

Eco-shipping project with a speed planning system for Japanese coastal vessels

Keiji Sato[✉], Toshiyuki Kano

National Maritime Research Institute, Japan
Shinkawa 6-38-1, Mitaka, Tokyo, 181-0004, Japan, e-mails: {sato-k, kano}@nmri.go.jp
[✉] corresponding author

Key words: slow steaming, coastal vessel, reduce CO₂ emissions, fuel reduction, cement carrier, oil tanker

Abstract

The Eco-Shipping Project has conducted demonstrative experiments since the beginning of this year using about 40 vessels including coastal cement carriers, oil tankers, and ro-ro ships supported by the Ministry of the Environment. The goal of this project is to reduce fuel and CO₂ emission by 15%. The authors developed a voyage speed planning system which calculates a vessel optimum speed plan that takes into account weather forecast information and generates minimized fuel consumption for an operation. This paper describes an approach to optimize speed profiles on ship just-in-time voyages to save fuel and reduce CO₂ emissions, and introduces some cases of experimental results.

Introduction

By 2050, greenhouse gas (GHG) emissions from marine transport are expected to increase three-fold from 2007 levels due to rising economic activities, in particular from emerging nations. Within the UN Framework Convention on Climate Change, the need for CO₂ reduction measures within marine transport were strongly expressed in the post-Kyoto Protocol discussions. The International Maritime Organization (IMO) promotes research on technical, operational, and economic means to reduce GHG emissions from ocean going ships. As part of the research on operational measures, the organization fostered a study on achieving higher efficiency in ship operations through improved voyage speed planning. Reducing the speed of ship operations could significantly reduce CO₂ emissions. Currently, to avoid the risk of delay due to weather conditions and other marine effects, ships tend to operate at excess speed and wait offshore at their destination port.

In order to produce a solution to this problem, this paper presents the Voyage Speed Planning System,

which generates an optimum ship speed for the purpose of reducing offshore wait times (just-in-time) and reduce CO₂ emission. To verify the effectiveness of our system, we apply it to the Japanese coastal vessels and present the results of the case studies of a cement carrier and an oil tanker.

Eco-shipping project

The project is to develop a ship scheduling system that allows for reduced speed operation and integrates that system with a just-in-time voyage speed planning system which takes into account the effects of weather and other factors on ships. Through real-time calculation of estimated arrival schedules (i.e., calculation based on speed reduction due to weather, marine, and other conditions), the goal of the project is to allow environmentally friendly operation and optimal routing at the minimum required speed and to significantly reduce the amount of CO₂ emissions by ships while mitigating the risk of delay in arrival.

To this end, in a three year plan beginning in FY2013, the National Maritime Research Institute

(NMRI) has collaborated with shippers, shipping companies, and other entities to use the system developed to complete demonstrative experiments on 40 vessels including cement carriers, oil tankers, and ro-ro ships.

Voyage speed planning system

Weather and tidal-current forecast

For the Voyage Speed Planning System, wind and wave forecast information is provided by the Japan Weather Association (JWA), and current forecast information is provided by the Japan Agency for Marine-Earth Science and Technology. A tide-resolving general circulation model (JCOPE-T) is used, which has been developed based on the Princeton Ocean Model with general coordinate of sigma (Mellor, Häkkinen & Tal and Patchen, 2002). It has a horizontal resolution of 1/36 deg. The nested outer model (JCOPE 2), has 46 generalized sigma layers, and covers a part of the Western North Pacific: 17–50 deg. N and 117–150 E (Miyazawa et al., 2009). Weather forecast information is updated every three hours.

Estimation of propulsion performance at sea

A model of a ship's propulsion performance at sea is described as following equation (1):

$$\frac{FOC/h}{V_s} = a_1 V_s^2 + c + a_2 f(\text{Wind}) + a_{3\theta} f(\text{Wave}) \quad (1)$$

where:

$(FOC/h)/V_s$ – hourly fuel oil consumption per speed [(l/h)/kn];

$a_1 V_s^2 + c$ – ship propulsion performance at calm sea;

$f(\text{Wind})$ – wind resistance (Fujiwara, 2006);

θ – relative wave direction;

$f(\text{Wave})$ – wave resistance (Tsujiyama, Kuroda & Sogihara, 2013).

The coefficients a_1 , c , a_2 and $a_{3\theta}$ are fitted using by measured data. The formulas for $f(\text{Wind})$ and $f(\text{Wave})$ are described as follows:

$$f(\text{Wind}) = \frac{\rho_a}{2A_T V_r^2 C_x(\gamma_r)} \quad (2)$$

$$f(\text{Wave}) = \frac{8\rho g H^2 B^2}{L_{pp}} K_{awc} \quad (3)$$

where:

ρ_a – air density;

A_T – front projected area above water line;

V_r – relative wind speed;

C_x – drag coefficients due to wind by Fujiwara's method,

ρ – fluid density;

g – gravitational acceleration;

H – significant wave height;

B – ship breadth;

L_{pp} – length between perpendiculars;

K_{awc} – non dimensional added resistance in waves.

