

Comparison of Master's Route Selection Criteria of Vehicle Carriers in North Pacific and North Atlantic Using Satellite AIS and Ocean Wave Data

M. Fujii

Marine Technical College, Japan agency of Maritime Education and Training for Seafarers, Ashiya, Japan

H. Hashimoto

Kobe Ocean-Bottom Exploration Center, Kobe University, Kobe, Japan

Y. Taniguchi

Graduate School of Maritime Sciences, Kobe University, Kobe, Japan

ABSTRACT: The operational measures in which a ship needs to avoid specified areas to escape ship stability failures were discussed at the International Maritime Organization as a part of the second generation intact stability criteria. It is necessary that the rationality and practicality of the operational measures are carefully investigated. In this study, master's route decision-making criteria of trans-ocean vehicle carriers have been clarified by comparing the Pacific and the Atlantic data, derived from Satellite AIS and ocean wave data. Features of voyage routes of each ocean were discussed, followed by analysis of the encountered wave direction and height during a voyage. The master's route selection criteria were defined by comparing the probability densities of the wave heights that occurred in the navigable area and that of the actual encountered waves. The navigation hours in a stormy area were also studied.

1 INTRODUCTION

Currently, the second generation intact stability criteria are being discussed at the International Maritime Organization (IMO) (IMO 2015, 2018). The criteria include a new concept, "operational measures (OMs)" (IMO 2019), for ensuring safety of ships at sea during ship operations. The implementation of the OMs has never been addressed in the history of intact stability criteria. Therefore, the rationality and practicality of the OMs in terms of implementation during actual ship operation must be carefully investigated. To facilitate discussion of the OMs, Hashimoto et al. presented a set of pioneering case studies on the OMs using a voyage simulation for an ocean-going container ship for a variety of scenarios (Hashimoto et al. 2017). This voyage simulation was developed based on a weather routing model (Kobayashi et al. 2011, Kobayashi et al. 2015).

Regarding the decision making for voyage routing during an actual voyage, captains consider fuel consumption, voyage distance, and safety factors, such as rolling and pitching effects on cargos (Koshimizu & Ishizuka 1994). A weather routing service, which considers above points, is commonly used in actual navigation (Fujii et al. 2017). This means that it is reasonable to develop a simulation tool for the investigation of OMs, which simulates practical navigation routes correctly, based on a weather routing model. However, captains decide a voyage route not only with the reference to a route recommended by weather routing service but also the safety margin especially when the rough weather is expected. Reliable voyage simulations need to simulate ship navigation routes with sufficient similarity to actual routes decided, by accounting for the preferred safety margin based on the weather conditions. Therefore, the route decision-making criterion of captains taking into account of the safety margin needs to be clarified.

The wave criterion of navigators has been defined by questionnaires and route planning experiments by seafarers in the past (Hayashi & Ishida 2004). However, it was derived from a limited amount of data covering only the North Pacific and could be significantly different from the universal criterion. Another research discussed the relationship between route selection and encountered wave height, combined with satellite AIS data and ocean wave data supplied by the National Centres for Environmental Prediction (NCEP) (available at <http://www.cdc.noaa.gov/>) (Fujii et al. 2019, Fujii et al. 2017). This research demonstrated that the encountered wave height during the voyage can be obtained as objective data by combining the ship's position obtained from the satellite AIS data and the weather information at the corresponding position and time. However, these researches were focused on the container carrier or a limited number of vehicle carriers only trans-Pacific.

In this study, the master's route decision-making criteria aimed at developing a reliable voyage simulation for discussion of OMs has been clarified by comparing the actual voyages of the trans-Pacific and the Atlantic. Firstly, the features of voyage routes of each ocean were discussed by using the ship's position from the Satellite AIS data. Secondly, the encountered wave direction and height during a voyage were analysed by data combined with satellite AIS data and ocean wave data. Thirdly, the master's route selection criteria were obtained by comparing the probability densities of wave heights that occurred in the navigable area with that of the actual encountered waves. Finally, the calculation result of navigation time, which is duration hours between entering and exiting a stormy area, was determined.

2 DETAILS OF THE ANALYSIS DATA

Currently, the automatic identification system (AIS) equipment is required to be installed on all ships, including the vehicle carriers over 300 GT, on international voyages. The signal is continuously transmitting during a voyage in the ocean. In this study, the ship's position data from the AIS, for a large number of vehicle carriers, were collected and analysed. The AIS data were purchased from exactEarth (<https://www.exactearth.com>), and collected by several satellites from December 2015 to February 2016. Figure 1 shows the received position of the AIS signal by the satellites in the purchased data. Nowadays, with the improvement in the AIS service, and increase in the number of satellites, the quality of data is becoming better year by year. The purchased data included a large number of received AIS data, as shown in Figure 1.

