangerous). In DSJ mode, degree of dangerous encounter is judged by the following rules:

(i) When SJ values of both own ship and target ship are positive, encounter is "safe" and both ships are shown by green color.

(ii) When SJ values of both own ship and target ship are between 0 and -1, or SJ value of one ship is positive and SJ value of the other ship is between 0 and -1, encounter is "cautious" and both ships are shown by yellow color.

(iii) When SJ value of both own ship and target ship are less than -1, or SJ value of one ship is less than -1, encounter is "dangerous" and both ships are shown by red color.

### 3.2 Judgment by Bumper Model

In crossing or head-on encounter, when distance between own ship and target ship becomes very small, SJ value tends to be positive because of large change rate of target ship direction. In overtaking, SJ value tends to be larger than -1 even if distance between two ships becomes considerably small. In order to indicate the danger of collision even in such cases, the bumper model is also used in DSJ mode.

In the bumper model, it is assumed that each ship is navigating with a bumper around the ship, and if the bumpers of two ships overlap, these two ships have a danger of collision. In general, the shape of bumper is semiellipse having semimajor axis of 6.4 L and semiminor axis of 1.6 L in the front side of a ship, and semicircle having radius of 1.6 L in the rear side of a ship, where L is length of the ship. In DSJ mode, the shape of bumper is approximated by rectangle to simplify the calculation as shown in Fig.2, and when the bumpers of own ship and target ship overlap, encounter is regarded as "dangerous" and both ships are shown by red color.

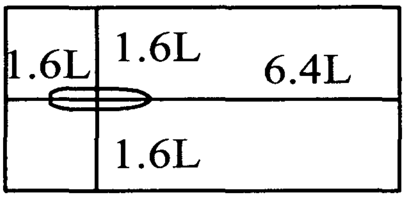

Fig.2 Rectangular bumper used in DSJ mode

## 4 *Onboard Experiments of Port Traffic Management System*

In the first-stage onboard experiments using Shioji-Maru, training ship of TUMST, the planned route of each ship was transmitted by mobile phone to the PTMS server at PTMS center on shore. However it was difficult to keep stable communication by mobile phone, and the planned route could not be sent in some cases off Port of Tokyo. This is because the mobile phone system has not been designed to be used at sea.

The AIS has a function to transmit the waypoints of the planned route as voyage related information. In order to use this function, however, it is necessary to manually input the latitudes and longitudes of the waypoints. Such input operation is difficult during a voyage in congested waters.

To overcome this difficulty, the software of the second-stage PTMS was developed in 2003 to send the waypoint data of the planned route generated on ENC display of PTMS portable terminal to AIS transponder and transmit these data as voyage related information. The AIS equipments for practical use produced by Japan Radio Co.,Ltd. were installed on a small research ship "Yayoi" (19.0 G/T, 17.8 m LOA) and a small training ship "Ootaka" (15.0 G/T, 16.5 m LOA) of the TUMST, and the onboard experiments to transmit planned route data were carried out in June 25, 2003.

On board "Yayoi" and "Ootaka", the PTMS portable terminal was set near the steering wheel on the bridge, and the AIS LAN server (PC) was set near the junction box and connected to the AIS transponder via junction box as shown in Fig.3. The planned route data of own ship were sent from PTMS portable terminal to AIS LAN server using wireless LAN. The PTMS portable terminal was set near the steering wheel on the bridge (see Fig.4). On the other hand, the AIS data such as ship's positions, speeds, courses, etc. of own ship and other ships as well as the planned route data of the other ship were sent from AIS LAN server to PTMS portable terminal using wireless LAN.

During the onboard experiments of the second-stage PTMS, various planned routes of both ships were transmitted with the AIS transponders. Those planned routes were received successfully and drawn on the ENC display of PTMS portable terminal. An example of the ENC display of PTMS portable terminal on board "Yayoi" when DSJ mode was carried out is shown in Fig.5. In Fig.5, the planned routes as well as present positions and predicted positions of both ships are drawn; the 5-minute speed vectors of both ships are also drawn. Since encounter situation at the predicted positions was "cautious" by SJ value, both ships are shown by gray circle.

