Safety-Economic Decision Making Model of Tropical Cyclone Avoidance Routing on Oceans

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Abstract: In order to take TC forecasts from different observatories into consideration, and make quantitative assessment and analysis for avoiding TC routes from the view of safety and cost, a new safe-economic decision making method of TC avoidance routing on ocean was put forward. This model is based on combining forecast of TC trace based on neural networks, technical method to determine the future TC wind and wave fields, technical method of fuzzy information optimization, risk analysis theory, and meteorological-economic decision making theory. It has applied to the simulation of *MV Tianlihai*'s shipping on ocean. The result shows that the model can select the optimum plan from 7 plans, the selected plan is in accordance with the one selected by experienced captains.

1. Introduction

The most concerned by decision makers in daily decision making for ships' TC avoidance routes are two questions, first is the route should be of fulfill ships' safety navigation request, and the second is the route should make the extra cost, such as loss of sailing time, be possibly small.

But it is very difficult to fulfill both above-mentioned requests. First, the accuracy of TC forecast is not high enough, that means a decision maker will take some risk if he makes his decision only according to the forecast from one observatory. But if he wants to take more observatory's forecasts into consideration, then there is absence in method helping comprehensively dealing with TC forecasting information from different observatories, so as not be able to give valuable reference to decision makers. Second, the only standard of present method of decision-making is just asking the route to be fulfilling the request of safety navigation, no quantitatively analysis on routes in benefit/cost concerned. For above purposes, this paper represents a new safety-economic decision-making model of TC avoidance routing on oceans.

2 Determination of future TC wind & wave fields

If a ship will be threatened by a TC when sailing along its original course, 24 hrs TC trace forecasts from CCMO, JMH and JTWC can be got in the Pacific Ocean. Using multi-sources combing analysis of TC trace forecast based on neural-network (FAN Tai-quan, 2002), forecasting positions and wind/wave fields of different probabilities can be got. Flow diagram see Figure 1.

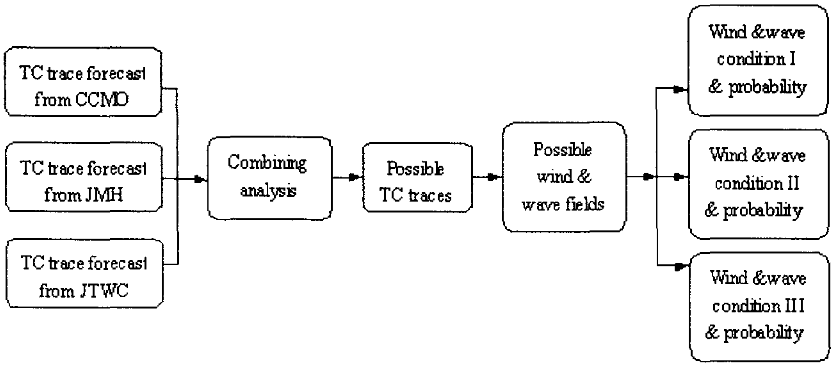

Fig. 1 Flow diagram of determining wind & wave fields of TC

3 Determination of risk degree for TC avoidance routes

Considering the actual operation of shipping companies, the risk degrees of ships' avoiding TC routes can be got. (See Tab. 1)

Tab.1 Risk degrees of TC avoidance routes

Risk degree	I	II	III	IV
Risk tendency	Basically no risk	Small risk	Risk should be considered	Big risk
Meaning	Basically no risk, the route can be used	The route can be used, unless the ship exists serious objections, such as in body structure , stability, balance and watertight.	The route cannot be used, unless the ship can fully fulfill the requests of sailing in heavy weather asked by shipping company.	Great risk existed, the route cannot be used.

