# Development of a ship weather routing system for energy efficient shipping

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## Abstract

In this paper, a new ship weather routing system is developed towards enhancing energy efficiency. The routes searching is essentially regarded as an optimisation process with two objectives, which are respectively ETA (estimated arrival time) and fuel consumption. When ship characteristics, loading conditions, ship speed, and sea conditions (wave, wind and currents) are imported to this system, together with departure and final points and departure time, a set of minimum fuel consumption routes under different ETA can be achieved. In this way, an optimal and safe enough route can be decided according to shipping schedule. A combination of global and local optimisation strategy is used in weather routing optimisation. Finally, an Aframax Oil Tanker is taken as a case study to prove the validity of this ship weather routing decision system.

**Keywords:** marine transport, weather routing, energy efficiency, two objectives optimisation

## 1. Introduction

In the shipping field, energy consumption is quite huge, as almost 90% goods traded worldwide are transported by sea. With the development of marine transport and people's enhancing awareness of energy conservation, the selection of ship routes is getting more and more attention in the shipping industry. Especially in recent years, the global economic recession led to a downturn in the shipping industry, improving energy saving capability of the ship from the technical level, to minimize the cost of transportation has become a pressing issue faced by the technician. In essentially, ship route searching can be defined as an optimisation process, which is always affected by hull form, weather, sea states and ship safety, etc. To save travel time, maximise safety or energy efficiency, people have developed many kinds of optimisation methods. Most common methods are listed as below.

Calculus of variations (Bijlsma S.J, 1975) is a method that calculates the optimal heading between two points by solving Euler equation. The optimal route can be determined by refining the gradients of arbitrary objective function in a continuous optimisation process.

Isochrone method (James, 1957) is a very common method used in ship routing and even much commercial software, like OpenCPN, qtVlm etc. It generates isochrones one by one repeatedly, which means setting several lines a ship can reach after a certain time from the departure point. From these lines, a minimum ETA route can be easily determined. It also has some modified version (Hagiwara H, 1989, Hagiwara H & Spaans JA, 1987) for different calculation objectives.

The principle of Isopone method (Klompstra MB et al., 1992, Spaans JA, 1995) is similar to Isochrone method. It defines the shipping boundary with equal fuel consumption in a three-dimensional space. This method can easily obtain minimum fuel consumption route.

Dijkstra's method (Padhy, 2008; Panigrahi, 2008, Hege Eskild, 2014) was introduced to ship routing recently, which is a kind of graph searching optimisation method. Before calculation, a network was built based on grids system, and then positive weights represent passage time or fuel consumption, etc. were assigned to the graph edges. By analysing the sum of weights on this network, optimal route with different objectives can be determined.

Dynamic programming method is developed based on Bellman's principle of optimality (Bellman, 1957). The main strategy is: solving the big problem by dividing it to many sub small problems. Results from each subproblem will form the final result. Some researchers (De Wit C, 1990, Calvert S et al., 1991) developed a 2-dimensional dynamic programming (2DDP) method for ship routing problem, which takes two dimensions: latitude and longitude into account. This method simplifies the problem and reduces the calculation time.

Based on that, Wei Shao (2012) developed a 3-dimensional dynamic programming (3DDP) method, which contains 3-dimensional variables: latitude, longitude and time and uses a forward algorithm in the optimisation process. This method can provide better ship routing results without increasing much calculation cost. Besides, there are also some evolutionary algorithms, like Genetic Algorithm (Harries, 2003, Hinnenthal, 2010, and J.Szłapczy´nska, 2009).

In this paper, a ship weather routing system for energy efficient shipping is developed. This system has relative more comprehensive functions, including grids system design, weather data download, shipping safety testing, fuel consumption calculation and optimal route selection etc. A combination of global and local optimisation strategy is used in weather routing optimisation. The system runs towards to two objectives: ETA and fuel consumption. Finally, an optimisation Pareto front can be generated, and then the optimal route according to different shipping requirements can be determined.