In order to perform a calculation for Voyage Speed Planning System, we determine the coefficients of equation (1) using by monitoring data of the past several months. Figure 1 displays the flow of the estimation procedure for actual ship propulsion performance at sea and Figure 2 shows the conceptual ship performance. Initially, the past monitoring data is input and cleaned. The ship performance coefficient a_1 and c are obtained by the least squares method with measured calm sea data (relative wind speed less than 5 m/s and wave height less than 0.5 m). Then, Δf is obtained by the difference between the measured fuel oil consumption per hour [liters of fuel/h] and consumption at the measured speed under calm conditions. Next, we regard the Δf as wind effect in case of the measured data with small wave height and the coefficient a_2 is obtained by the least squares method. Note that the wave height data is forecast data by JWA. Then, take the wind effect away from Δf , the rest is assumed as the wave effect (i.e., $\Delta f - f(\text{Wind}) V_s = f(\text{Wave}) V_s$). The wave effect data are divided by relative wave direction and coefficients $a_{3\theta}$ of equation (1) is obtained by the least squares method. Wave effect estimation is taken into account based on the relative wave direction. Detail of the methodology was presented by (Kano & Sato, 2015).

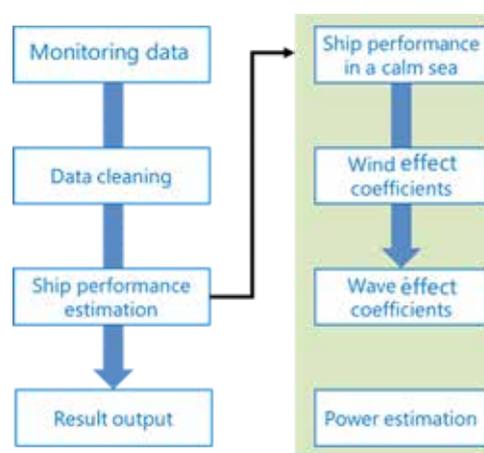


Figure 1. Flow of propulsion performance estimation

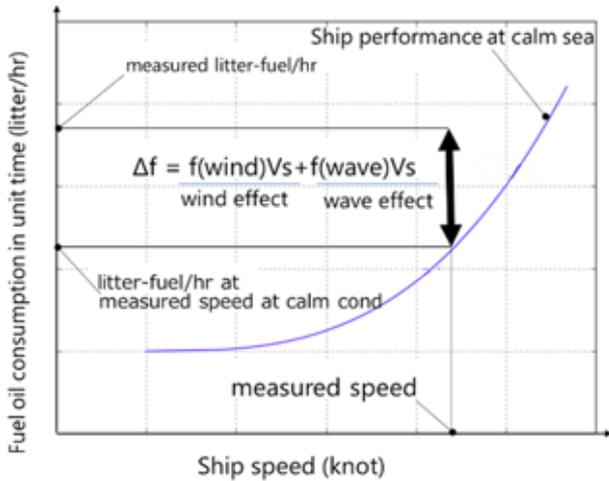


Figure 2. Conceptual ship performance

Ship speed optimization algorithm

To minimize the risk of delay, the Voyage Speed Planning System was developed by taking accurate forecast information of wind, wave, and tidal-current. Then a high-accuracy methodology of estimating the ship’s actual propulsive performance at sea and voyage speed planning method was developed through dynamic programming (Bellman, 1953).

Dynamic programming reduces the number of computations by moving systematically from one side of the equation to the other, building the best solution as it goes. Figure 3 presents schematic views of the voyage speed planning example. Each column

corresponds to a waypoint (WP1, WP2...) and each column box corresponds to a node which contains the arrival time and total cost (fuel oil consumption) from the start until arrival at the WP. The arrows correspond to control variables (110 rpm, 105 rpm...) and the numerical value of the side of the arrow corresponds to the cost between WPs. For example, we assume the case in which a ship departs at 0:00 and arrives at 21:00 and that ship has three control variables (high, middle, low (e.g., 110 rpm, 105 rpm, and 100 rpm)). In the case of node (1), we calculate the time and cost from WP_{start} and WP₁ using the ship speed at the high control variable. The ship speed is calculated by equation (1). Furthermore, the start node is set to the node (1) as previous node. Similarly, node (2) and node (3) are obtained. In the case of node (6), there are three arrows of arriving at WP₂ at 1:30 from WP₁. The total cost to pass through node (1) to node (6) is 30 + 25 = 55, the cost to pass through node (2) to node (6) is 24 + 26 = 50 and the cost to pass through node (3) to node (6) is 20 + 28 = 48. In this case, the minimum cost which arrival at WP₂ at 1:30 is 48 and the node (3) is set to the node (6) as previous node. Similarly, we can consider each box in this column in turn and compute the smallest total cost as a result of being in each box. Finally, to get the optimal solution, we choose a node with the smallest cost in which the ship arrives earlier than 21:00 and then choose the previous node back to the WP_{start}.