After getting the wind/wave fields of different probabilities, we will have to make our decision according to the wind/wave fields of 100% probability, as it is shipping companies' custom to take the most dangerous condition into consideration. So the relative movement line (RML) between TC and sailing ship should be made in the wind/wave fields of 100% probability. According to these, we can get the sailing distances of the ship in different TC areas, different wind/wave angels, and different wind/wave scales. Calculate the actual ship's speed using the pre-got speed drop curve for certain ship, then the values of each disaster-causing element can be got.

The affection of natural factors to ship must be considered when selecting disaster-making elements (LIU Da-gang, 2005). To the risk degree of avoiding TC routes, TC's intensity, including central pressure, maximum wind speed near center, radius of over 50kn wind speed area, maximum wave height, radius of higher than 6m wave area, etc., will be of great important. But, on the result of investigation to experienced captains, especially to those who have the experience of avoiding TC at short distances, and further study on TC structures, it has been discovered that the risk degree of avoiding TC routes will be mainly decided by the following indexes of TC, which can also be called as disaster-causing elements:

S1: Sailing time in dangerous semicircle of TC and wave height more then 5m;

S2: Sailing time in dangerous semicircle of TC and wave height more then 3m;

S3: Maximum wave height of beam sea;

S4: Maximum wave height of beam/follow sea lasted more then 4 hrs in dangerous hemisphere;

S5: Maximum wave height of other directions lasted more then 4 hrs in dangerous hemisphere

S6: Maximum wave height of beam/follow sea lasted more then 4 hrs in navigable hemisphere;

S7: Maximum wave height of other directions lasted more then 4 hrs in navigable hemisphere;

S8: Minimum distance between ship and TC;

S9: Maximum distance between any two 24hrs forecasting positions made by CCMO, JMH and JTWC.

If the domain of the risk degree for TC avoidance route is

$$\mathbf{V} \square \{\mathrm{I},\ \mathrm{II},\ \mathrm{III},\ \mathrm{IV}\} \tag{1}$$

and the domain of disaster-causing elements is

$$\mathbf{U} \square \{S_1, S_2, \cdots, S_9\} \tag{2}$$

To assess the risk degree of avoiding TC routes is to study the relationship between fuzzy subset of disaster-causing elements and fuzzy set of risk degree (HUANG Chong-fu, 1995).

The fuzzy subset of disaster-causing elements used to describe ship's avoiding TC route can be described as

$$\underset{\sim}{\mathbf{A}} = \frac{a_1}{S_1} + \frac{a_2}{S_2} + \cdots + \frac{a_9}{S_9} \tag{3}$$

Here a_1, a_2, $\cdots$, a_9 are the memberships of S_1, S_2, $\cdots$, S_9.

As the actual accidents rarely happen in the processes of avoiding TCs, it is almost impossible to get sufficient primary data for the analysis of risk degree of avoiding TC routes. In this paper, on the basis of questionnaire to experienced captains, using the technique of fuzzy information optimization, the relationship between values ranges for each disaster-causing element and risk degrees had been got. According to pre-got membership of each disaster-causing element to risk degree, the fuzzy relationship matrix of each disaster-causing element to risk degree of each route can be got. Based on this, the membership of each disaster-causing element to risk degree can be got using the technique of gray relational analysis.

$$\underset{\sim}{\mathbf{A}} = \frac{0.1313}{S_1} + \frac{0.1313}{S_2} + \frac{0.1146}{S_3} + \frac{0.1313}{S_4} + \frac{0.1146}{S_5} + \frac{0.1146}{S_6} + \frac{0.1066}{S_7} + \frac{0.0567}{S_8} + \frac{0.099}{S_9} \tag{4}$$

In the actual process of determine risk degree of avoiding TC routes, we can get the actual values of each disaster-causing element in each route from the RML drawing. And then, according to the relevant values of membership, the fuzzy relationship matrix of each disaster-causing element to risk degree for each route can be got.