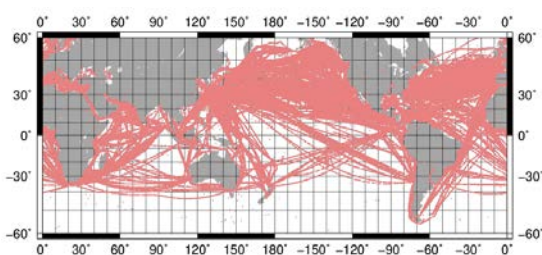


Figure 1. Received position of AIS signal by the satellites

This study is focused on the master's judgment in a rough sea, especially the Pacific Ocean and the Atlantic Ocean in winter. Therefore, the AIS data for analysis was picked up from the purchased data which contained the worldwide data. Analysis data for the Pacific Ocean was picked up from the received data between latitude 0°N to 70°N and longitude 100°E to 100°W, and for the Atlantic Ocean between latitude 10°N to 70°N and longitude 0°E to 80°W. For exclusion of error data in the AIS ship position, the speed between neighbouring positions was calculated from the position and received time. If the speed was greater than the speed limit (24.7 kn), the corresponding data were omitted as error data (Fujii et al. 2017). In addition, voyages that were not received within 24 hours were excluded from the analysis due to poor reliability. Secondly, the trans-ocean voyages were picked up from the data in the designated area. The definitional lines were set on both the eastern and western sides of the North Pacific for the definition of the term "trans-Pacific", as shown in Figure 2. Similarly, the lines were set for the North Atlantic in reference to the major routes (Vettor & Soares 2015). Here, east-bound voyage means that a ship departs from westerly of the west side definitional line to easterly of the east side definitional line, west-bound voyage is opposite.

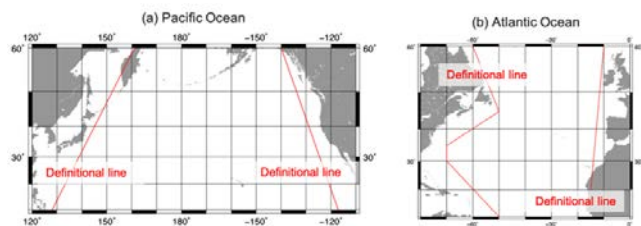


Figure 2. Definitional line for trans-ocean in the (a) Pacific and the (b) Atlantic

From these steps, the analysis voyages were picked up, the details of which are shown in Table 1. The number of ships was 174 in the Pacific Ocean and 124 in the Atlantic Ocean. The number of voyages was 198 in the Atlantic Ocean and 257 (1.3 times more) in the Pacific Ocean. However, this number is more significant than the previous research (Fujii et al. 2017) and sufficient to analyse.

Table 1. Number of analysed ships and voyages

	Number of ships	Number of Voyages		Total
		East-bound	West-bound	
Pacific Ocean	174	151	106	257
Atlantic Ocean	124	108	90	198

The AIS data includes a ship's position, the time of transition, and more. However, the wave height at that point is not included. Therefore, weather data has to be imported from a different source while analysing the height and direction of the encountered wave. In this study, the oceanic data corresponding to the ship's position during the navigation was obtained from the ocean wave data supplied by the National Centers for Environmental Prediction (NCEP). The encountered wave height and direction are defined by combining the received ship's position data and the oceanic data. The ship's position every 3

hours based on 00 UTC was used in this study, which was obtained from the position information of the AIS data. This time interval is the same as that of the NCEP weather forecast data. The mesh of the weather data has a longitudinal interval of 1.25° and a latitudinal interval of 1.0° . To determine the weather conditions at a ship's position at a given time, a simple linear interpolation was used. The accuracy of analysis for the encountered wave and direction depends on the reliability of the weather data.

3 COMPARISON OF ANALYSIS DATA WITH THE PACIFIC OCEAN AND ATLANTIC OCEAN

3.1 Wave height in each ocean

The average of the top 10% wave heights were calculated for the Pacific and Atlantic from December 2015 to February 2016, and are shown in Figure 3. The Americas are depicted in the centre of the map. The area with wave height above 7 m is widely distributed in both the North Pacific Ocean and the North Atlantic Ocean. The wave height in the centre of the North Pacific Ocean was above 10 m. In the Atlantic, the area with wave height above 8 m is distributed in the Northern part. The past research showed that the PCC, which means vehicle carrier in this study, could navigate in area wave height above 4 m (Fujii et al. 2017). It means that both oceans were stormy at the timing of analysis.