## 2. Ship weather routing system

### 2.1. Preparatory work

Before calculation in the ship weather routing system, some necessary files and data should be collected in advance. Firstly, for a certain ship, its characteristics are collected, including ship geometry, main engine and propeller parameters. Secondly, based on Holtrop 84 (1984) resistance prediction method and strip theory, ship calm water resistance coefficient curve and response amplitude operators for different motions can be calculated respectively. Strip theory can also be used to define transfer functions. Next ship response in the irregular sea can be found by combining the transfer function with the wave spectrum (JONSWAP). Besides, added resistance due to waves, wind resistance coefficient curve and propeller open water performance file are also calculated. Added resistance file are calculated based on the method presented by Gerritsma and Beukelman (1972). Loukakis and Sclavounos (1978) extended this method from only valid for head sea waves to oblique waves. This file includes relative wave angle, mean wave period and significant height of combined wind waves and swell, and corresponding added resistance value under these conditions. So that when three arbitrary conditions are given, a certain added resistance value due to waves can be got. Similarly, propeller open water performance file contains advance coefficient, thrust coefficient, torque coefficient and open water efficiency.

### 2.2 Grids system design module

Grids system is designed in advance for leading the ship travel. In this grids system, great circle (The shortest distance between two points on a sphere) is taken as the reference, which is divided into several equal stages with certain numbers of points. Through every point, a straight line can be drawn perpendicular to its tangent line around the circle. Next, certain numbers of points can be distributed along this vertical line, including upper and lower parts of the great circle. The number of stages and distance between two points in one stage are both adjustable. The grids system can be clearly explained in Figure 1.

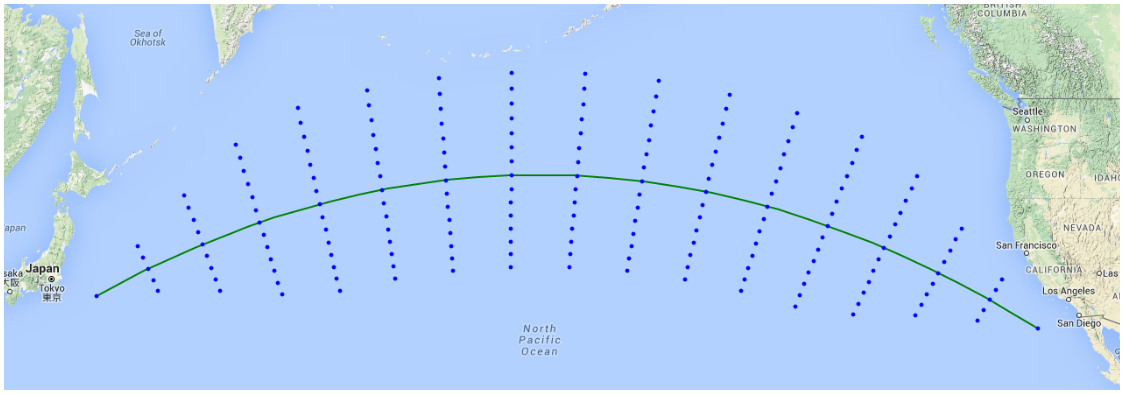


**Figure 1 – Grids system**

After the grids system is fixed, travel directions should be determined from every departure point to arrival point. Considering the larger course deviations are not feasible and would be unrealistic for an optimum route, five directions are better. So that, from departure point, except points near the grids border, a ship at every point can travel to next five potential points, which can be seen in Figure 2. With these nodes are connected, many potential arcs are formed.

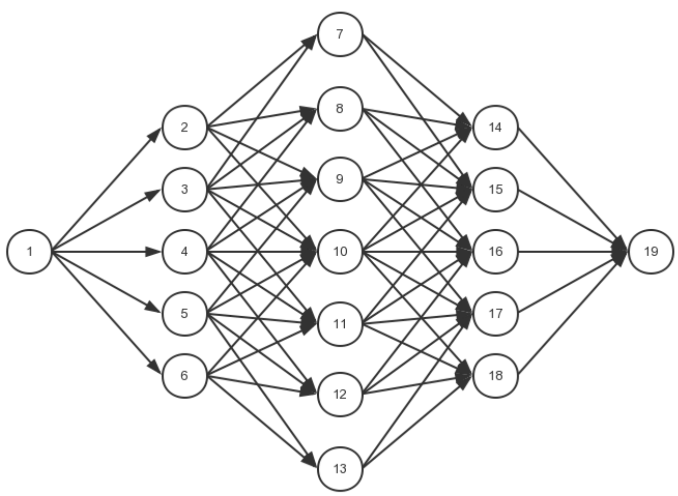


**Figure 2 – Ship routing network**

**2.3 Files reading module**

This is also the entry point to the whole weather routing system. Two file types should be read and decoded.

First, from 2.1, based on ship characteristics, many calculation result files have been got, including calm water resistance coefficient curve, transfer functions for different motions, added resistance file due to waves, wind resistance coefficient curve and propeller open water performance file. All of the files are edited to certain form in a .txt file, which will be input to the system for weather routing calculation.