$$\mathbf{R}_i = \begin{array}{c} \\ S_1(i) \\ S_2(i) \\ \vdots \\ S_9(i) \end{array} \begin{array}{c} \begin{array}{cccc} \mathrm{I} & \mathrm{II} & \mathrm{III} & \mathrm{IV} \end{array} \\ \begin{pmatrix} r_{11}(i) & r_{12}(i) & r_{13}(i) & r_{14}(i) \\ r_{21}(i) & r_{22}(i) & r_{23}(i) & r_{24}(i) \\ \vdots & \vdots & \vdots & \vdots \\ r_{91}(i) & r_{92}(i) & r_{93}(i) & r_{94}(i) \end{pmatrix} \end{array} \tag{5}$$

Here $i = 1, 2, \cdots, n$ represent different avoiding TC routes.

Then, from

$$\underset{\sim}{\mathbf{B}}_{\mathbf{i}} = \underset{\sim}{\mathbf{A}} \circ \mathbf{R}_{\mathbf{i}}$$
$$= \left(\max_{1\le j\le 9}\{a_j \cdot r_{j1}(i)\},\ \max_{1\le j\le 9}\{a_j \cdot r_{j2}(i)\},\ \max_{1\le j\le 9}\{a_j \cdot r_{j3}(i)\},\ \max_{1\le j\le 9}\{a_j \cdot r_{j4}(i)\} \right) \tag{6}$$

we get

$$\underset{\sim}{\mathbf{B}}_{\mathbf{i}} = (x_1(i),\ x_2(i),\ x_3(i),\ x_4(i)). \tag{7}$$

Formula (7) is risk degree of ship's avoiding TC route described in the form of fuzzy vector.

Finally, cancel the routes with too high risk degrees, keep those can fulfill the requests of safety avoiding TC for the further analysis of cost and utility.

The flow diagram of determine risk degree of each avoiding TC route see Fig. 2.