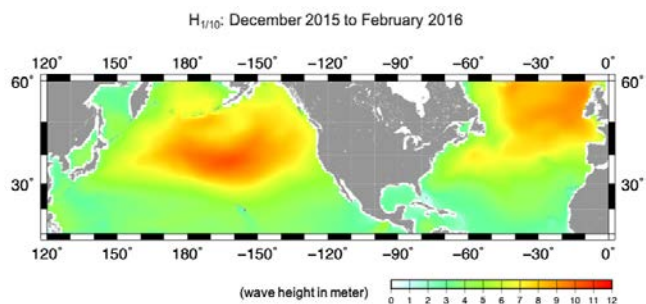


Figure 3. The top 10% wave heights between December 2015 to February 2016

3.2 Voyage Routes

Voyage routes in the Pacific Ocean are shown in Figure 4. The east-bound voyages mainly used Great-circle sailing route between latitude 30°N to 40°N . In addition, the vessels tend to navigate around the centre of the North Pacific Ocean. On the other hand, the west-bound voyages seem to have two major routes: one through the Bering Sea and the other around the south of latitude 30°N . Most west-bound voyages used Mercator sailing, while Great-circle sailing was only used in the case of the eastern departure point in latitude 50°N or more.

In the case of the Atlantic, it is shown that the east-bound voyages navigated almost on the Great-circle route, not deviating too far from the shortest route. However, the west-bound voyages show that routes in the southern part of the Great-circle, were taken especially in the area latitude 45°N and longitude 30°W . This area had higher wave height than the other

areas, as shown in Figure 3. Hence, it seems that ships avoided the stormy sea. However, the routes of the east-bound and west-bound vessels are similar to each other, unlike the Pacific cases.

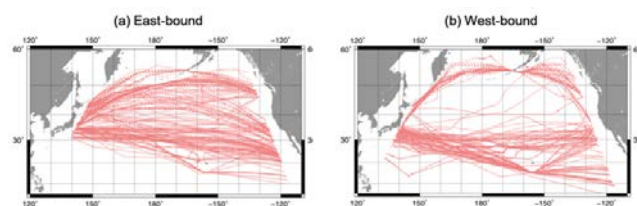


Figure 4. Voyage routes of vehicle carrier in the Pacific Ocean

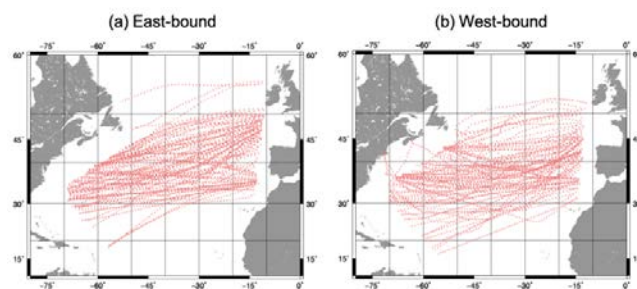


Figure 5. Voyage routes of vehicle carrier in the Atlantic Ocean

3.3 Direction and height of the encountered waves

The trends of east-bound and west-bound trans-Pacific voyages are different. However, the trans-Atlantic routes of both east-bound and west-bound vessels are similar to each other, as mentioned before. The cause of the route trend difference from wave direction and height point of view, is discussed in this section.

Figure 6 shows the probability density of the directions of encountered waves for the east-bound and west-bound voyages. Here, 0° on the horizontal axis represents head waves, 180° represents following waves, a positive angle means that the wave is incoming from the starboard side, and a negative angle means the opposite. The figures show that the east-bound voyages received following waves and the west-bound received head waves from the starboard. This trend is quite similar to the Pacific voyages and Atlantic voyages.

Figure 7 shows the histograms of the encountered wave heights in the Pacific and the Atlantic which is not categorised in voyage direction. The vertical axis of these figures represents the probability density, and the horizontal axis represents the encountered wave height. The number of data (n) in each ocean is over 10,000. It means that the value is enough for the analysis. Here, the cause of difference of the number between the Pacific and the Atlantic is expected voyage time, in addition to the differences of a number of navigated vessels. Because the voyage distance between the western and the eastern in the Pacific is much farther than the Atlantic one. The mean encountered wave height in the Pacific is lower than the Atlantic; the mean height is 3.17 m in the Pacific and 3.45 m in the Atlantic. In the Pacific, a peak of the encountered wave height is between 2.0 m

to 3.5 m. However, the Atlantic one is distributed more widely between 2.0 m to 4.0 m. Besides, a changing rate of the histogram is gentler in the Atlantic.