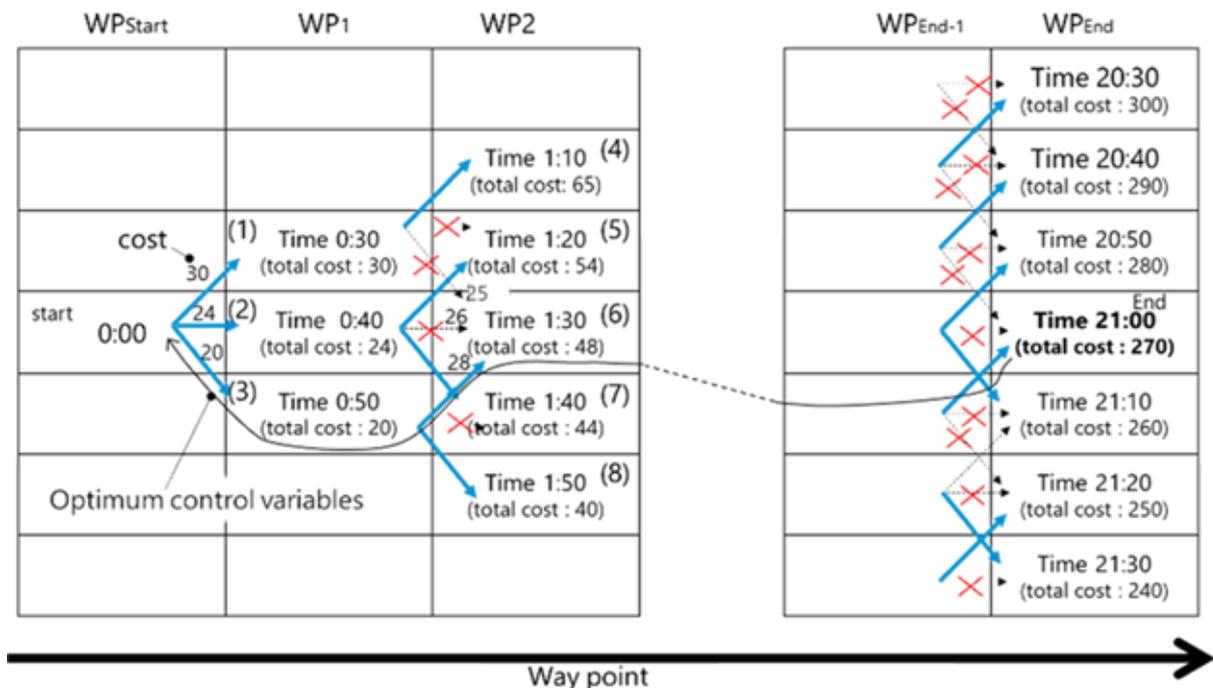


Figure 3. Schematic views of the voyage speed planning example

Evaluation

In order to evaluate our system, we have to obtain Business As Usual (BAU) fuel oil consumption per hour. BAU fuel oil consumption per hour is defined by average value of fuel oil consumption per hour without the usage of Voyage Speed Planning System for several months. Then we calculate the differences between the CO₂ emission of the actual voyage with the Voyage Speed Planning System support and the simulated voyage with BAU fuel oil consumption (Kano & Namie, 2014). The route of simulated voyage is same as the actual voyage.

Case study 1: Ship A (cement carrier)

Ship performances at sea

Here, we present the case of one of the cement carriers, Ship A, selected for a case study. Table 1 shows principal particulars of Ship A. In order to obtain a performance to be used for the Voyage Speed Planning System, we obtain coefficients of

equation (1) by using monitoring data from the past several months, and Figure 4 shows fitting results. The reason for the blank axis in the figure is because real ship performance data cannot be published. Figure 4 (A) introduces the performance in calm seas. Gray dots represent measured data, black dots represent data of a calm sea and black line represents ship performance in a calm sea. Figure 4 (B) shows comparison of measured wind effect and estimated wind effect. The estimated wind effect is obtained using measured relative wind speed and direction. Black circles present measured wind effect, and blue squares present estimated wind effect. Estimated wind effect agrees well with the measured data. Figure 4 (C) presents a comparison of wave effect and estimated wave effect. The estimated wave effect is obtained using forecast data by JWA. Wave effect data is divided for each 30° relative wave directions; red dots represent measured wave effect, and green dots represent estimated wave effect. Estimated wave effect agrees well with the measured data.

