A case study on operational limitations by means of navigation simulation

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ABSTRACT

In the second generation intact stability criterion, even a ship who fails to pass the level 2 vulnerability criteria, can be operated by imposing operational limitations. Since the introduction of operational limitations is a new attempt to guarantee the safety of ships at sea, which is out of the framework of the conventional safety standards, careful consideration and sufficient number of case studies are necessary. Therefore, a case study is performed to investigate the impact of operational limitations on actual ship navigation by means of navigation simulation. In this study, parametric roll is selected as a major stability failure mode and requirements for the implementation of operational limitations are discussed.

Keywords: *Second Generation Intact Stability Criteria, Operational Limitations, Navigation Simulation, Parametric Roll, Container Ship*

1. INTRODUCTION

Currently, a lot of intensive discussions and works are made toward the finalization of the Second Generation Intact Stability Criteria (SGISC) at International Maritime Organization (IMO) [IMO, 2017]. In SGISC, the risk of failure of a ship is evaluated in three levels for five stability failure modes, i.e. pure loss of stability, parametric roll, surf-riding/broaching, dead ship and excessive acceleration. The level 1 vulnerability criteria can be easily applied instead of setting the maximum safety level, and the evaluation complexity becomes higher while the safety margin does smaller in the level 2 vulnerability criteria. The third level is so called direct stability assessment (DSA) which requires complex calculations to evaluate the safety level of ships. Model experiments could be required in DSA but the safety margin becomes lowest. If a ship fails to pass the level 1 vulnerability criteria, the ship has to pass level 2 or DSA criteria to guarantee the safety at sea. However, ships can be operated even though they fail to pass level 2 or DSA, by imposing operational limitations (OL) or operational guidance (OG) as risk control option. In principle, the introduction of OL and OG into SGISC has been agreed at IMO. However, there is almost no research on this topic whereas it is an important issue for the finalization of SGISC. Therefore, at this moment, it is not clear how to implement OL/OG and how much operational efforts are needed when they are imposed. It is a big challenge to guarantee the safety of ships by means of the combination of passive design criteria and active operational measures [Bačkalov et al., 2016]. In order to make the OL useful and practically executable as the risk control option, sufficient number of case studies is needed to reveal positive and negative impacts on actual operation and to propose how to avoid specified dangerous conditions during navigation. It is also important to involve shipping companies and ship masters who actually operate ships to formulate rational but executable OL.

In response to these situations, we conducted a numerical study using navigation simulation to provide information for the formulation of OL. Since a container ship is selected as the subject ship, parametric roll is a typical stability failure mode and hence OL for parametric roll is discussed in this paper. Based on the simulation results, we try to derive appropriate limiting parameters for OL from viewpoints of degree of achievement of safe navigation and change of ship route, and delay time.

2. OPERATIONAL LIMITATIONS AND OPERATIONAL GUIDANCE

Operational limitations

The discussion on OL has just started at the Ship Design and Construction (SDC) sub-committee at IMO and specific requirements have not been decided, but it has been agreed that OL should be set based on calculation results of Level 2 criteria or DSA. Since it is hard to execute DSA because of its high calculation-complexity, OL would be set from the Level 2 results in most cases. Based on calculation results for each stability failure mode, dangerous conditions to be avoided are obtained depending on loading conditions as the combination of significant wave height, average zero-crossing wave period, and ship speed. Only measures for surf-riding are considered for the surf-riding/broaching failure mode as the level 2 criteria. In case one or more possible loading conditions from departure to arrival do not pass the level 2 vulnerability criteria, a captain needs to change the loading condition or to avoid specified dangerous conditions by following the OL procedure. In case applying OL, navigation guidance of MSC/Circ.1228 is superseded by OL. The reason why the avoidance of specified dangerous conditions is not mandatory is that SGISC will be in the non-mandatory part (Part B) of Intact Stability (IS) code for the time being. Because the dangerous conditions to be avoided are determined from numerical results of the Level 2 vulnerability criteria which are simpler and has larger safety margin than DSA, the specified dangerous conditions are wider and patterns of ship speed and wave relative direction are quite limited. In this sense, it is the rough estimation of dangerous condition, so OL has the aspect of route selection/change in navigation rather than detailed requests for ship handling. Although the wave data, such as significant wave height and wave period, is essential for the implementation of OL, it is hard to accurately predict/measure them on the ship especially in stormy weather. Therefore it is desirable to use navigation supporting systems combined with reliable weather forecast and on-board measurement.