4 LIMITATION WAVE HEIGHT AND NAVIGATION TIME IN THE ROUGH SEA

Table 2 is indicating the average wave height categorised by the head wave and the following wave. In both the Pacific and the Atlantic, the head wave is lower than the following wave. It means that the Captain's judgment for selection of route have different standards between the case of the head wave and the following wave.

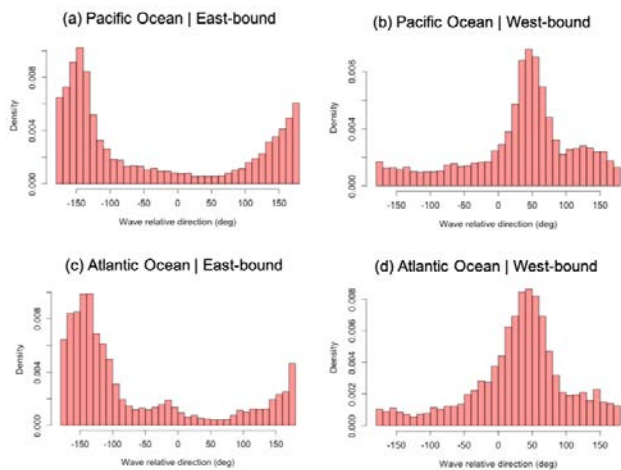


Figure 6. Probability density of encountered wave direction corresponding to the (a) Pacific east-bound, (b) Pacific west-bound, (c) Atlantic east-bound, and (d) Atlantic west-bound voyages

Table 2. Average wave height categorised by encountered direction

	Head Wave (m)		Following Wave (m)	
	Mean	SD	Mean	SD
Pacific	3.00	1.01	3.28	1.14
Atlantic	3.35	1.18	3.53	1.28

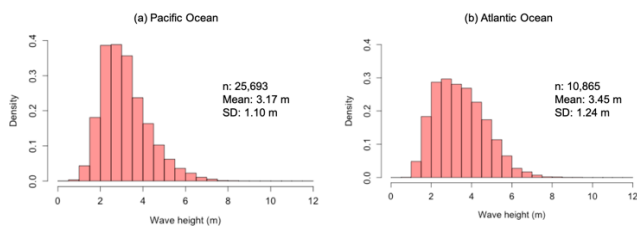


Figure 7. Probability density of encountered wave heights corresponding to the (a) Pacific, and (b) Atlantic voyages

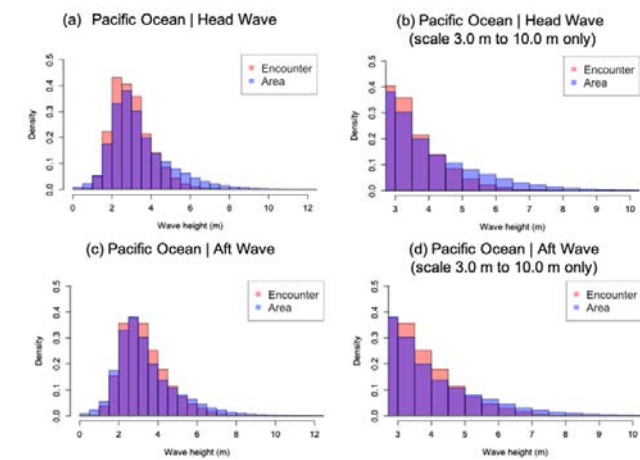


Figure 9. Comparison of probability densities of waves observed in navigable areas and encountered waves in the Pacific Ocean

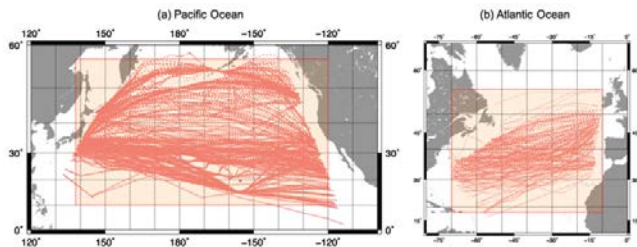


Figure 8. Assumed navigable area in the (a) Pacific and (b) Atlantic

To compare the occurred wave height in each ocean, the wave height in the assumed navigable area where was shown in figure 8 was calculated. It was set based on the AIS position data, and the area between 10 °N to 57 °N and 138 °E to 120 °W in the North Pacific, and 18 °N to 56 °N and 70 °W to 19 °W in the Atlantic. As a result, the average wave height of the area in the Pacific was found to be higher than in the Atlantic; 3.42 m in the Pacific and 3.29 m in the Atlantic. However, the encountered wave height in the Pacific is lower than the Atlantic. Therefore, opposite results were achieved in occurred wave height and encountered wave height. As a result, it can be said that the trans-Pacific voyage can be selected avoiding a route through heavy weather area, while a trans-Atlantic voyage cannot choose a route through a non-stormy area.