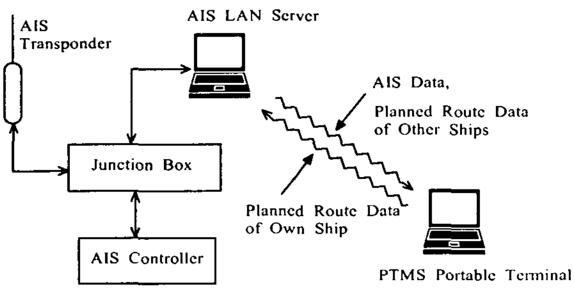

Fig.3 Configuration of the second-stage PTMS used for the onboard experiments

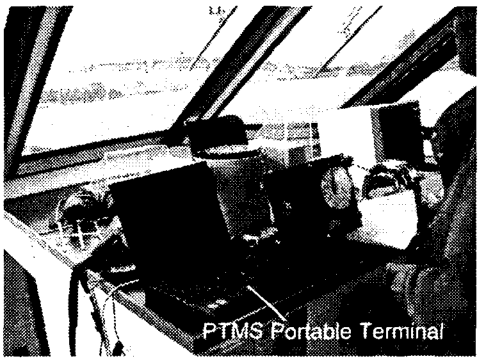

Fig.4 PTMS portable terminal installed on the bridge of "Ootaka"

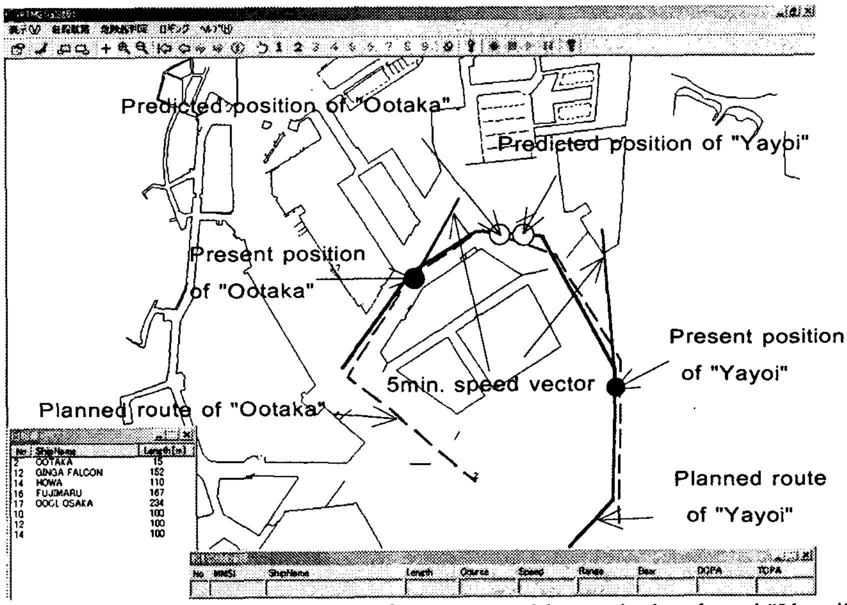


Fig.5 Example of ENC display of PTMS portable terminal on board "Yayoi"

## 5 Simulator Experiment of PTMS

In onboard experiment, the effectiveness of PTMS in congested waters was not confirmed because only two ships were available. In order to verity the effectiveness of PTMS in congested waters, comprehensive simulator experiments were carried out at National Maritime Research Institute.

In the simulator scenario, own ship (training ship (105m) or container ship (319m)) was maneuvered by captain/pilots in congested waters using PTMS. The own ship navigated to Tokyo West Passage from East Fairway off Kawasaki. There are 5 ships with PTMS. Speeds, initial headings and lengths of other ships are shown in Table 1. Other ship's planned routes are shown in PTMS terminal. Ship contours in Fig.6 show initial positions and headings.

In the simulator experiment, captains/pilot used PTMS portable terminal that had used in actual ship experiment. The own ships planned route was set by captain/pilot at any time. One of the results of simulator experiment is shown in Fig.6. Own ship position (black circle) and other ship's positions (white circle) are plotted at intervals of one minute, and planned routes of other ship are drawn. After passing through the back of ship C, own ship navigated to the destination.

Captains and pilot suggested that planned routes of other ship are effective to decide own ship's planned route. DSJ is effective to know how dangerous planned route is. Captains/pilot suggested that it is very beneficial if the optimal route of own ship is automatically calculated.