Operational guidance

It has been already agreed that OG should be set based on calculation results of DSA. OG is guidance to avoid stability failure by operational countermeasures in ship navigation and ship handling. Even though a ship, who fails to pass DSA, can be operated if a ship master follows the OG procedure to avoid specified dangerous conditions at sea. Based on numerical results of DSA, dangerous conditions to be avoided are determined depending on loading conditions as the combination of significant wave height, average zero-crossing wave period, ship speed and wave relative direction, for each stability failure modes. Thanks to detailed calculations in DSA, broaching itself is considered in OG while surf-riding is done in OL. In case one or more possible loading conditions from departure to arrival do not pass DSA, a captain needs to change the loading condition or to avoid specified dangerous conditions by following the OG procedure. In this case, number of selections of ship speed is larger than that of OL and the influence of wave relative direction can be considered in OG. In order to take advantage of OG, advanced instruments to accurately measure sea state on-board, using like X-band wave radar, is important and real-time supporting systems for ship handling are desired in the future.

3. NAVIGATION SIMULATION

Simulation model

In this study, we use a ship navigation simulation to investigate the influence of introduction of OL on actual navigation. The navigation simulation is based on a simulation model developed for weather routing [Kobayashi et al., 2015]. In this model, a mathematical model for ship manoeuvre so-called MMG model, is used and solved to calculate ship horizontal motions at sea. And then the ship arrival point is calculated by Mercator's sailing from moving distance and course, which are obtained by solving the MMG model. Hydrodynamic forces by ocean currents and winds, and added resistance in waves are taken into account as external forces acting on the ship hull. The wind pressure is calculated by an empirical formula [Fujiwara et al., 1998] and the added resistance is done by Enhanced Unified Theory [Kashiwagi, 1992] provided by Osaka University.

With respect to ocean currents, 5-day average data with the longitude interval of 1.0 ° and the latitude interval of 1.0 ° are used, which are provided by NOAA (American Oceanic and Atmospheric Administration). With respect to winds and waves, every 6 hours data supplied by NCEP (American Environment Prediction Center) are used and are collected for number of days needed for simulation. Here the longitude interval is 1.25 ° and the latitude interval is 1.0 °. The Powell method which is an unconstrained nonlinear optimization method [Powell, 1964] is used to search for the optimum route that minimizes an evaluation function such as amount of fuel consumption. Bezier curve is adopted as a mean for conveniently expressing complicated route curves with small number of control points. In the navigation simulation taking OL into account, an extraordinary large penalty fee is imposed according to the staying time in specified dangerous conditions, and the optimum route is selected to minimize the total operational cost (fuel cost + penalty fee). By this way, the most economical route can be obtained while complying with OL.

Simulation condition

In this study, a container ship is selected as the subject ship because container ships play a major role for international trading. Since container ships have relatively slender body, and exaggerated bow flare and transom stern, they prone to suffer parametric roll due to the significant variation of stability in waves. A case study is performed for a C11 container ship engaged in trans-Pacific services (Yokohama - San Francisco) in winter, by means of the navigation simulation mentioned above. We try to confirm whether the ship can avoid specified dangerous conditions by operational efforts and to reveal how navigation routes and navigation time are changed by imposing OL. Principal particulars of the subject C11 container ship in full load condition are shown in Table 1 [Levadou and van't Veer, 2006]. The hull form of this ship is similar to that of the accident ship who experienced parametric roll of about 40 degrees in the North Pacific in 1998.