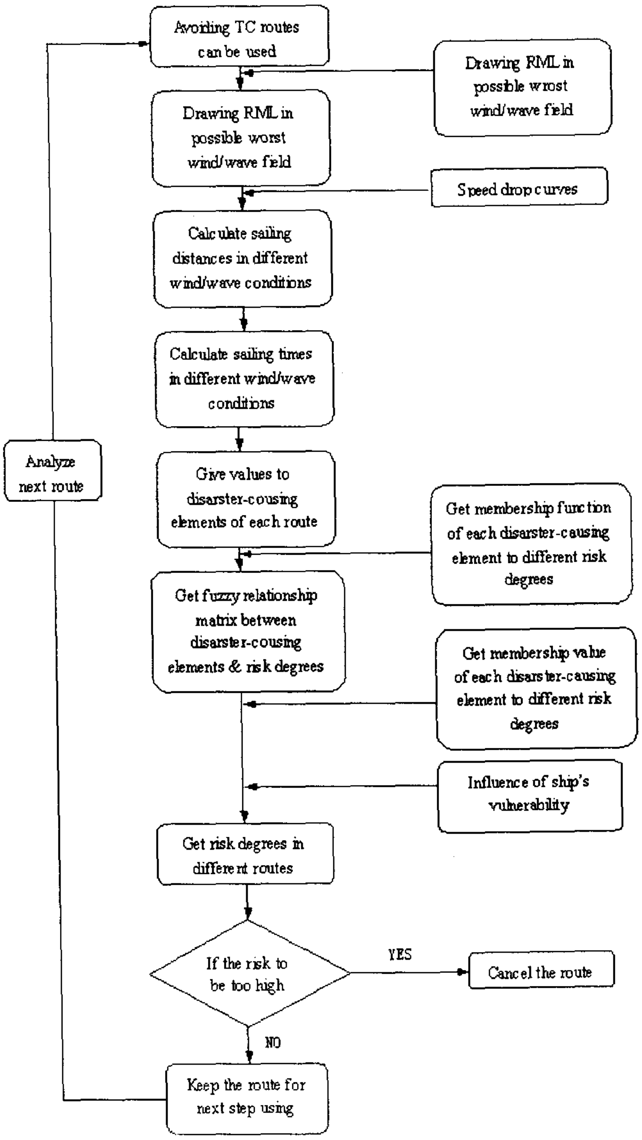

Fig. 2 Flow diagram of determine risk degree of avoiding TC routes

4 Cost & utility assessment for avoiding TC routes

Make RML of each route in wind/wave fields of 75% probability, so as to get the sailing distances under different probability, different part of TC, different wind/wave angels and different wind/wave scales. Then using the speed drop curves and fuel oil consumption curves for concerned ship type, get the totally sailing times and oil consumptions, comparing with the values when no strong wind or high wave caused by TC so no avoidance needed, refering to the present price of fuel oil and daily rent of concerned ship, the non-accidental loss and relevant loss matrices of avoiding TC routes of this type of ship can be got (LIU Da-gang, 2004).

Finally, using the cost assessment and utility assessment of optimum avoiding TC route decision making model based on meteorological-ecomomic decision making theory, make assessment to each avoiding TC route so as to get routes of lowest cost and optimum utility for decision makers' reference (SHEN Chang-si, 1997).

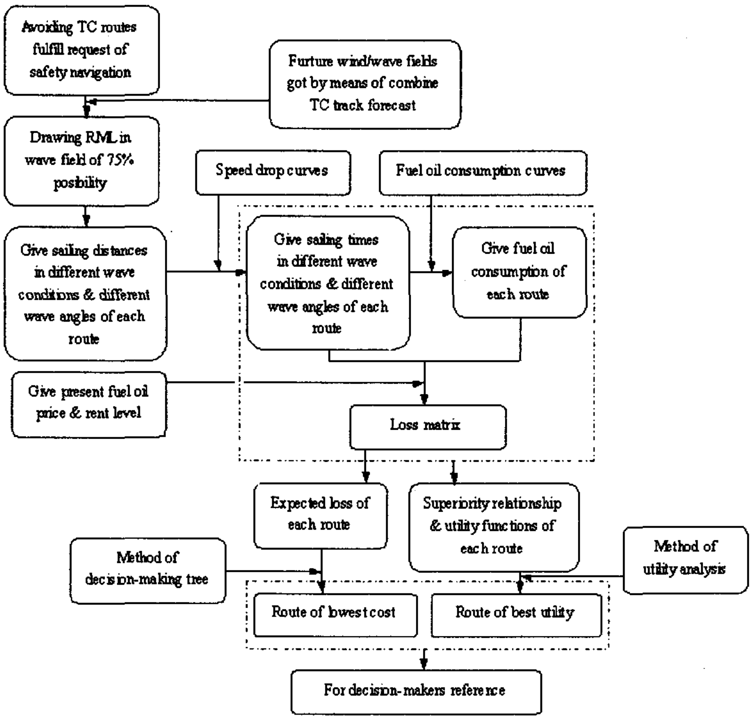

Fig. 3 Flow diagram of cost & utility assessment for avoiding TC routes

5 Calculation of actual example

MV Tianlihai, which belongs to COSCO BULK CARRIER CO., LTD, with a length of 270m, width of 44m, 149,000DWT, load draught 17.5m, fully load speed 14kn, delivery time 1999.

At 12th Oct.2005 0000UTC, *MV Tianlihai* was at the position of 28.5° N, 127.5° E, course 150°. At that time, T0520 Kirogi was bearing 145° and range 560mn. The maximum wind speed of T0520 was 70kn, maximum wave height was 8m, radius of over 6m wave was 120mn, width of wave height 5-6m area was 60mn, width of wave height 4-5m area was 90mn, and width of wave height 3-4m area was 120mn.

According to the forecasted positions made by CCMO, JMH and JTWC, using the method of multi-sources combine TC track forecast, we can get that T0520 would be in a circle centered 21.4° N, 131.8° E in the future 24 hrs, and the probabilities for radius of possible position areas of 18nm、36nm and 60nm would be 75%、95% and 100%.