To confirm the accuracy of the determined coefficients, Figure 4 (D) shows the histogram of the

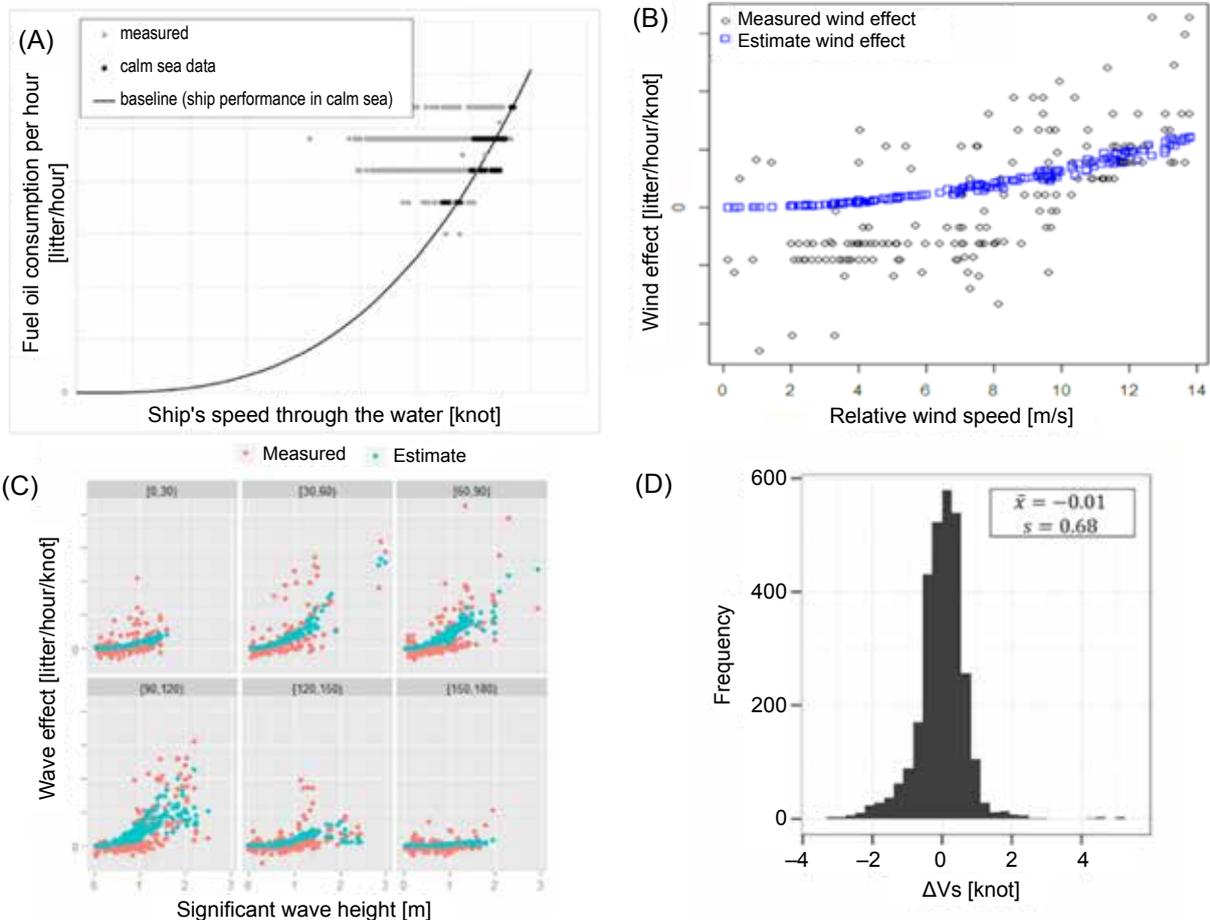


Figure 4. Performances of Ship A

difference between the measured and estimated ship speed. The term ΔV_s is obtained by subtraction of estimated ship speed from measured ship speed. Estimate ship speed is calculated by equation (1) using measured data (wind speed, direction and fuel oil consumption per hour) and forecast data (wave height, direction, and period). The estimated ship speed is obtained using measured data forecast data by JWA. The mean value of the differences is -0.01 knot and the standard deviation is 0.68 knot. The estimation result is accurately determined.

Table 1. Principal particulars of Ship A

Ship A			
Length	105 m	MCR	3089 Kw
Breadth	18 m	Gross tonnage	4944 tons
Depth	7.5 m	Nominal Speed	14.2 knots

BAU of the Ship A

To obtain the BAU of Ship A, we monitored data for the duration of ten months from January to October of 2014. The voyage in this period did not use the Voyage Speed Planning System. Figure 5 displays the histograms of fuel oil consumption per hour [liter/h] and the controllable pitch propellers (CPP) angle of the main propulsion. The captain used 16.87 degrees (average) and the average of fuel oil consumption per hour is 467 liter/h. Therefore, we set 467 liter/h as the BAU of the Ship A.