Table 1: Principal particulars of the subject ship.

Length between perpendiculars : L_{pp}	262.0 m
Breadth : B	40.0 m
Draught : d	11.5 m
Depth : D	24.45 m
Total projected area of bilge keels : A_{BK}	30.6 m^2
Navigation speed in calm water : V	20.0 kt
Metacentric height : GM	1.965 m
Designed natural roll period : T_ϕ	25.1 s

The dangerous conditions for parametric roll exceeding 25 degrees used for OL are obtained by a calculation program developed by Osaka University [Maki, et al., 2011]. The subject ship in full load condition fails to pass neither the first nor second checks of the Level 2 vulnerability criteria. This result is reasonable because the required value is set to reject the accident ship. Since the dangerous conditions to be avoided are determined based on the results of Level 2 vulnerability criteria, the operational effort to avoid the danger discussed in this study is considered as OL not OG. The specific dangerous conditions for the subject ship are shown in Fig.1. Here $H_{1/3}$ denotes significant wave height and T_z does average zero-crossing wave period. The heading angle of 0 degrees means following waves and 180 degrees does head waves, and Fn represents the Froude number. Although calculation results in following waves are not presented, parametric roll exceeding 25 degrees does not occur in any conditions.

In case wave relative direction is used as a limiting parameter for OL, it is set to avoid the encounter angle of 90 to 270 degrees because parametric roll only happens in head sea condition for the subject ship. This means that the ship could be judged as dangerous when the major encounter angle is in 90 to 270 degrees. The ship speed in calm water is set as 20 knots. In the navigation simulation, a navigation route that minimizes the operational cost including the penalty fee is obtained as the optimal route while avoiding the specified dangerous conditions for parametric roll occurrence.

Heading angle = 0 & 180 deg, Fn=0.0

$H_{1/3}$ (m) \ T_z (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
16.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
15.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
14.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
13.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
12.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
11.5	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
10.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
9.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
8.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
7.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
6.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
5.5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
4.5	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	0
3.5	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Heading angle = 0 & 180 deg, Fn=0.101

$H_{1/3}$ (m) \ T_z (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
16.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
15.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
14.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
13.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
12.5	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1
11.5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1
10.5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	0
9.5	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0
8.5	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0
7.5	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
6.5	0	0	0	0	0	0	1	1	1	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Heading angle = 0 & 180 deg, Fn=0.176

$H_{1/3}$ (m) \ T_z (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
16.5	0	0	0	0	0	1	1	1	1	1	1	0	0	0	0	0
15.5	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0
14.5	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0
13.5	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Heading angle = 0 & 180 deg, Fn=0.203

$H_{1/3}$ (m) \ T_z (s)	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5	14.5	15.5	16.5	17.5	18.5
16.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
15.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
14.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
13.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
12.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
11.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
10.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
9.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
8.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
7.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
6.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
5.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
2.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 1: Tables of dangerous condition.

Validation of navigation simulation

Before the numerical investigation on OL, the validity of the navigation simulation should be demonstrated. Therefore actual navigation records are compared with simulation results. The actual navigation records are derived from AIS (Automatic Identification System) data collected by a satellite in 2015-2016. The ship length is obtained from the static data of AIS. Some required information for the navigation simulation, such as average navigation speed, is obtained from the dynamic data of AIS. To obtain numerical results to be compared with the actual navigation data, we prepared the data of ocean currents, winds and waves for the corresponding period to the AIS data, and navigation simulations were performed by matching the departure time, the departure point and the destination. Figure 1 shows examples of the comparison result for a container ship engaged in the North Pacific routes in winter. Since the present simulation is seeking for a route that minimizes operational cost but the safety margin generally set by a ship master due to the uncertainty of weather forecast is not reflected, the navigation simulation avoided the harsh sea area at the minimum safety distance. Although this is one of points to be improved to realize more accurate navigation simulation, the present navigation simulation looks reproducing the actual navigation qualitatively. Therefore we use it for the discussion on OL in the following.