Table 1 Speeds, initial headings and lengths of other ships in simulator experiments

| | Speed [knots] | Initial heading [deg] | Length [m] |
|---|---|---|---|
| A | 10.0 | 158 | 192 |
| B | 10.0 | 258 | 76 |
| C | 12.0 | 80 | 94 |
| D | 8.0 | 150 | 94 |
| E | 9.8 | 135 | 70 |

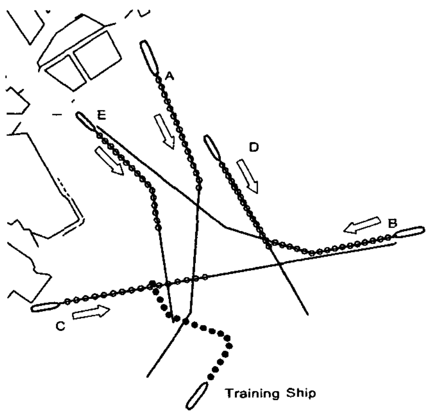


Fig.6 One of the results of simulator experiments

## 6 Optimal Route by Dynamic Programming

The method to automatically calculate the optimal route by Dynamic Programming (DP) using AIS and PTMS information (other ship's position, speed over the ground, planned route and own ship's position, destination, own ship's speed over the ground) was developed.

Here, the optimal route is defined as minimum time route without dangerous encounters (On the optimal route, SJ value should be greater than predetermined level or bumpers are not overlapped).

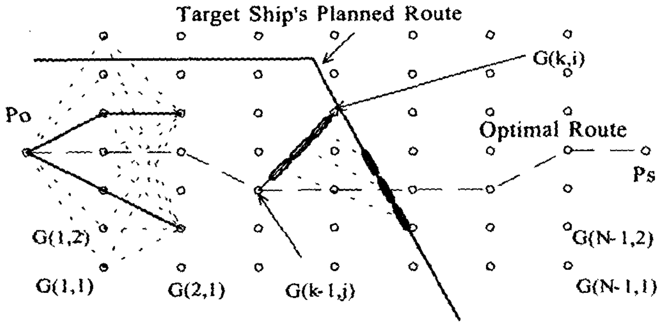


Fig.7 Calculation of Optimal Route by Dynamic Programming

An algorithm of determining optimal route by DP is as follows.

The line from present position Po to destination Ps is equally divided into N parts. Vertical lines to this line Po Ps are drawn passing through these dividing points, and grids are set on these vertical lines (see Fig.7). The $i$-th grid on the $k$-th vertical line from Po is described as $G(k,i)$. Minimum passage time from Po to $G(k,i)$ is described as $T_{min}(k,i)$. Own ship passes to destination passing through these grids.

Minimum passage time from Po to $G(k,i)$ is calculated by following formula.

$$T_{\min}(k,i) = \underset{j}{Min}\left\{T\left(G(k-1,j),G(k,i)\right)+T_{\min}(k-1,j)\right\} \qquad (5)$$

where, $T(G(k\text{-}1),G(k,i))$ is the passage time from $G(k\text{-}1,j)$ to $G(k,i)$. means minimizing the right-term by $j$.

Between the grids, SJ value and bumper are calculated at interval of 10 seconds. If SJ becomes less than the predetermined level, or two bumpers overlap, calculation between these grids is stopped.

Minimum passage times from Po to all grids $G(k,j)$ ($k$=1,2, $\cdots$, $N$-1) are calculated, and minimum passage time from Po to Ps is finally obtained.

The Optimal route is determined by tracing the grids from Ps to Po.

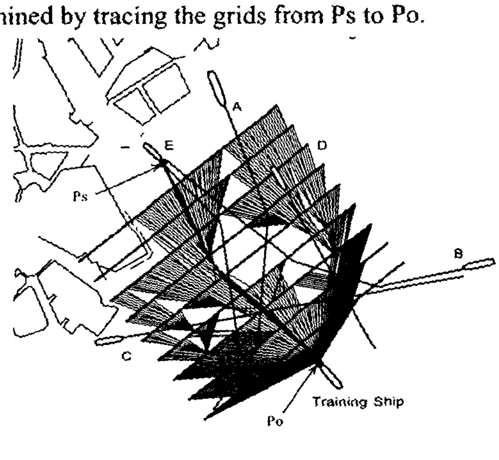


Fig.8 Optimal routes to all grids from present position

An example of optimal route is shown in Fig.8. The own ship's length is 105m. A distance from Po to Ps is 10076m. The line from present position to destination is equally divided to 10 parts. The distance between neighboring grids on each line is 100 m. The thin lines indicate the minimum time routes to all grids from present position. The bold line from the present position Po to destination Ps is optimal route which gives minimum passage time keeping SJ value under predetermined level -0.5. The optimal routes don't exist from present position to the grids without thin lines because SJ value becomes less than the predetermined level.

