Voyage Optimization Supersedes Weather Routing

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Introduction

Many weather routing service providers claim the ability to save fuel and increase safety and schedule reliability; yet ships still founder, hundreds of lives are put at risk and more than 5000 containers are lost overboard every year. P&I club reported container total losses have increased one third over 2006 and 2007, and serious partial losses have gone up 270% in the last decade. A major survey conducted by Maritime Economics and Logistics in 2007 revealed that over 40% of the vessels deployed on worldwide liner services arrived one or more days behind schedule.

With exaggerated capabilities and unsubstantiated benefits being advertised by weather routing companies, ship owners, operators and charterers often face the difficult task of selecting the right service provider and level of technology suitable for their operations. Anticipating high fuel prices in years to come and the recent emphasis on reducing greenhouse gas (GHG) emission have resulted in renewed interest in further optimizing ship performance. A recent IMO study (MEPC58/INF.21) indicated that while weather routing can achieve 2% to 4% reduction in fuel consumption and associated GHG emission, as much as 50% improvement can be achieved through technical and operational measures such as speed management and fleet planning.

To achieve such improvements, voyage optimization must take into account the performance characteristics specific to actual ship loading conditions in the ocean environment caused by changing weather. The outdated weather routing technology based on weather avoidance using a set of speed reduction curves cannot be adapted to the new operational requires such as Slow Steaming and Virtual Arrival. Now is the time to review traditional weather routing and to discuss state-of-the-art technologies for voyage optimization as the logical progression toward increasing safety and efficiency of marine transportation as well as improving environmental protection.

All Weather Routing Services Are Not Equal

Traditional shore-based weather routing services, and some of the onboard weather routing programs, operate on the principle of “storm avoidance”. A typical system allows the user to plan a route using a set of generic speed reduction curves (% speed reduction as a function of wave height in head, beam and following seas) to dead reckon ship positions in order to avoid storms as depicted by the lows on surface pressure charts.
After trying out several candidate routes, the recommended route is sent in a brief email/telex to the ship requesting the service, with updates when workloads permit or when requested by the ship. The fuel consumption is estimated based on tonnes per day and number of days to arrive.

Furthermore, such cursory route advisories often do not take into account navigation hazards and shipping lanes. The user has to manually modify the route on ECDIS or nautical charts to ensure safe navigation.

More than 50% of weather routing services are ordered by charterers to monitor their chartered vessel for speed claims. As a result, there are a few “good enough” weather routing companies with minimal technology to perform post voyage analysis. Vessel response to wind and waves is of little concern. The criteria for routing and charter party speed claims are still based on the Beaufort Wind Force Scale, invented in the 1800s, regardless of the size of the ship and loading condition or its reaction to varying forecast wave height period and direction. Consequently, fuel saving is “hit and miss”, when weather routing can lead to unnecessary diversions (i.e. longer distance steamed) to avoid bad weather, compared to a strategy of slowing down to let a storm pass and then catch up to arrive on time.

Jeppesen, a Boeing company, launched the Vessel and Voyage Optimization Solution (VVOS) to deliver a return on investment that exceeds traditional weather routing methods. This article will discuss the effects of key issues in voyage optimization.

![Route plotted on a navigation chart using Jeppesen C-Map Professional Chart. The optimized route can be directly imported into ECDIS for final validation.](image)
Weather Routing Does Not Take Into Account Ship Responses

A ship slows down due to one of two reasons: involuntary speed reduction due to increased resistance from the onset of wind and waves, and voluntary speed reduction due to navigation hazards or fear of heavy weather damage resulting from excessive ship motion, propeller racing, slamming or boarding seas. The weather routing advisory service must take both involuntary and voluntary speed reductions into account when estimating dead-reckoned ship positions in relation to the movement of weather systems; otherwise, the best route perceived by the unknowing planner could lead to a dangerous situation.

One example is the famous m.v. *Derbyshire* incident. Would the master still have taken the action to outrun Typhoon Orchid if he had known that his vessel would be slowed down due to severe motions caused by advancing waves ahead of the eye of the storm? In the case of m.v. *APL China*, how can one responsibly recommend a route if the weather routing software cannot predict the risk of excessive accelerations due to Parametric Roll along that route? More importantly, if the ship speed cannot be accurately predicted using the simplistic speed reduction curves, can the weather routing advisory be trusted, since the dead-reckoned future positions in relation to the forecast storm tract may be wrong?