As the ship would encounter T0520 if it sail along its original course, and have great risk, so it should be take avoidance to T0520.

According to the forecasted movement and wind/wave fields of T0520, two groups of TC avoidance routes, one from eastern side and another from western side of TC, had been primarily selected.

The routes of avoiding TC from its western side:

W_1: Sail 36hrs on the course of 190°, then turn to course 150°, sail 12hrs, then turn to "returning point" positioned 14.0°N, 135.0°E;

W_2: Sail 24hrs on the course of 185°, then turn to course 170°, sail 24hrs, then turn to "returning point";

W_3: Sail 24hrs on the course of 180°, then turn to course 151°, sail 24hrs, then turn to "returning point";

W_4: Sail 24hrs on the course of 170°, then turn to "returning point".

The routes of avoiding TC from its eastern side:

E_1: Sail 36hrs on the course of 130°, then turn to "returning point";

E_2: Sail 36hrs on the course of 125°, then turn to "returning point";

E_3: Sail 36hrs on the course of 110°, then turn to "returning point".

After that, make RML of each avoiding TC route in wave field of 100% probability. (See Fig.4).

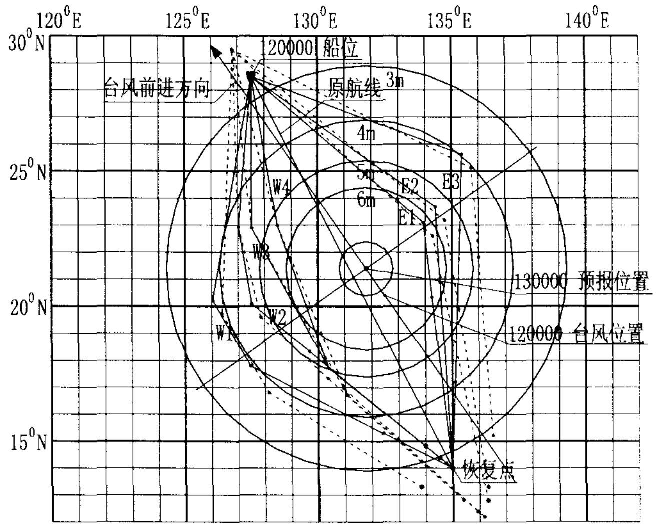

Fig. 4 Wave field of 100% probability and avoiding TC routes

According to the RML, the values of each disaster-causing element of each avoiding TC route can be got. Based on these, using the technical method of fuzzy information optimization, the membership function of the values of disaster-causing elements to different risk degrees can be got, and the fuzzy matrices of the values of disaster-causing elements to different risk degrees can be got as well. Then use the technique of gray relational analysis to get the membership of each disaster-causing element to different risk degree, and the index of risk degree of each avoiding TC route can be got according to formula (6).

$$F_{W_1} = (0.179,\ \underline{0.357},\ 0.308,\ 0.156)$$

$$F_{W_2} = (0.160,\ \underline{0.323},\ 0.279,\ 0.238)$$

$$F_{W_3} = (0.081,\ 0.242,\ \underline{0.403},\ 0.274)$$

$$F_{W_4} = (0.069,\ 0.206,\ 0.344,\ \underline{0.381})$$

$$F_{E_1} = (0.067,\ 0.201,\ 0.336,\ \underline{0.396})$$

$$F_{E_2} = (0.138,\ 0.277,\ 0.242,\ \underline{0.343})$$

$$F_{E_3} = (0.143,\ 0.174,\ 0.290,\ \underline{0.393}).$$

From above indexes of risk degrees of each route we get conclusion as below:
The routes avoiding TC from its east side (E_1, E_2 and E_3) have to be cancelled because they all belong to risk degree IV that has too high risk, and also the route W_4 for the same reason.
For route W_3, certain risk existed; it cannot be used unless the ship can fully fulfill the requests of sailing in heavy weather asked by shipping company.
For W_1 and W_2, the route can be used, unless the ship exists serious objections, such as in body structure, stability, balance and watertight.