Optimal route passes through the border of dangerous waters.

## 7 Optimal route simulations

The optimal routes are calculated using the same scenario as the simulator experiments. It's assumed other ships with PTMS navigate on their planned route.

### 7.1 Optimal Route of Training Ship (Considering SJ Value of Own Ship Only)

Optimal routes of training ship (length = 105 m) for SJ value limit -1.0, -0.8, ···, 0.0 are shown in Fig.9.

Optimal routes for SJ value limit -1.0 or -0.8 are nearly direct route to destination. On these routes, own ship passed front of ship A, ship C and back of ship E. Optimal routes for SJ value limit over -0.6 passed the left side of direct route. Own ship passed front of ship A, ship C and ship E.

For SJ value limit -1.0, time histories of SJ value of own ship for 5 other ships are shown in Fig.10. In this case, SJ value for ship A becomes minimum.

For SJ value limit 0.0, time histories of SJ values of own ship for 5 other ships are shown in Fig.11. In this case, SJ value for ship C and ship E decrease to the limit value.

When SJ value limit is high, optimal route makes a long detour because dangerous encounter area is wide. (see Table 2)

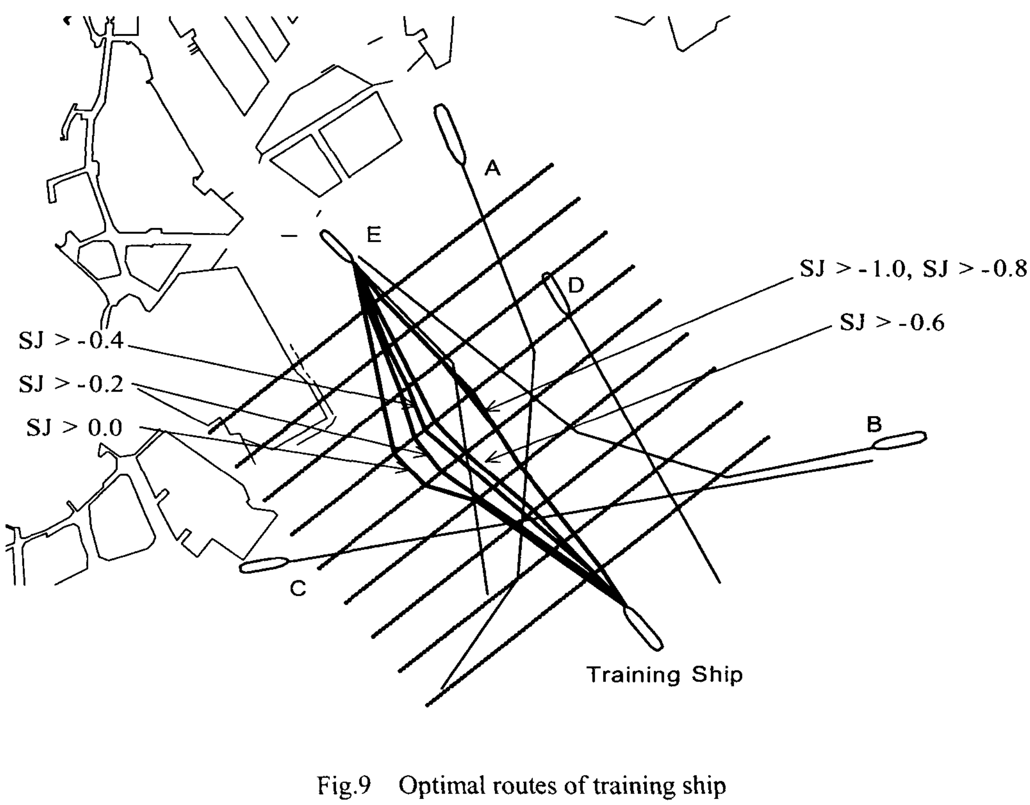


Fig.9 Optimal routes of training ship

Table 2 Passage times on optimal routes

| SJ value limits | Passage time (sec.) |
|---|---|
| -1.0 | 1683 |
| -0.8 | 1684 |
| -0.6 | 1702 |
| -0.4 | 1722 |
| -0.2 | 1752 |
| 0.0 | 1824 |