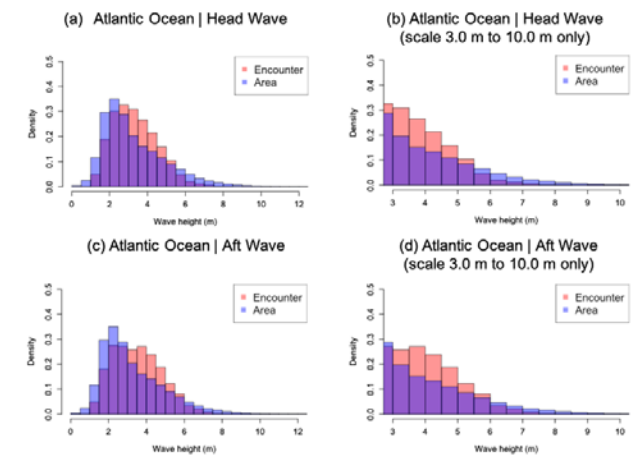


Figure 10. Comparison of probability densities of waves observed in navigable areas and encountered waves in the Atlantic Ocean

The probability densities of wave heights that occurred in the navigable area and actual encountered waves are shown in Figure 9 for the Pacific and in Figure 10 for the Atlantic. If Captains did not avoid the stormy area intentionally, the two histograms would be the same. However, the two histograms do not match. From this fact, it is expected that captains avoid rough sea area if the wave height is beyond the

threshold. It can be said that the threshold would be the wave height where the two histograms were reversed. Therefore, the thresholds are 4.5 m in head wave and 5.0 m in following wave in the Pacific, as shown in Figure 9. Similarly, 5.5 m in head wave and 6.0 m in following wave in the Atlantic as shown in Figure 10.

Figure 9 and Figure 10 show probability densities indicated even when the wave height is beyond the threshold. It means that a few ships still navigate on the area beyond the threshold wave height. It is considered that navigation time in stormy weather affects the Captain's judgment. Hence, the calculation results of navigation time in a stormy area beyond the threshold are shown in Table 3. This result has been measured in the time between entering and exiting the area. In this study, the ship's position is aligned with the weather data which means every 3 hours. So, the calculation time is also 3 hours unit. The navigation time during a stormy area in the Pacific is approximately twice as much as the Atlantic one. From the results, the threshold in the Atlantic is higher than the Pacific, however, it can be said that once entered in the heavy weather area, the voyages in the Pacific need to stay for a long time.

Table 3. Navigation time in area beyond the threshold

	Mean	Median
Pacific Ocean	34.6 hours	30 hours
Atlantic Ocean	18.4 hours	15 hours

5 CONCLUSION

This study compared the master's route selection pattern, especially encountered wave direction and wave height for vehicle carriers derived by Satellite AIS and ocean wave data. The summary of this study is as follows:

- Comparing the voyage routes in the Pacific and the Atlantic derived by the Satellite AIS position data of vehicle carriers, the trans-Pacific east-bound routes were in the middle of the North Pacific Ocean and west-bound routes were divided to two major routes to avoid the middle. However, in the Atlantic cases, east-bound and west-bound routes are not different from the Pacific cases.
- The average wave height of the area in the Pacific is higher than the Atlantic; 3.42 m in the Pacific and 3.29 m in the Atlantic. However, the ship's encountered wave height in the Pacific is lower than the Atlantic. Therefore, it can be said that the trans-Pacific voyage can be selected avoiding route to the heavy weather area while a ship under trans-Atlantic voyage could not choose a way to a non-stormy area in comparison to the Pacific voyage.
- Based on the result of the comparison of the probability densities of wave heights that occurred in the navigable area and encountered waves, it is expected that Captains avoid rough sea area. The wave height in the area was 4.5 m in the head wave and 5.0 m in the following wave, in the

Pacific; and 5.5 m in in head wave and 6.0 m in following wave, in the Atlantic.

- The calculation result of navigation time, which is the duration (hours) between entering and exiting a stormy area beyond the threshold, shows that the trans-Pacific voyages need to stay for a long time than the trans-Atlantic, if a ship enters a heavy weather area once. The navigation time is approximately twice the Atlantic one. The median time of the Pacific is 30 hours.

In the past research, the analysis is focused on the container ships or analysis with a few data. These results can supplement the previous research. Additionally, the figures derived from satellite AIS data and ocean wave data will help when the master's route selection pattern is put into the voyage simulation.

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