Second, weather forecast files are downloaded from different database. This system will take winds, waves and currents into account together. For waves and winds, they are downloaded from ECMWF (European Centre for Medium-Range Weather Forecasts) (.grib), including 10 meter U wind component, 10 meter V wind component, mean wave direction, mean wave period and significant height of combined wind waves and swell, and they all update every 6 hours. For currents, it is downloaded from NOAA (National Oceanic and Atmospheric Administration) (.nc), including 15-meter depth U current component and V current component, and updates every five days. All of these weather data files contain time, latitude and longitude. Once time, latitude and longitude at a certain point on the earth were given, detailed weather data at that point will be known in this module.

### 2.4 Ship navigation safety module

This is a very important module since it relates to the safety of ship and crew. Seakeeping performance is introduced here to guarantee the ship navigation safety. Within this module, four parameters are calculated according to NORDFORSK criteria (1987). They are probability of slamming, probability of deck wetness, RMS of roll and RMS of relative vertical acceleration. All of them should be less than corresponding criteria according to different navigation situation. They are all calculated based on transfer functions pre-calculated in 2.1. Seakeeping performance can be regarded as a constraint for the following optimisation. If the sea condition of a certain area does not satisfy the ship's navigation requirements, a "No Entry" signal will be assigned to this area, so that the ship will not go through this area.

### 2.5 Fuel consumption calculation module

In this system, only added resistance due to waves and winds are taken into account. Total resistance can be calculated by:

$$R_{total}=R_{calm}+R_{waves}+R_{winds} \tag{1}$$

Among them, when a certain speed in calm water is given, $R_{calm}$ can be easily got by interpolation with calm water resistance coefficient curve. $R_{waves}$ can be calculated by the file "added resistance due to waves" mentioned in 2.1, with introduced waves weather data.

Similarly, according to winds weather data, $R_{winds}$ can be got by interpolation with wind resistance coefficient curve as well.

Ship engine effective power can be calculated by:

$$P_E = R_{total} \cdot V_{ship} \qquad (2)$$

Where $V_{ship}$ is ship speed in rough sea. In this system, ship speed consists of three parts: ship speed in calm water, speed loss due to waves and winds and speed change due to currents. Speed loss can be calculated based two main references: Faltinsen et al. and Minsaas et al. (1981 and 1983). As to currents, to simplify the progress and without loss of accuracy, the components of currents velocities along the ship course are linearly added to ship velocities (Lo, H. and McCord, M. 1998, 1999).