It is reassuring that some of the weather routing companies have started to realize the limitations of their methods and are trying to develop ship response prediction capabilities. Ship motion theory has been around for decades. To predict ship motions, the first step is to digitize the ship’s body plan, bilge keels and other appendages, and calculate its loading conditions in terms of fore and aft drafts and GM. A sophisticated hydrodynamic program then computes added mass and damping coefficients and solves the equation for motion. The results are the so-called Response Amplitude Operators (RAO), which are then combined with forecast wave spectra to predict ship responses. Only during the last few years have such sophisticated tools become part of the onboard software to provide seakeeping guidance and safe operating limits for ship routing. Figure 2 is an example of a polar diagram that shows the speed and heading combinations (red areas) that will exceed the safe operating limits in forecast wave conditions, providing the Master with immediate guidance in setting the speed and heading to stay within safe operating limits. Figure 3 shows the plot of wave-induced bending moments and shear forces at critical frames for ± 90 degree heading changes from the current ship course.
Since response characteristics can be vastly different for different loading conditions, the computation must be carried out for the ship’s current draft and metacentric height (GM). Shortcuts such as pre-computed RAOs or Warning of Resonance using empirical approaches may lead to dangerous situations and/or unnecessary route diversion. More importantly, such approaches cannot predict Parametric Roll, which occurs when roll and pitch periods have certain ratios, and the ship’s flare immerses in waves.

**Weather Routing Does Not Take into Account Engine Overload**

The competitive nature of the shipbuilding industry and marine classification societies have resulted in reduced design safety margins in ship structures. Shipyards use sophisticated finite element models and high tensile steels to reduce steel weight and production costs in order to be competitive. Similarly, the propulsion systems are often optimized for calm weather trial conditions in order to satisfy the recent IMO requirement on Energy Efficiency Design Index (EEDI). One such design consequence for slow speed diesel engines with direct-drive fixed-pitch propellers is high pitch coupled with minimum acceptable sea margin. With calm weather and a clean hull lightly loaded, the vessel easily makes the contracted speed and good EEDI. Unfortunately, such practice leads to frequent engine overload when the ship is in service encountering high wind/seas and/or as its hull/propeller starts to get rough, resulting higher resistance.

Again, if such events cannot be predicted by the weather routing tools, it can lead to over-predicted ship speed and wrong diversion decisions when facing heavy weather, not to mention inaccurate estimates of fuel consumption and time of arrival.
All Optimization Algorithms Are Not Equal

There has been substantial research over the years in the area of ship routing algorithms. Most of the weather routing software uses variations of the Dijkstra Algorithm, in which the program simulates a vessel departing with full power toward the arrival port with different headings. After each time interval (e.g. six hours), the ship’s dead-reckoned position forms so-called “isochrones” until it arrives at the destination. A route is then traced back from the earliest arrival time, and fuel consumption is estimated using a tons-per-day rate. The premise is that minimum time results in minimum fuel consumption. The solution is fast, especially when only using speed reduction curves and not taking into account ship motion responses or engine overload.

Unfortunately, the problem with such an approach is that the algorithm ignores one important option: speed management. As storms move across the ocean, it is possible for the ship to slow down and let them pass and then catch up, instead of sailing a longer distance to go around or “hove-to” in bad weather. Such strategy not only significantly reduces fuel consumption for a given arrival time, it also reduces the risk of heavy weather damage when fully implemented with ship response and engine overload.

Since speed and heading are both introduced into the route optimization, the problem becomes multi-dimensional. The simple speed reduction curves used in weather routing algorithm simply cannot find the optimum since it operates only in one dimension. Without modeling the ship performance from first principle, it is not possible to minimize the fuel consumption for a given arrival time without exceeding the safe operating limits.