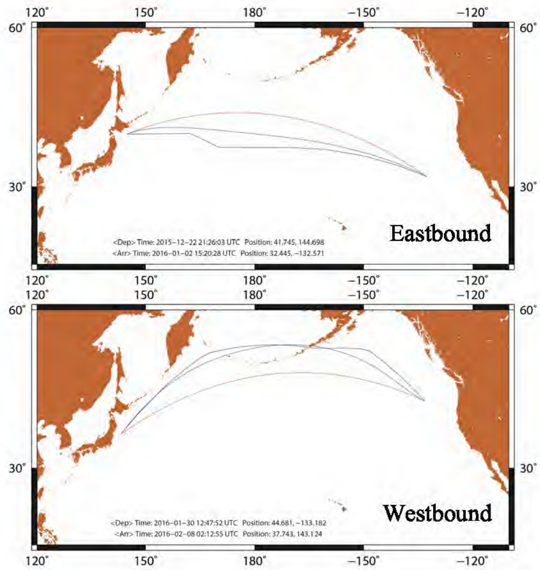

Figure 2: Comparison of navigation routes between AIS data and navigation simulation.
(Red: great circle, Black: AIS data, Blue: simulation)

4. RESULTS AND DISCUSSION

Limiting parameters for operational limitations

Although it is needed to select limiting parameters used for OL, there would be significant influence on ship operation in terms of planning and changing of navigation routes, so careful discussion on the impact of OL on actual navigation is necessary. Of course it is desirable to keep the number of limiting parameters to minimum to suppress the complexity in implementation. The combination of limiting parameters in the investigation is shown in Table 2. Here, significant wave height is the most important factor to assess the stability failure, so it is used as the limiting parameter in all cases. Ship speed is the most important control parameter in operation and the encounter wave period is determined according to the speed, so the priority of them is lower than that of significant wave height. Case 0 means normal operation without OL. As the Case number increases the number of limiting parameters used in OL increases, so the difficulty level of execution becomes higher. Although the dangerous range of wave direction is not determined in the Level 2 vulnerability criteria, parametric roll does not occur in following waves for the tested loading condition, according to Fig.1. Therefore it is judged as not dangerous if the major wave relative direction is in -90 to 90 degrees regardless of other conditions. This situation (Case 4-6) could be considered as an example of simplified OG.

Table 2: Combination of limiting parameters for OL.

Case	$H_{1/3}$	Ship speed	T_z	Wave encounter angle
0				
1	✔			
2	✔	✔		
3	✔	✔	✔	
4	✔			✔
5	✔	✔		✔
6	✔	✔	✔	✔

Influence of operational limitations on ship navigation

Figure 3-4 shows numerical results of navigation simulation imposing OL. As sample cases in the North Pacific in winter, three dates of departure, December 6, 2008, January 10 and 17, 2009, are selected. The maximum and average of significant wave height and mean wave period, encountered in the navigation along the great circle, are shown in Table 3. In case the departure date is January 10, the average significant wave height is 5.24 m in eastbound, which is a very severe condition of the top 3% of the North Pacific in winter. In the figures, GC shows the great circle giving minimum navigation distance. FOC shows the optimum navigation route in terms of fuel oil consumption without OL, which corresponds to Case 0, and other six results are ship routes with consideration of OL according to the combinations of limiting parameters in Table 2. Figure 5-6 shows the percentage of time staying in the dangerous conditions and the total navigation time. GC means the simulation result navigating along the great circle, and OR means the result corresponding to Case 0 ~ 6.

Table 3: Sea state for navigation simulation.