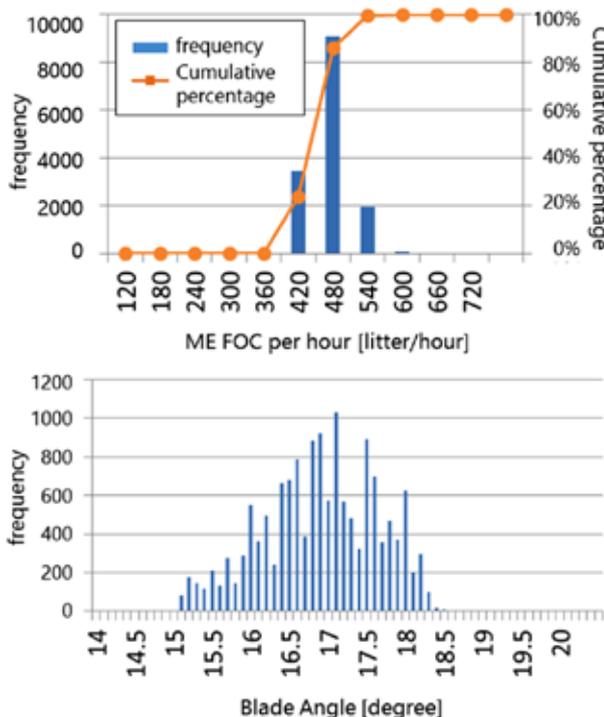


Figure 5. BAU of Ship A

Effect of CO₂ emission reduction

Here, we present the case of a voyage for an investigation of the effect of CO₂ emission reduction. Figure 6 shows a route of Ship A for the case study. The voyage is ballast condition from Tagonoura to Ube. Table 2 shows the effect of CO₂ emission reduction of the voyage. The BAU column shows the simulation result of the voyage used the BAU FOC [liter/h], the Actual column shows the result of the captained voyage in reference to the recommendation of the Voyage Speed Planning System, and the Recommended column shows the simulation result of the Voyage Speed Planning System recommended voyage.

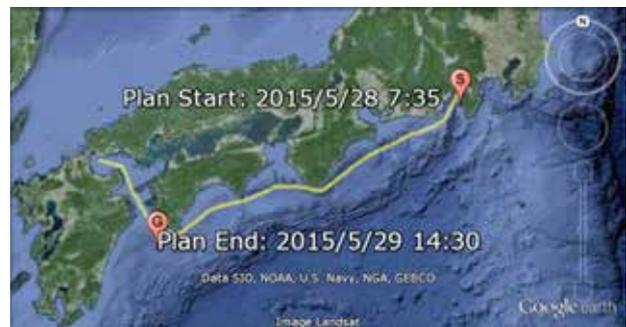


Figure 6. Route of the voyage (Ship A)

Table 2. Results of Ship A

	BAU	Actual	Recommended
Nav. Time [h]	25.8	27.7	30.5
Margin	5:04	3:20	0:20
FOC (kL)	12.0	10.6	8.7
CO ₂ (ton)	36.3	31.9	26.2
Reduction ratio	–	12.2%	27.7%

Figure 7 (A) introduces the time series result, and Figure 7 (B) demonstrates the weather conditions along the route. The horizontal axis represents a time, and the vertical axis represents fuel oil consumption [liters/h] respectively. In the case of BAU without the Voyage Speed Planning System, the voyage lasted 25.8 hours; it arrived 5 hours 4 minutes earlier than the required time of arrival, and total FOC was 12.0 kL. In the case of the Actual voyage with reference to the Voyage Speed Planning System, the voyage lasted 27.7 hours; it reduced offshore waiting times by 1 hour 44 minutes compared to the BAU voyage. Total CO₂ emission was reduced 12.2% compared with BAU. Furthermore, in the case of Recommended, the voyage lasted 30.5 hours; it reduced offshore waiting times by

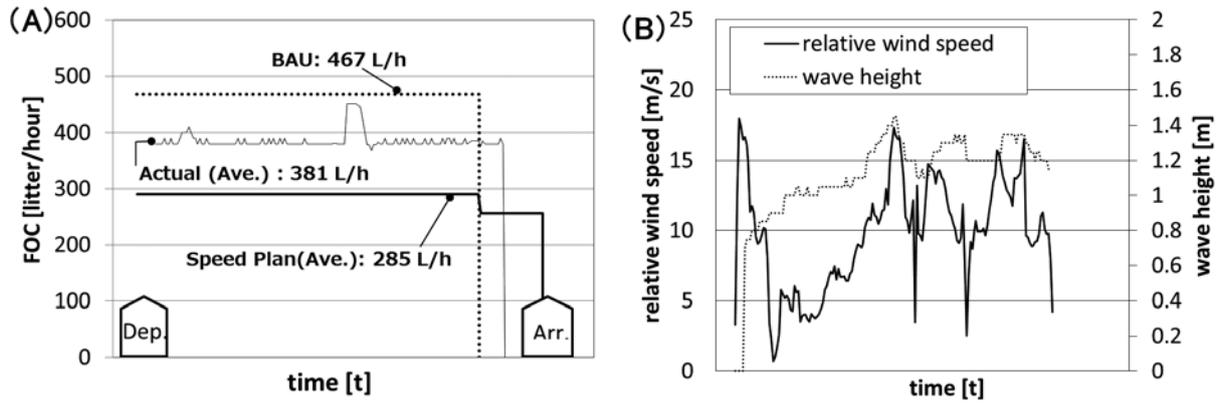


Figure 7. Time series result of Ship A

4 hours 44 minutes compared to the BAU voyage, and total CO₂ emission was reduced 27.7% compared with BAU.