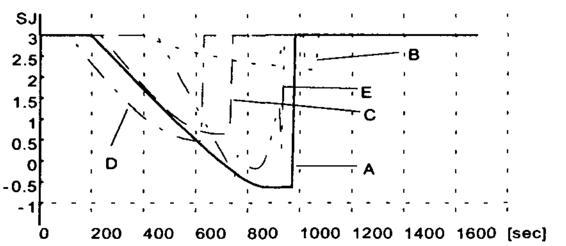


Fig.10 Time histories of SJ values of own ship (SJ > -1.0)

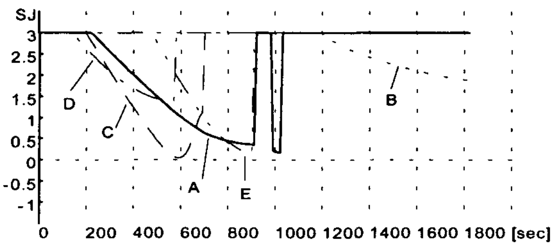


Fig.11 Time histories of SJ values of own ship (SJ > 0.0)

**7.2 Optimal route of training ship (Considering SJ values of both own ship and other ships)**

In previous section, SJ value limit was applied to only own ship.

In this section, SJ value limit is applied to both own ship and other ships.

Optimal routes of training ship for SJ value limit -1.0, -0.8, ···, 0.0 are shown in Fig.12. The optimal route for SJ value limit -1.0 or -0.8, own ship passed back of ship E. The optimal route for SJ value limit -0.6 or -0.4, own ship passed front of ship E. The optimal route for SJ value limit -0.2 or −0.0, own ship passed back of ship C. Passage times of those optimal routes are shown in Table 3.

When SJ value limit is -0.4, time histories of SJ values of own ship for 5 other ships and SJ values of 5 other ships for own ship are shown in Fig.13. When SJ value limit is 0.0, time histories of SJ values of own ship for 5 other ships and SJ values of 5 other ships for own ship are shown in Fig.14.

Calculation methods of SJ value were explained in 2. On crossing encounter, SJ value of stand-on ship and SJ value of give-way ship are different. In Fig.13, minimum SJ value of own ship that is stand-on for ship C is 0.4, but minimum SJ value of ship C that is give-way for own ship is -0.4.

When SJ value limit is 0.0 or -0.2, the optimal route that passes front of ship C don't exist because SJ value of ship C for the own ship is under the SJ value limit.

Table 3 Passage times on optimal routes

| SJ value limit | Passage time (sec.) |
|---|---|
| -1.0 | 1684 |
| -0.8 | 1688 |
| -0.6 | 1707 |
| -0.4 | 1739 |
| -0.2 | 2016 |
| 0.0 | 2101 |