A 3-D Dynamic Programming algorithm can be used to minimize fuel consumption for a range of arrival times subjected to the constraints of safe operating limits imposed by the Master. The optimization is performed on a user-defined grid for safe navigation. Figure 5 shows an example of a range of estimated arrival times versus predicted fuel consumptions over a grid of possible routes. (The green pointer indicates the scheduled arrival time). This allows trade-off between fuel cost versus arrival time.
Figure 5. Optimization using Dynamic Programming in VVOS

The computation effort is obviously greater since the algorithm must evaluate thousands of speed and heading options compared with hundreds in the case of heading-only weather routing; but with computer processor speeds doubling every year, the time to solve the problem is reduced from several hours to a few minutes, including the full implementation of ship responses and engine overload. Such systems can be implemented at routing centers shore-side, or onboard ships with daily updates of forecast environmental conditions via satellite communication.

Routing based on ship responses versus wave height limits

Since VVOS has the capability to use response limits such as roll, pitch, slamming, accelerations, etc., or wave height limits in head beam and following seas, as constraints in the optimization, it is possible to compare the two approaches for the same passage in hindcast weather. Figure 6 shows a comparison between two routes using respective safe operating limits. Both passages arrive at the same time with the one using wave height limits spending 183 tonnes more fuel because the algorithm found a way between two storms without exceeding the limits, whereas the response-based route went above the storms. A more detailed comparison below shows that while the Motion Optimum encountered 7 meter waves, resulting roll and pitch angles were smaller than in 5.3 meter waves.
Fuel saving using speed management instead of constant RPM

Another wrong strategy often used by weather routing service provider is advising the ship to use minimum RPM to arrive on time. This strategy only makes sense in calm weather since low RPM means less fuel consumption and horse power increases as cubic power of ship speed. In severe head sea conditions, the added resistance result 50% or more horsepower required for calm sea in order to maintain speed. VVOS optimizes the speed profile on a single route to arrive on-time by slowing down in head seas and speed up in beam/following seas to catch up after storm passes. Figure 7 shows an example of speed management on a trans-pacific route encountering severe storm in Gulf of Alaska. The following comparison shows the two speed profiles arrived at the same time, with the constant RPM spending 28 more tonnes of fuel, as the ship had to sail through the bad weather, whereas the speed-managed strategy slowed down ahead of the storm and caught up after the storm passed.
All Weather Forecasts Are Not Equal

The advent of Super Computers and numerical models has significantly improved the accuracy of weather forecasts over the past decade. National centers such as NCEP/NOAA, US Navy, UKMET, JMA and ECWF are routinely producing long range wind and wave forecasts for 15 days and beyond. However, the accuracy of each model varies due to model resolutions, how the physics are implemented, and initial conditions from observations as input at the cut-off time, as well as many other factors. Forecasters tend to calibrate their models to perform better when storms threaten their own countries, but pay less attention to mid-ocean storms passing shipping lanes.

None of the models can consistently produce accurate forecasts for tropical cyclones due to the complex physics and rapid development of the cyclones. Human forecasters are employed during the typhoon/hurricane seasons to issue track and intensity forecasts based on consensus of model outputs as well as past experience. In any case, accuracy starts to deteriorate after 3-5 days, leading to even larger uncertainties between 5-7 days.

Most of the weather routing service providers use products from only one forecast center. In the U.S., surface pressure, wind and sea state forecasts are available for free download over the Internet. While the quality of such forecasts may be good enough for weather routing, their level of detail is not sufficient for ship motion response prediction and voyage optimization. This is particularly true in predicting the sea and swells generated by tropical cyclones, since meteorologists at typhoon/hurricane centers often issue vastly different forecasts from the model predictions.

Currently, the best approach to ocean weather forecasts is to adopt a “man-machine” mix, in which experienced forecasters quality-control the sea surface pressure forecasts including the wind fields derived from the track and intensity forecasts from various forecast centers. This forms the input to a marine boundary layer wind model and the output drives a numerical wave directional spectra model. The “Super Ensemble” forecast approach takes the best of each national center forecast and quantifies the uncertainties in wind and waves. At each grid point in every forecast horizon extending to beyond 15 days, the values for mean and standard deviation can be used to judge the accuracy levels of the forecast. The spread between minimum and maximum typically is smaller in shorter range forecasts, as the various models are more in agreement. The spread will increase as the forecast horizon increases and the accuracy of the forecast models differ. This type of consensus knowledge will provide greater insight in selecting the optimum route taking into account the risk of heavy weather damage due to forecast uncertainties.