Case study 2: Ship B (oil tanker)

Ship performances at sea

Here, we present a case of one oil tanker, Ship B, selected for a case study; and Table 3 shows principal particulars of Ship B.

Table 3. Principal particulars of Ship B

Ship B			
Length	98.5 m	MCR	3250 kw
Breadth	16 m	Gross tonnage	3700 tons
Depth	8.2 m	Nominal Speed	13.5 knots

In order to perform a calculation to be used for the Voyage Speed Planning System, we obtain coefficients of equation (1) by using monitoring data of

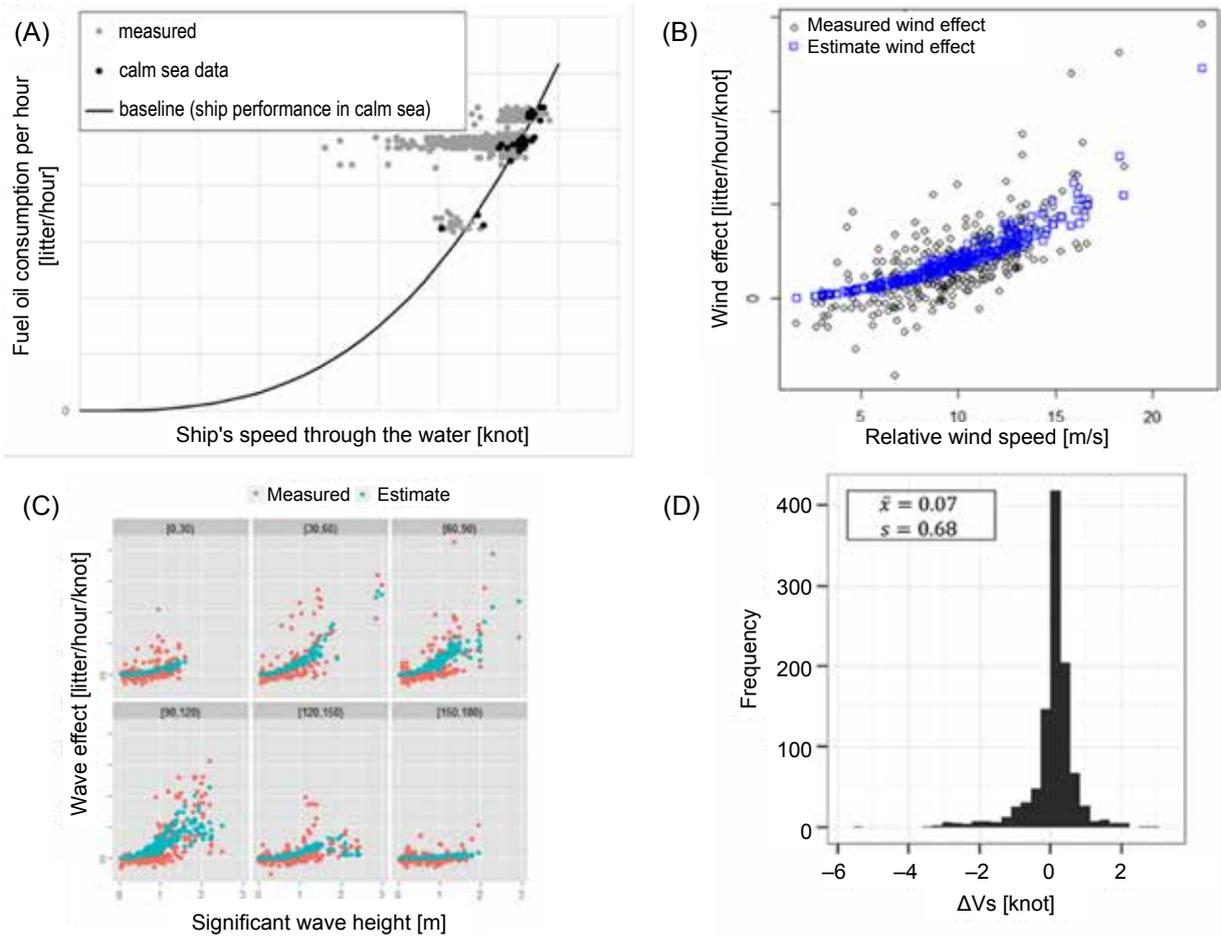


Figure 8. Performance of Ship B

the past several months; and Figure 8 shows fitting results. Figures 8 (A), (B), and (C) illustrate the performance in calm sea; comparison of measured wind effect and estimated wind effect; and comparison of measured wave effect and estimated wave effect.