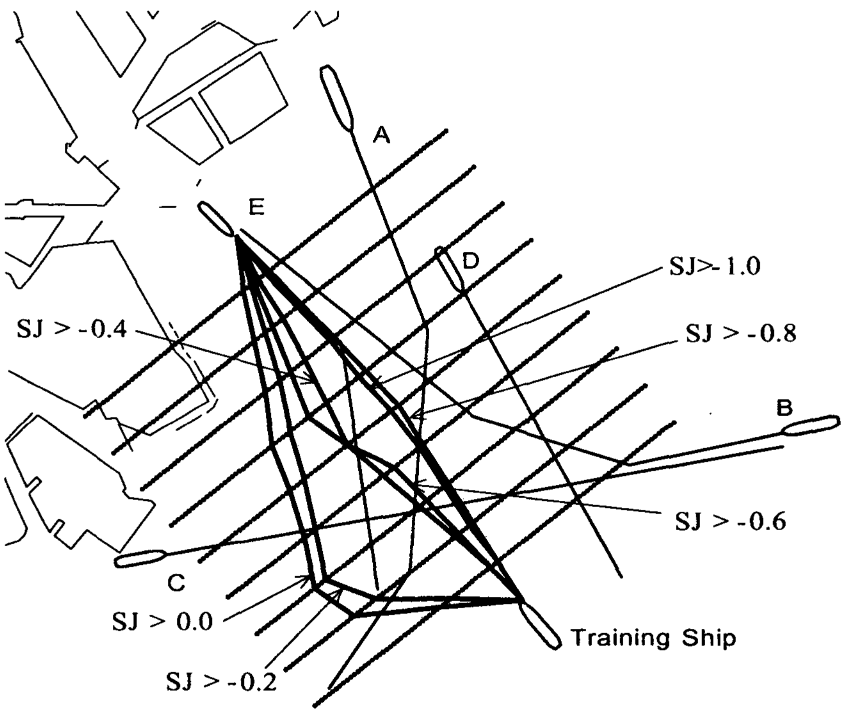


Fig.12 Optimal routes of training ship

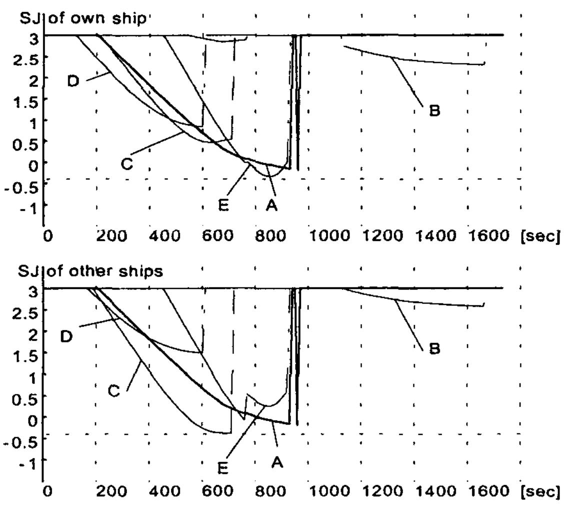


Fig.13 Time histories of SJ values of own ship and other ships (SJ > -0.4)

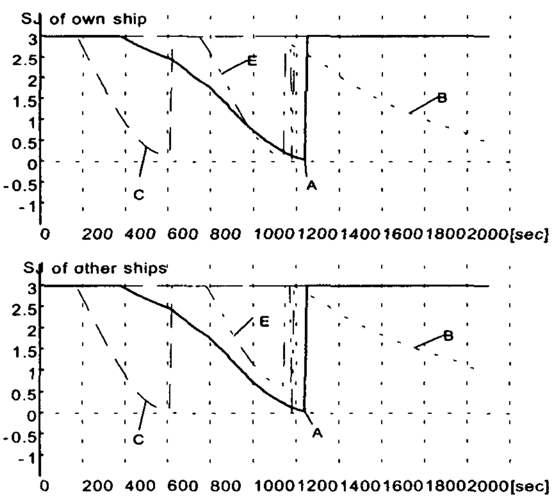


Fig.14 Time histories of SJ values of own ship and other ships (SJ > 0.0)

## 8 Conclusions

In this paper, the basic concept and operation procedure of PTMS based on AIS were described, and the result of onboard experiment of PTMS using two small vessels of the TUMST as well as the result of simulator experiment were shown.

In the onboard experiments using two small vessels, the planned route of own ship was successfully transmitted with AIS transponder, and it was received and shown on the ENC display of PTMS portable terminal of the other ship. In the simulator experiments, effectiveness of PTMS in congested waters were confirmed.

The new function of PTMS to automatically calculate the optimal route was developed. The optimal route which minimizes passage time keeping SJ value under predetermined level was calculated using Dynamic Programming. For the calculation of optimal route, SJ value limit was applied to only own ship or both own ship and other ships. Optimal routes were different for these two cases.

In this system, other ships' planned routes were fixed first. If own ship does not request to other ships to correct their planned route, optimal route of own ship should be calculated considering SJ values of both own ship and other ships.

As the future studies, onboard experiments to transmit optimal route calculated by DP is planned, and optimal routes in congested waters like off Kawasaki or Yokohama will be calculated using actual vessel traffic data.

**Acknowledgment**

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