Considering the actual conditions of *MV Tianlihai*, we think that routes W_1, W_2 and W_3 can be used. But further analysis on cost and utility must be made to know which route is the optimum.

The first step is the cost analysis for the 3 avoiding TC routes left.

In the following analysis, considering the wind fields is generally accordant to the wave fields, the affection of strong wind will be included in that of big wave, so only the analysis of affection made by wave field was given.

Draw out RMLs in the wave field of 75% probability, and give the sailing distances, sailing times and oil consumptions at different wave angels, different wave height of each avoiding TC route (see Fig.5).

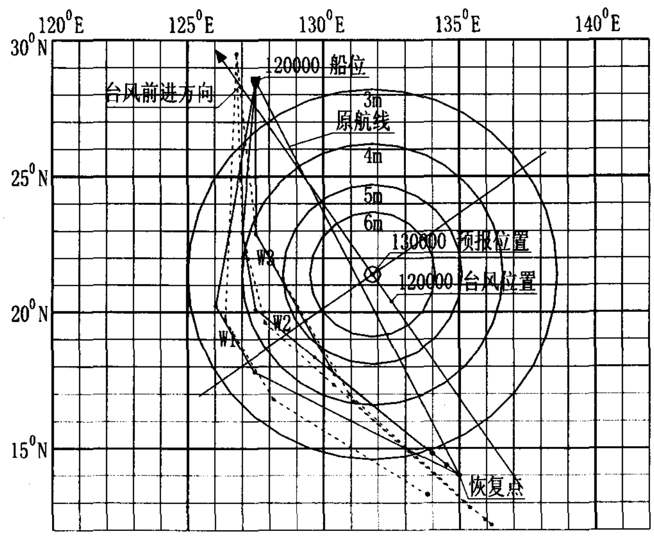

Fig. 5 Wave field of 75% probability and avoiding TC routes and RMLs

Thus, the actual sailing time and oil consumption of each route can be got. Comparing with sailing time of 69.9hrs and 160.19MT fuel oil at normal condition of no TC, considering the present average unit price of fuel oil 380cst at 320USD/MT, and the present Baltic Index when the time charter averages on 29,000USD/day, the extra cost at different wave probabilities of different routes and the non-accident loss matrices of avoiding TC of *MV Tianlian* can be got.

$$\begin{array}{r} \\ \text{Route } W_1 \\ \text{Route } W_2 \\ \text{Route } W_3 \end{array} \begin{array}{c} \text{Probability 75\%} \quad \text{Probability 25\%} \\ \begin{bmatrix} 3.01 & 2.86 \\ 1.94 & 1.76 \\ 1.64 & 1.35 \end{bmatrix} \end{array}$$

The next step, we can use the method of decision-making tree for optimizing avoiding TC route, so as to get expected cost of each route (LIU Da-gang, 2004).

$$E\ (W_1) = 30.1 \times 0.75 + 28.6 \times 0.25 = 29.7 \text{ thousand USD}$$
$$E\ (W_2) = 19.4 \times 0.75 + 17.6 \times 0.25 = 19.0 \text{ thousand USD}$$
$$E\ (W_3) = 16.4 \times 0.75 + 13.5 \times 0.25 = 15.7 \text{ thousand USD}$$

According to the principle of minimum cost, route W_3 is considered the optimum route.

It can be seen in this process that here all the decision makers are assumed to be rational, and the decision was made on the value of money. But the personality of certain people and the mentality and behavior of the decision makers had been neglected. Actually, the attitudes on the risk brought by random decision-making are differed according to the makers' status, experience and personal characters.

To solve this problem, we need further utility analysis (DIAO Zai-jun, 2004).