To confirm the accuracy of the determined coefficients, Figure 8 (D) presents the histogram of the difference between measured and estimated ship speed. Estimated ship speed is calculated by equation (1). The mean value of the differences is -0.01 knot, and the standard deviation is 0.68 knot. The estimation result is accurately determined.

BAU of the Ship B

To obtain the BAU of Ship B, we monitored data for the duration of ten months from January to October of 2014. The voyage of this period did not use the Voyage Speed Planning System. Figure 9 shows the histograms of fuel oil consumption per hour [liter/h] and the controllable pitch propellers (CPP) angle of the main propulsion. The captain uses 17.85 degrees (average) and the average of fuel oil consumption per hour is 481 liter/h. Therefore, we set 481 liter/h as the BAU of the Ship B.

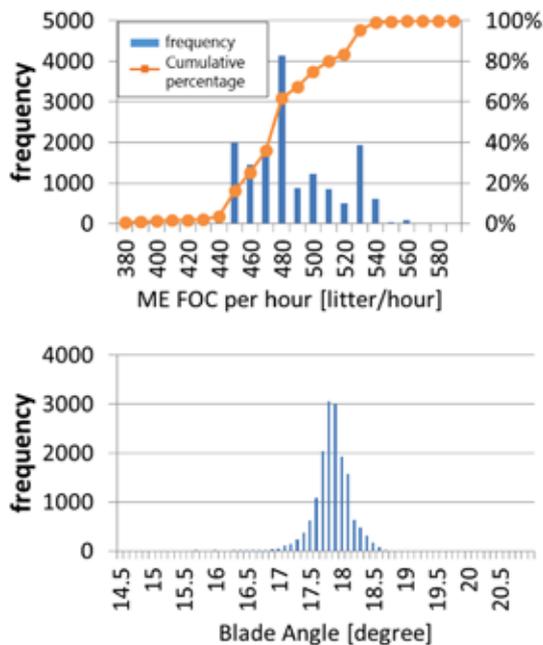


Figure 9. BAU of Ship B

Effect of CO₂ emission reduction

Here, we present the case of a voyage for an investigation of the effect of CO₂ emission reduction. Figure 10 shows a route of Ship B for the case study. The voyage is loaded condition from Nagoya

to Oita. Table 4 shows the voyage result summary, Figure 11 (A) shows the time series result, and Figure 11 (B) shows the weather condition along the route. The horizontal axis represents time and vertical axis represents FOC [liter/h] respectively. In the case of BAU without the Voyage Speed Planning System, the voyage took 21.8 hours; it arrived 1 hours 44 minutes earlier than the required time of arrival and total FOC was 10.5 kL. In the case of the Actual voyage with reference to the Voyage Speed Planning System, the voyage took 27.7 hours; it reduced offshore waiting times by 45 minutes compared to the BAU voyage. Total CO₂ emission was reduced 5.5% compared to the BAU voyage. Furthermore, in the case of Recommended, the voyage took 22.6 hours; it reduced offshore waiting times by 51 minutes compared to the BAU voyage and total CO₂ emission was reduced 6.0% compared with BAU.

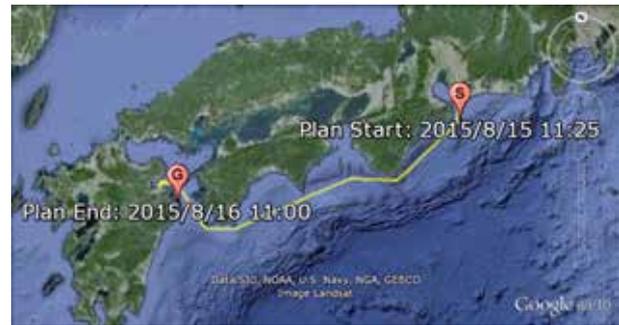


Figure 10. Route of the voyage

Table 4. Result of Ship B

	BAU	Actual	Recommended
Nav. Time [h]	21.8	22.7	22.6
Margin	1:44	0:59	0:51
FOC (kL)	10.5	9.9	9.8
CO ₂ [ton]	31.6	29.9	29.6
Reduction ratio	–	5.5%	6.0%

Conclusions

This paper introduces the Voyage Speed Planning System, which generates a just-in-time voyage considering weather effects, to reduce CO₂ emission. Through the experiments on the Japanese coastal vessels, we have revealed that our Voyage Speed Planning System can generate speed plans that reduce CO₂ emission. In detail, (1) the standard deviation of the arrival time of voyage per three hours is about 10 minutes, (2) in a case of cement carrier, using the Voyage Speed Planning System