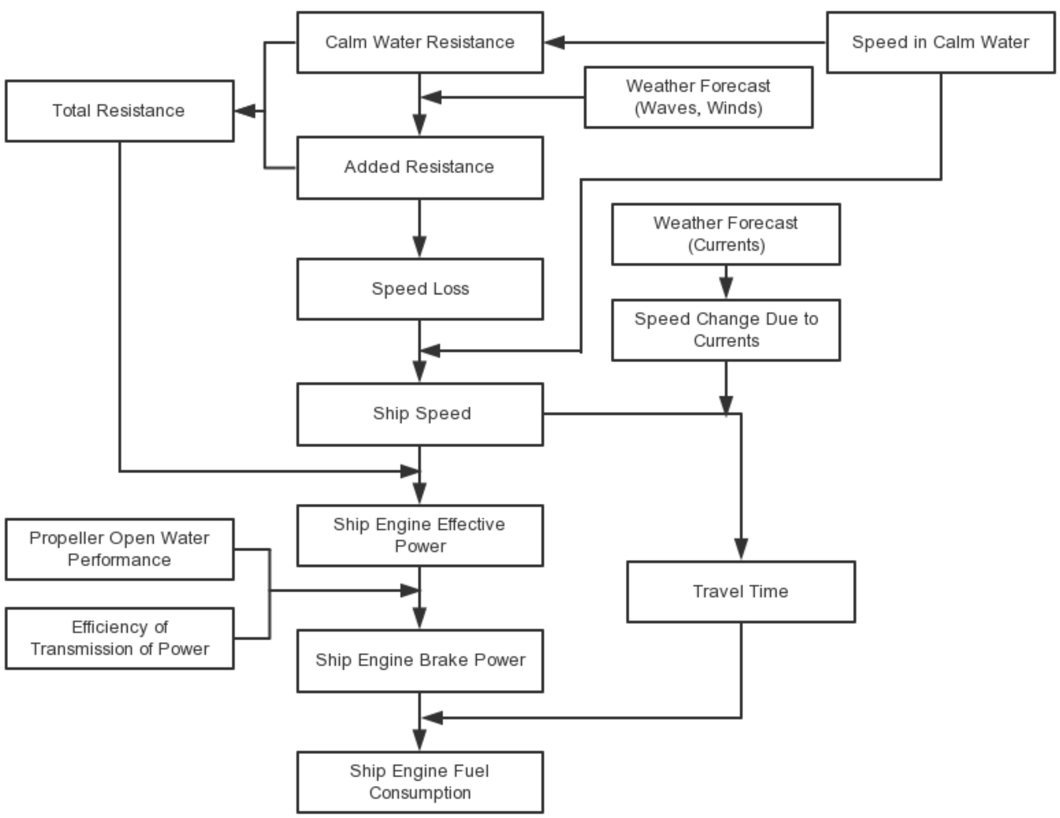


**Figure 3 – Calculation flow towards fuel consumption**

Next, propeller characteristics and open water performance file are introduced here to calculate the hull efficiency $\eta_H$, open water efficiency $\eta_0$ and relative rotative efficiency $\eta_R$. Together with the mechanism transmission efficiency: shaft efficiency $\eta_S$ and gearbox efficiency $\eta_{gb}$, the engine brake power can be determined from:

$$P_B = \frac{P_E}{\eta_H \eta_0 \eta_R \eta_S \eta_{gb}} \tag{3}$$

Finally, the fuel consumption for a certain arc can be calculated by:

$$FC = P_B \cdot sfoc \cdot t \tag{4}$$

Where, $sfoc$ (g/kWh) is specific fuel oil consumption of the engine, which is assumed as a constant value in this system. $t$ is ship navigation duration, which can be easily got when the length of the arc and actual ship speed are known.

The calculation flow of ship fuel consumption for every small arc can be seen in Figure 3.

### 2.6 Route optimisation module

The route optimisation strategy used in this system is a combination of global and local optimisation with two objectives: ETA and fuel consumption.

The calculation starts from the departure point. Firstly, the system reads the weather data at the departure point by local longitude, latitude and departure time. Secondly, as can be seen from the grids system in 2.2 and Figure 4, the whole travel route can be divided into several stages, so that the ship can travel along the route stage by stage. Within every stage, there are many departure points and arrival points, and almost every point (without the point near the grids border) can go to next stage by five directions. So there are many potential route arcs in one stage.

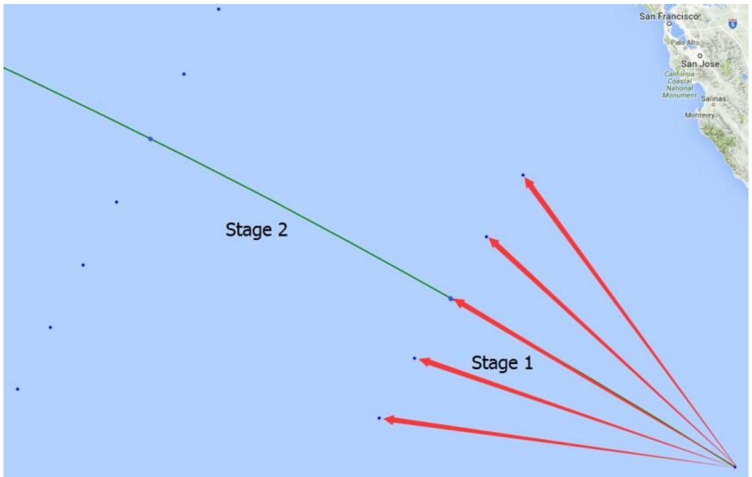


**Figure 4 – Ship routing stages**

In the beginning, a random speed is assigned to a travel direction in stage 1. This speed ranges from minimum speed to maximum speed with an interval speed $\Delta V$ . Having the weather data and ship speed, according to fuel consumption calculation method in 2.5, the fuel consumption on this arc can be easily determined under these conditions. Then the navigation information of this arc under this certain condition will be stored in its arrival point, including fuel consumption, ship speed, navigation duration, local time (calculated by adding navigation duration to departure time ) and coordinates of the departure point. Next, the arrival point in Stage 1 becomes the departure point in Stage 2. According to the information stored in this point, new weather data will be read and new random speed will be assigned to a travel direction, and then new round calculation will carry out in Stage 2, and results will be accumulated to store in next arrival point. This process also realises the weather data real time updating function.