For above 3 avoiding TC routes, the superiority order can be decided according to the maximum beam sea, maximum wave height and extra cost of each route (See Tab.2).

Tab.2 Results for avoiding TC routes

Probability	index	Route		
		W_1	W_2	W_3
75%	Code of result	C_{11}	C_{21}	C_{31}
	Max height of beam sea lasted more then 4 hrs	3-4m	4-5m	4-5m
	Max height of wave lasted more then 4 hrs	4-5m	4-5m	5-6m
	Extra cost	30.1 thousand USD	19.4 thousand USD	16.4 thousand USD
25%	Code of result6	C_{12}	C_{22}	C_{32}
	Max height of beam sea lasted more then 4 hrs	<3m	3-4m	3-4m
	Max height of wave lasted more then 4 hrs	3-4m	3-4m	4-5m
	Extra cost	28.6 thousand USD	17.6 thousand USD	13.5 thousand USD

Using the symbol of "$\succ$" means "better than", the following superiority order can be got

$$C_{32} \succ C_{22} \succ C_{21} \succ C_{31} \succ C_{12} \succ C_{11} \quad (10)$$

Then, using seeking method to determine the utility function for optimizing avoiding TC route:

Tab.3 Utility function values

route	Probability of big wave	
	75%	25%
W_1	$U(C_{11}) = 0.00$	$U(C_{12}) = 0.45$
W_2	$U(C_{21}) = 0.85$	$U(C_{22}) = 0.95$
W_3	$U(C_{31}) = 0.70$	$U(C_{32}) = 1.00$

According to utility function values of this question(see Tab.3), the utility curve can be got (see Fig.6).

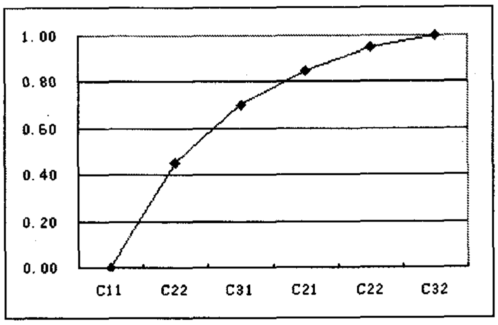

Fig.6 Utility function curve

Based on the utility function, the optimum avoiding TC route can be got using the principle of maximum utility (LIU Da-gang, 2005).

For route W_1: $E^{W}_{1}[U(C)] = 0.75 \times 0.00 + 0.25 \times 0.42 = 0.11$

For route W_2: $E^{W}_{2}[U(C)] = 0.75 \times 0.85 + 0.25 \times 0.93 = 0.87$

For route W_3: $E^{W}_{3}[U(C)] = 0.75 \times 0.65 + 0.25 \times 1.00 = 0.74$

Here we can see route W_2 is the optimum avoiding TC route that fulfills the request best utility.

The above result is almost the same with the result got by discussion of a group of experienced captains.

6 Results and Discussions

The safety-economic decision making model of TC avoidance routing on oceans presented in this paper, used the up-to-date ideas and results of science and technology, such as combining forecast of TC trace based on neural networks, technical method to determine future TC wind and wave fields from multi-sources of forecast, technical method of fuzzy information optimization, risk analyze theory, and the theory of meteorological-economic decision making.

Using the method of this model, we can make a combining analysis on the TC trace forecasts made by CCMO, JMH and JTWC, so as to get a TC forecasting position with higher accuracy and wind/wave fields with different probabilities. Based on these, the risk assessment for all avoiding TC routes can be made. After canceling the routes with too high risk degree, using cost analysis and utility analysis, the optimum routes of benefit and utility can be got separately , so as to for the reference of different requests.

The calculated result for *MV Tianlihai* shows almost no difference between the optimum route got by this model and the result got by discussion of a group of experienced captains. This model can be used as theoretical support and important reference for developing a safety-economic decision making system of TC avoidance.

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