Day of departure	Max. $H_{1/3}$	Ave. $H_{1/3}$	Ave. T_z
Eastbound			
6/12/2008	5.41 m	3.62 m	7.38 s
10/1/2009	9.60 m	5.24 m	10.10 s
17/1/2009	5.68 m	3.50 m	9.29 s
Westbound			
6/12/2008	7.41 m	3.54 m	8.91 s
10/1/2009	8.32 m	4.53 m	9.40 s
17/1/2009	6.15 m	3.66 m	9.42 s

In case of eastbound, Case 2 and 3 show the same navigation route while Case 1, using significant wave height alone, does much different result from them. In addition, the consideration of encounter wave direction has no influence on the results because ship runs in following seas in most situations. In case of westbound, the significant difference can be seen in the navigation routes and numerical results with OL are apart from the FOC result. The consideration of encounter wave direction helps to avoid the dangerous conditions for the case with the departure date of 6/12/2008. Figure 5-6 shows the numerical results of rate of stay in dangerous conditions and navigation time. The ship cannot avoid the dangerous conditions appropriately in Case 1 both in the eastbound and westbound results. On the other hand, numerical results of Case 2-6 can achieve the safe navigation with the reasonable navigation time. In the case with departure date of 10/1/2009 in westbound, the ship cannot avoid the specified dangerous conditions completely in Case 2-3 because the sea state is the top 3% of the North Pacific in winter. It is noteworthy that the ship can avoid all the dangerous conditions when the wave encounter angle is added to the limiting parameters for OL even in such severe weather.

From the numerical investigation using the navigation simulation, it is demonstrated that the influence of OL on actual navigation is small in eastbound while it is significantly large in westbound. The reason is that the major wave encounter direction is following seas in eastbound and is head seas in westbound, in the North Pacific in winter. It is also demonstrated that OL using significant wave height alone cannot achieve the safe navigation even with the operational effort. According to Figure 1, the ship is not navigable in water area where significant wave height exceeds 2.5 m if the speed or other elements are not used as the limiting parameters. Therefore there is no route that the ship can avoid the dangerous conditions completely. Although OL using significant wave height alone as the limiting parameter is preferable to suppress the complexity in implementation, it cannot be recommended as an operational countermeasure for the stability failure due to parametric roll. On the other hand, it is mostly possible to avoid dangerous conditions if ship speed is added to the limiting parameters for OL. Since the speed control to ensure the stability, depending on the sea state encountered, is not easy on board, it is expected to develop navigation supporting systems to help making decision for ship masters.

5. CONCLUSIONS

The influence of operational limitations on ship navigation was numerically investigated by means of the navigation simulation for the C11 container ship in trans-Pacific in winter. Several combinations of limiting parameters were investigated for operational limitations on parametric roll. As a result, it is demonstrated that the operational limitations using significant wave height alone cannot achieve the safe navigation at all. On the other hand, it is mostly possible to avoid the specified dangerous conditions if the ship speed is added to the limiting parameters. In this case, the delay of arrival due to OL would be practically acceptable. In addition, the consideration of wave encounter angle helps to realize the safe navigation in some cases.

Further investigation for different type of ships, different water areas is desired and similar case studies on other stability failure modes are also important toward the finalization of second generation intact stability criteria. For actual uses of OL, wave radars or advanced technologies should be preferably implemented.