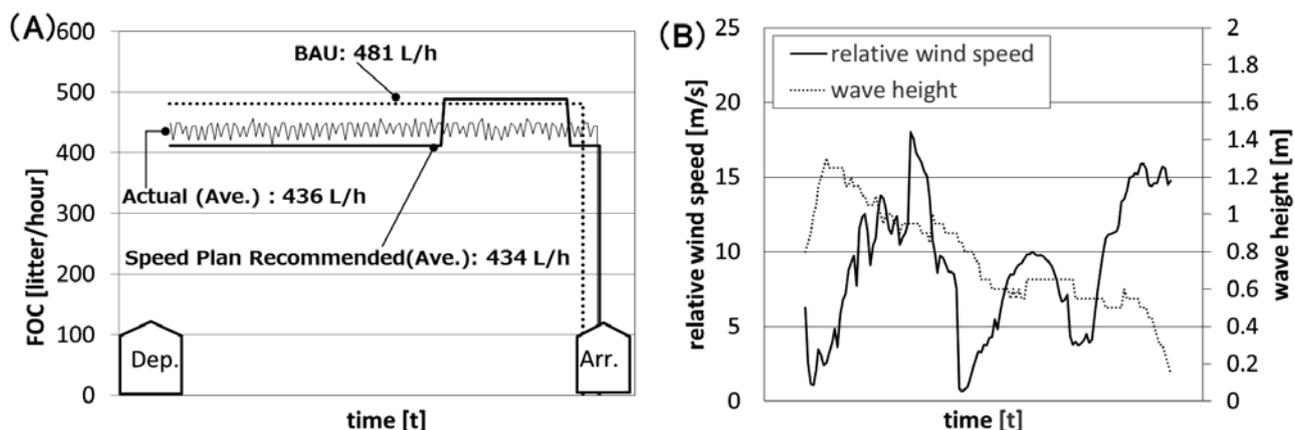


Figure 11. Result of CO₂ emission reduction on a voyage (Ship B)

saved 1 hour 44 minutes of offshore waiting time and an estimated 12.2% of CO₂ compared with the case without the system, and (3) in a case of oil tanker, using the Voyage Speed Planning System saved 45 minutes of offshore waiting time and an estimated 5.5% of CO₂ compared with the case without the system. However, in both cases, there still remains a margin and we need to win trust from captains.

This demonstrative experiment will continue until March, 2016, and we will verify the effectiveness by the developed MRV (Kano & Namie, 2014) of CO₂ reduction effects.

Acknowledgments

The work presented in this paper resulted from a project which is supported by the “Low Carbon Technology Research and Development Program”, Ministry of the Environment (MOE) of Japan. We would like to express our sincere appreciation to the MOE, and shipping companies for their kind and invaluable cooperation in collecting data. The authors are also indebted to Mr. Yamashita, Y (Ube-Mitsubishi Cement Corporation) and Mr. Imazu, H (Asahi Tanker CO., LTD) and gratefully acknowledged for their valuable suggestions and persevering job.

References

- BELLMAN, R.E. (1953) *An introduction to the theory of dynamic programming*. Rand Corporation.
- FUJIWARA, T. (2006) *Research on estimation of wind pressure on vessel in strong winds, and operational performance*. PhD Thesis, Osaka.
- KANO, T. & NAMIE, S. (2014) *A study on estimation of GHG emission for speed planning operation using energy efficiency index and time-series monitoring data*. 13th Conference on Computer and IT Applications in the Maritime Industry (COMPIT), Redworth.
- KANO, T. & SATO, K. (2015) *Eco-shipping project for Japanese coastal vessels – verification project for CO₂ emission reductions with ship-scheduling/voyage-planning system*. 14th Conference on Computer and IT Applications in the Maritime Industry (COMPIT), Ulrichshusen, 11–13 May 2015.
- MELLOR, G., HÄKKINEN, S., EZER, T. & PATCHEN, R. (2002) A generalization of a sigma coordinate ocean model and an intercomparison of model vertical grids. In: *Ocean Forecasting: Conceptual Basis and Applications*. N. Pinardi, J. Woods (Eds.), Berlin: Springer. pp. 55–72.
- MIYAZAWA, Y., ZHANG, R., GUO, X., TAMURA, H., AMBE, D., LEE, J.-S., OKUNO, A., YOSHINARI, H., SETOU, T. & KOMATSU, K. (2009) Water mass variability in the western North Pacific detected in a 15-year eddy resolving ocean reanalysis. *Journal of Oceanography* 65. pp. 737–756.
- TSUJIMOTO, M., KURODA, M. & SOGIHARA, N. (2013) *Development of a calculation method for fuel consumption of ships in actual seas with performance evaluation*. ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering, American Society of Mechanical Engineers.