Figure 8 shows a plot of forecast significant wave height from the ensemble members on a grid point in the North Pacific Ocean. The 7 meter event is unlikely to occur on day 5 as none of the members exceeded 5 meters.
Besides the more accurate wind and wave forecasts, voyage optimization should also take into account sea surface currents, since they can significantly impact ship speed and fuel consumption. High resolution global circulation models enhanced by satellite measurements can now produce accurate depictions of major currents and eddies daily. Figure 9 shows examples of current maps. The 1/32-degree resolution allows the locations of Kuroshio and Loop currents to be clearly identified. The speed and direction at every grid point are used in Jeppesen’s VVOS voyage optimization algorithm.
Benefits of Voyage Optimization

It is clear that past decades of “hit and miss” weather routing approaches can be much improved with today’s technology. Accurate ship seakeeping performance models can help Masters to make better route decisions that save fuel and avoid heavy weather damage. Benefits of voyage optimization can be further extended to the ship design, deployment and operations logistics. Here are some examples:

- Take advantage of SLOW STEAMING to save fuel.
- Implement win-win VIRTUAL ARRIVAL concept between charterers and owners to save fuel cost when arrival port is congested.
- Determine ship design criteria such as speed, sea margin, maximum ship motion and bending moment by repeatedly simulating the voyages using historic wind and wave hindcast databases.
- Optimize the deployment and schedule of vessels for the trade route, taking into consideration schedule reliability, fuel cost and seakeeping capability.
- Estimate the probability of on-time arrival so that shore-side operations such as loading/unloading truck and trains can be efficiently scheduled.
- Extend the fatigue life of ship structures by predicting stress cycles and providing ships’ officers with seakeeping guidance to reduce ship stresses.

Without a doubt, significant benefits in saving energy as well as reductions in GHG emissions can be achieved through technical and operational measures as expressed by the IMO study. The capabilities of weather routing have evolved into the science of voyage optimization in order to bring added benefits in ship design and operational logistics. To achieve such benefits, the key ingredients are:

- Quality-controlled ocean wind and wave predictions with additional Super Ensemble forecasts
- High-resolution tidal currents and global circulation currents
- State-of-the-art full ship motion modeling for actual drafts, GM and loading conditions during the voyage
- A powerful optimization algorithm to find the optimum route with minimum fuel consumption for a desired arrival time and not exceeding the safe operating limits.
- Global wind and wave hindcast database for voyage simulations to establish benchmarks for voyage efficiency and CO2 index
- A method for estimating the probability of on-time arrival taking into account weather forecast uncertainties and ship capabilities.
- Computer-based training to transfer the knowledge to aid operations decision
- Shore-based support centers to assist ships at sea at any time.

Ship operators and owners should be made aware that voyage optimization will result not only in very high Return On Investment (ROI), through increased operating safety and efficiency, but also the benefit of being proactive in reducing GHG to protect the environment.
Yes, the benefits can be proved by using the (Patent Pending) Benchmark process

Obviously, it is impractical to conduct an experiment involving two sister ships with identical loading conditions sailing on the same schedule between the same port pair, with one following the Vessel and Voyage Optimization Solution (VVOS) and the other following a typical weather routing service. However, it is possible to benchmark both methodologies by using historical passages that a ship sailed under weather routing and see if VVOS could have performed better in terms of fuel saving and less vessel motion for the same departure and arrival times. The annualized cumulative savings would indicate the potential benefits of voyage optimization over the existing weather routing services for future voyages.

The following flow chart shows the benchmarking process:

Notice that the resulting performances are relative to the best one can do with and without weather uncertainties removed. For every passage, there is an optimum for the period of the weather between the departure and arrival times. This allows the performance of VVOS and weather routing to be compared on the same basis during good or bad weather. Typically on trans-ocean passages, VVOS has shown up to 5% annualized improvement over the traditional weather routing.

This unique benchmarking process (patent pending) not only allows the management to evaluate how well their current weather routing service provider perform over the years, but also allows them to track improvements and Return On Investment using VVOS.