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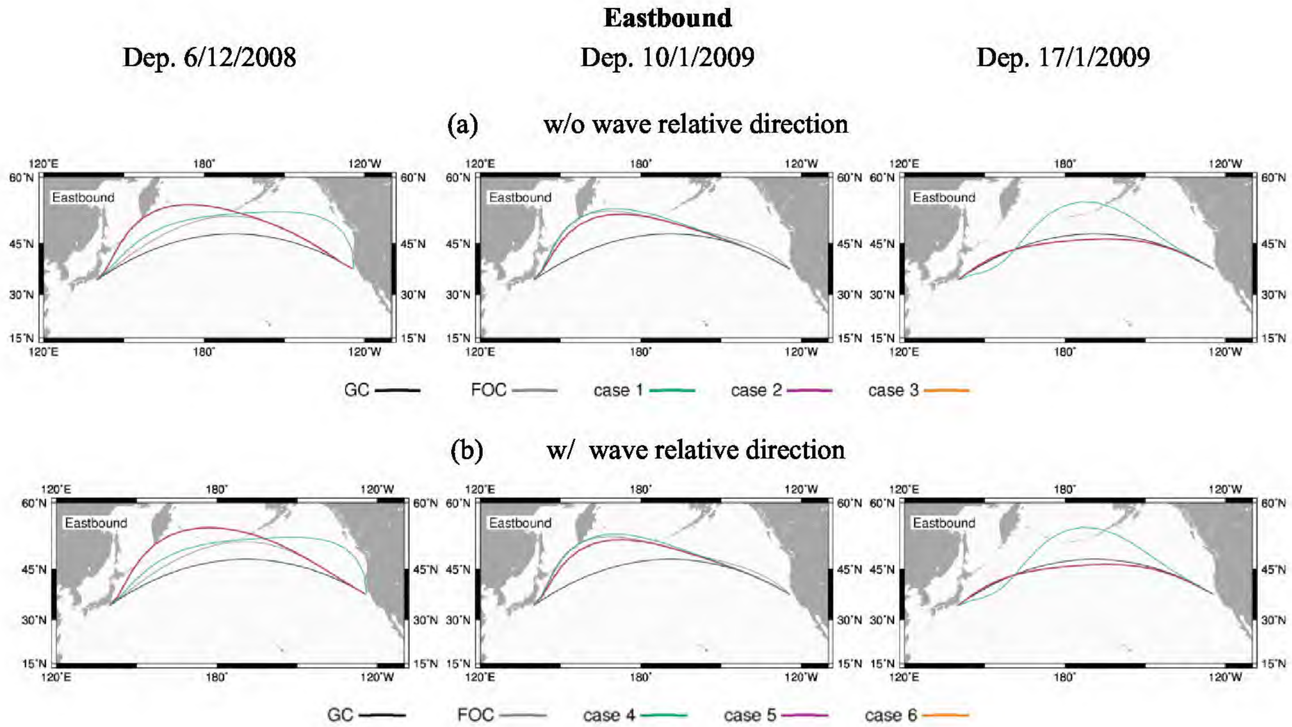

Figure 3: Comparison of navigation routes imposing operational limitations. (Eastbound)