With the same method, the fuel consumption calculation repeats over all stages until reaching the final destination point, which covers all potential route arcs, and traverses all the potential travel directions and all the speed options. After calculation, every point will store many sets of navigation results. Through continuous accumulation, each set of results presents the information of a potential route from the initial departure point to this point, which contains fuel consumption and navigation duration in every arc that the ship passed and the sum of them up to this point, and also coordinates of each point the ship passed. It is noteworthy that every potential route should pass the seakeeping test in 2.4 to guarantee the ship safety. Otherwise, this route will be deleted automatically. Finally, by checking the route information stored in final destination point, a Pareto front (ETA vs. Fuel consumption) can be drawn. Moreover, then a minimum fuel consumption and safe enough route plan can be selected according to the ship navigation schedule (ETA). The whole process can be regarded as a global optimisation.

By the way, when a ship travels from a stage to next, it will produce many different ETA and fuel consumption results due to so many speed and direction options. If continuous iteration lasts until final destination point, the quantity of final results will be prohibitively huge. This will lead to a huge calculation cost. Here, local optimisation strategy is introduced. For a certain arrival point, it is sure that it will receive many ETA and fuel consumption results from the last stage. Among them, there must be some results have same arrive time but different fuel consumption. So this method just keeps the minimum fuel consumption under every same arrival time and deletes all of the others. Thus, keeping a Pareto front for every local waypoint. With this method, when fuel consumption calculation carries out from this waypoint, only the left results will be traversed. So it will definitely save the calculation cost.

## 3. Case study and discussion

In this case study, an Aframax oil tanker is taken as the ship model. The departure point and destination point are respectively 121°29'W \ 31°55'N and 144°21'E \ 34°34'N. Departure time is 2011-09-13, 19:00. The grids system has 16 stages, and every stage has maximum 19 waypoints with equal distance of 60 nautical miles. Ship speed ranges from minimum 9.5 knots to 15.8 knots with the interval speed 0.1 knot. The weather routing optimisation Pareto front results are shown in Figure 5.

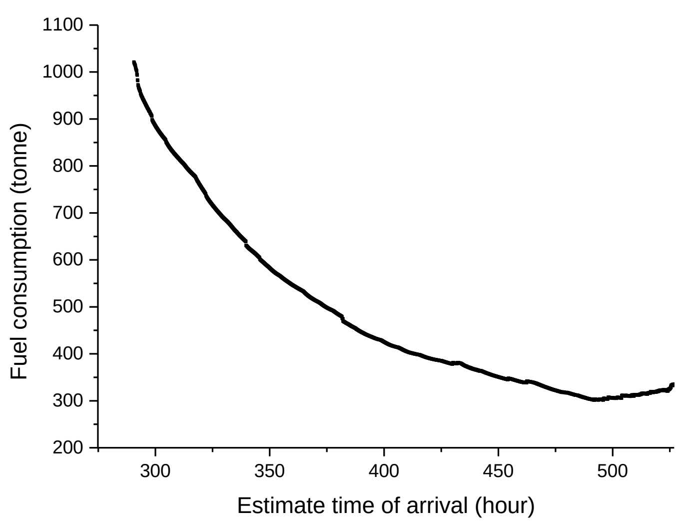


**Figure 5 – Pareto front of case study**

It can be seen from Fig 5. There are almost 2000 potential route plans during this voyage. The ETA ranges from 290.6 h to 528.3 h, while the fuel consumption ranges from 301.09 tonnes to 1021.19 tonnes. Speed sets, ETA and fuel consumption of four typical routes: Noon report recorded route, 392h ETA route, Minimum fuel consumption route and Minimum ETA route were listed in Table 1.