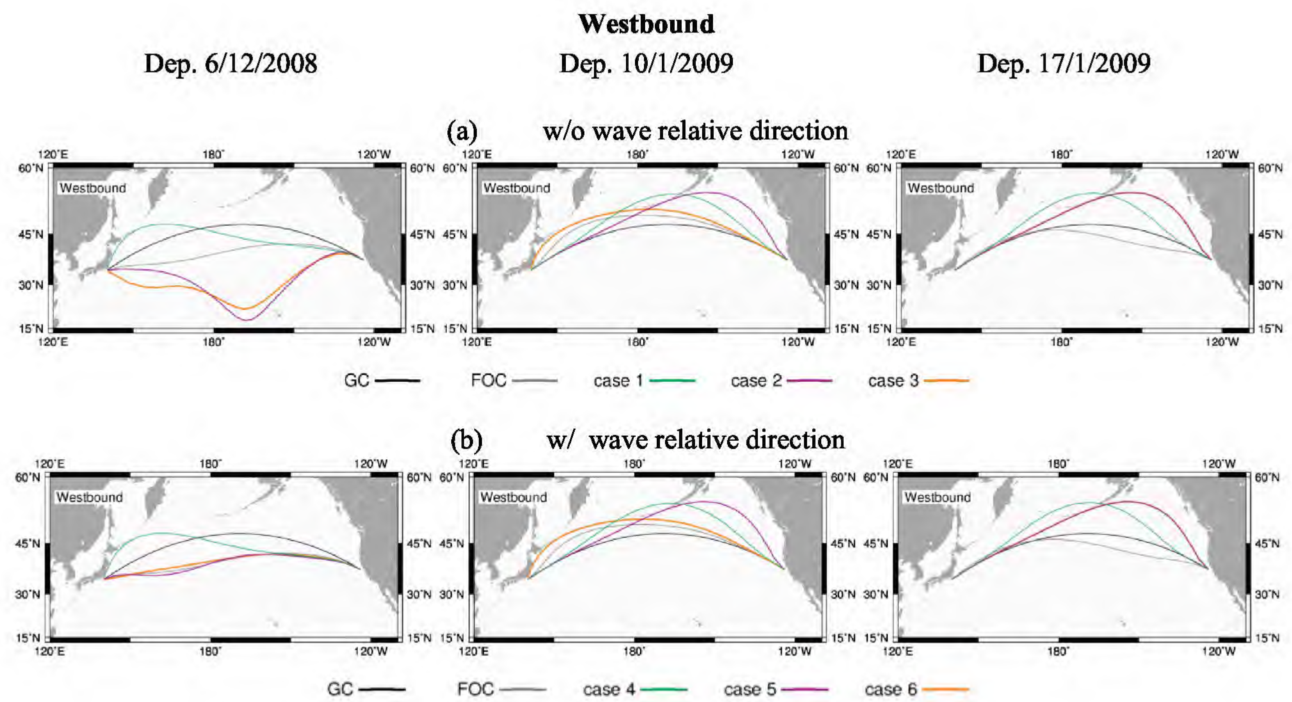

Figure 4: Comparison of navigation trajectory imposing operational limitations. (Westbound)

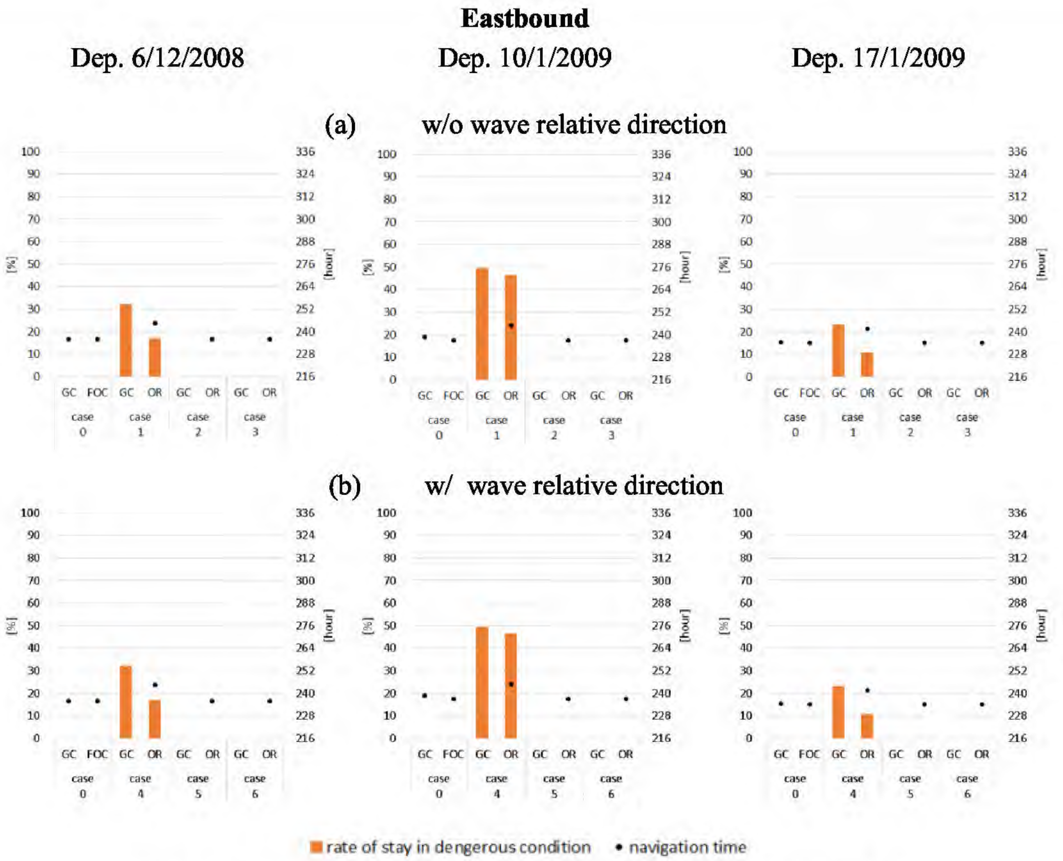

Figure 5: Comparison of achievement of safe navigation and navigation time.

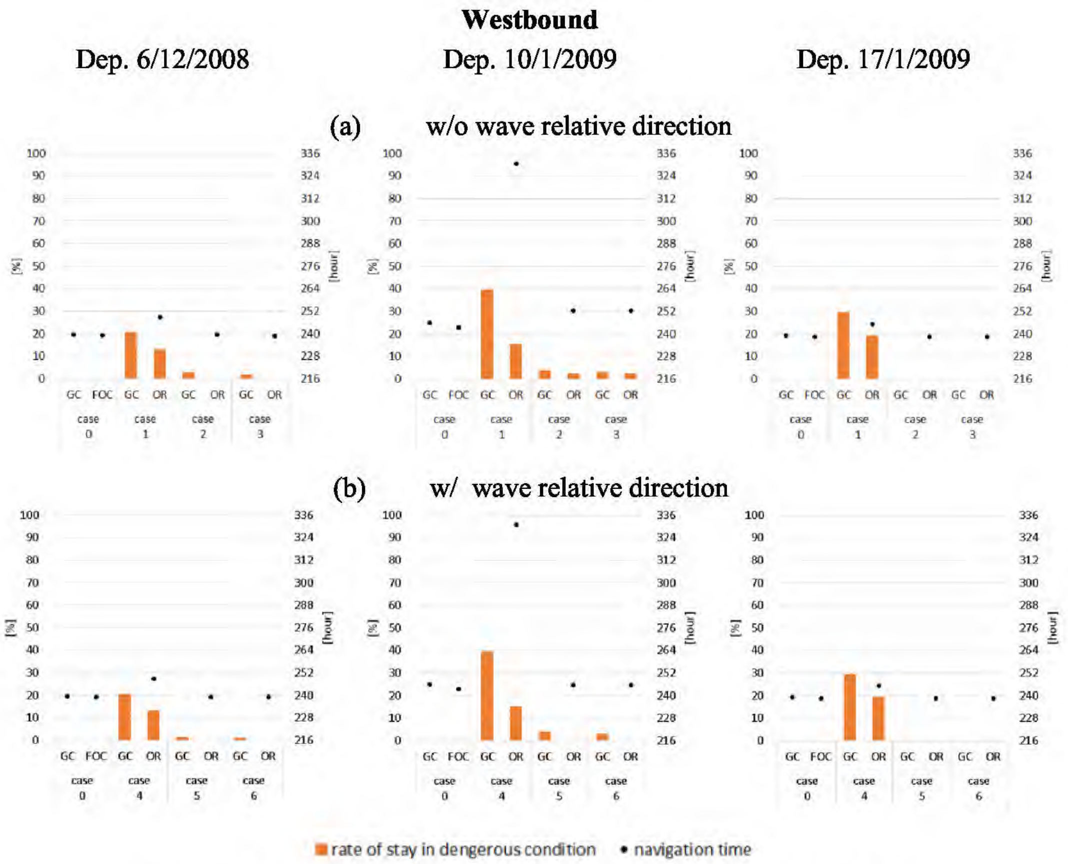

Figure 6: Comparison of achievement of safe navigation and navigation time