**Table 1 – Total results**

| | Stage | Noon report recorded route | 392h ETA route | Minimum fuel consumption route | Minimum ETA route |
|---|---|---|---|---|---|
| Speed sets (knots) | 1 | 12.5 | 12.6 | 9.5 | 15.8 |
| | 2 | 12.6 | 12.8 | 9.5 | 15.8 |
| | 3 | 12.9 | 12.5 | 9.5 | 15.8 |
| | 4 | 12.6 | 13.2 | 9.5 | 15.8 |
| | 5 | 12.3 | 12.7 | 9.5 | 15.8 |
| | 6 | 11.9 | 12.8 | 9.5 | 15.8 |
| | 7 | 11.1 | 9.9 | 9.5 | 15.8 |
| | 8 | 11.7 | 9.6 | 9.5 | 15.8 |
| | 9 | 11.9 | 9.5 | 9.5 | 15.8 |
| | 10 | 12.8 | 10.9 | 9.5 | 15.8 |
| | 11 | 12.1 | 10.5 | 9.5 | 15.8 |
| | 12 | 12.8 | 12 | 9.7 | 15.8 |
| | 13 | 12.3 | 11.9 | 9.7 | 15.8 |
| | 14 | 10.4 | 12.7 | 9.5 | 15.8 |
| | 15 | 10.5 | 13.4 | 9.5 | 15.8 |
| | 16 | 9.9 | 14.4 | 9.5 | 15.8 |
| ETA (hours) | | 392.0 | 392.0 | 492.1 | 290.6 |
| Fuel consumption (tonnes) | | 623.3 | 450.98 | 301.09 | 1021.19 |

According to history noon report, the recorded route has 392 h of ETA and 623.3 tonnes of fuel consumption. For the sake of comparison, the potential route with same ETA is selected. Although their average speed is quite similar: 11.89 knots and 11.96 knots, their speed sets have different changing trends: the recorded results are steady, while the calculated results show the ship decelerated at the first half stages and then accelerated at the second stages. The speed sets of the calculated route also reflect weather conditions are changing. In that calculated route, the wind and wave condition in middle stages are worse, so the ship should reduce the speed to guarantee the safety. When the weather becomes better, the ship can run much faster. However, in the aspect of fuel consumption, which is most important indicator, the route calculated in this system has 450.98 tonnes of fuel consumption, which use 27.65% less fuel than the recorded route. That means this system can provide more optimal route plan for the shipmasters.

Besides, from the final Pareto front, both minimum fuel consumption route and minimum ETA route can be extracted. For the former route, it has 492.1 h of ETA and 301.09 tonnes of fuel consumption with almost slowest average speed 9.5 knots; while for the latter route, it has 290.6 h of ETA and 1021.19 tonnes of fuel consumption, but with fastest average speed 15.8 knots.

These four typical routes are all drawn in Figure 6.

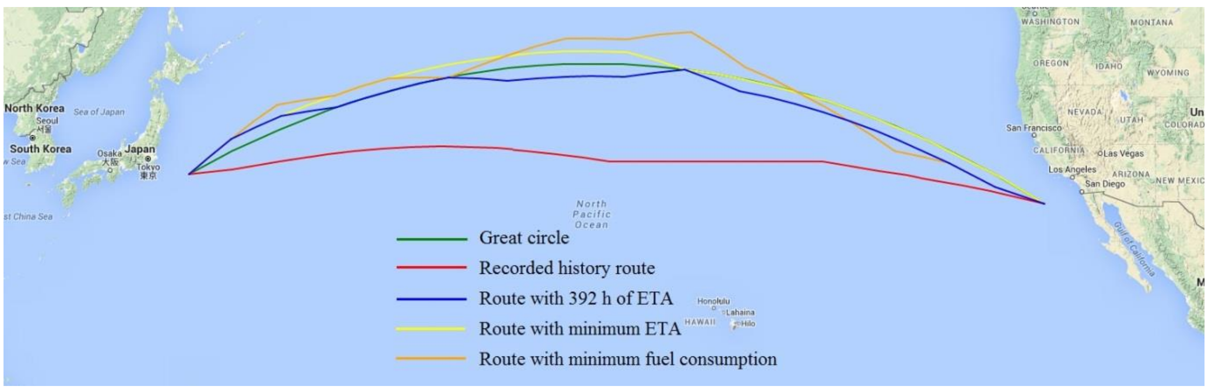


**Figure 6 – Optimal routes based on different requirements**

## 4. Conclusion

This paper presents a ship weather routing system for energy efficient shipping. The structure and mainly calculation and optimisation strategy used in this system are introduced in great detail. A case study with Aframax oil tanker has been made. As can be seen from results, with the strategy of a combination of global and local optimisation, this system can provide related stakeholders much better routes towards minimum ETA or minimum fuel consumption. The whole calculation flow in this system is easy to understand, and its required parameters are also not complicated.

However, there is still some rough work to be improved in this system. For example, ship resistance is estimated by empirical equations, some assumption and simplification are applied in ship navigation performance calculation, etc. All of these may make the results not accurate enough. Besides, this is still not a fully functional system, some other function modules like land avoidance module need to be further developed. Since the whole framework of this system works well, there is a reason to believe that the next generation of the ship weather routing system in the future will become more perfect.

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