THE IMPORTANCE OF ADDED RESISTANCE AND SPEED OF SHIPS DUE TO WAVES FOR SHIPS DESIGNED FOR SLOW-STEAMING

by

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The importance of added resistance and speed of ships due to waves for ships designed for slow-steaming

One obvious way of reducing the fuel consumption of ships is to reduce their transit speed. It is currently debated how much energy and thereby CO2 emissions can be reduced by reducing the transit speed, and very low figures – in the order of 5 knots – are mentioned. The analyses have so far mainly been based on calm water conditions. The reason why slow steaming is attractive is that the energy consumption per kilometer is roughly proportional to the speed squared. However, this is true only for calm water and no wind. In realistic, representative weather conditions the conclusion is expected to be quite different, as has already been shown in some preliminary analyses.

Objective

The objective of the Msc project is on this background to further investigate how the inclusion of added resistance and speed loss due to waves and wind influences the fuel and transport efficiency of slow-steaming ships.

In the Msc-project, it is expected that the candidate shall:

1. Give an overview over current knowledge with regards to the effect of slow-steaming on energy consumption and transport efficiency of ships.
2. Carry out a case-study on slow steaming ships, where both calm water (for reference) and realistic weather conditions are included.
3. Discuss how realistic weather conditions influence the optimum speed with respect to energy consumption and CO2 emissions from ship transportation.

The candidate should in his report give a personal contribution to the solution of the problem formulated in this text. All assumptions and conclusions must be supported by mathematical models and/or references to physical effects in a logical manner.

The candidate should apply all available sources to find relevant literature and information on the actual problem.

In the thesis the candidate shall present his personal contribution to the resolution of problem within the scope of the thesis work.

Theories and conclusions should be based on mathematical derivations and/or logic reasoning identifying the various steps in the deduction.

The candidate should utilize the existing possibilities for obtaining relevant literature.

The thesis should be organized in a rational manner to give a clear exposition of results, assessments, and conclusions. The text should be brief and to the point, with a clear language. Telegraphic language should be avoided.

The thesis shall contain the following elements: A text defining the scope, preface, list of contents, summary, main body of thesis, conclusions with recommendations for further work, list of symbols and acronyms, reference and (optional) appendices. All figures, tables and equations shall be numerated.

The supervisor may require that the candidate, in an early stage of the work, present a written plan for the completion of the work. The plan should include a budget for the use of computer and laboratory resources that will be charged to the department. Overruns shall be reported to the supervisor.

The original contribution of the candidate and material taken from other sources shall be clearly defined. Work from other sources shall be properly referenced using an acknowledged referencing system.

The thesis shall be submitted in two copies:

- Signed by the candidate
- The text defining the scope included
- In bound volume(s)
- Drawings and/or computer prints that cannot be bound should be organized in a separate folder.
- The bound volume shall be accompanied by a CD or DVD containing the written thesis in Word or PDF format. In case computer programs have been made as part of the thesis work, the source code shall be included. In case of experimental work, the experimental results shall be included in a suitable electronic format.

Supervisor : Sverre Steen
Start : 17th of January 2011
Deadline : 14 June, 2011

Trondheim

Supervisor

Sverre Steen

Preface

This Master thesis is written in the 10th and last semester of the Marine Technology Master study and is counting as 30 credits. It is written at the department of Marine Technology at the Norwegian University of Science and Technology in Trondheim, Norway. The time available to work on the Master thesis is 20 weeks.

I want to thank my supervisor Professor Sverre Steen for the help and guidance on this Master thesis, Professor Dag Myrhaug with getting wave statistics for the Atlantic Ocean, Senior Research Engineer Dariusz Fathi, Research scientist Edvard Ringen and Research Scientist Bjørn Ola Berge at Marintek for helping me with ShipX. I will also thank the librarians at Marine Technology Library at Tyholt who have helped me collecting good and useful articles about Slow Steaming.

Carl Arthur Sunde
Trondheim 2011-06-14

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Nomenclature

Symbol	SI unit	
B	[m]	Ship (model) beam
Cr	[-]	Resistance coefficient
D	[m]	Moulded depth
Dwt	[kg]	Deadweight tonnage, a measure of how much weight a ship safely can carry
g	$[m/s^2]$	Acceleration of gravity
h	[m]	Propeller shaft immersion
Hs	[m]	Significant wave height, mean of the 1/3 highest waves
J	[-]	Advance coefficient
K_Q	[-]	Torque coefficient
K_T	[-]	Thrust coefficient
L	[m]	Length
LOA	[m]	Length overall
LPP	[m]	Length between perpendiculars
m_0	$[m^2]$	Spectral moment
m_1	$[m^2/s]$	Specral moment
P_B	[W]	Break power
P_E	[W]	Effective power
R	[m]	Propeller Radius
R_{AW}	[N]	Added resistance
Rt	[N]	Total ship resistance
T	[m]	Mean draught
T	[N]	Propeller thrust
t	[-]	Thrust deduction factor
t	[s]	Time
T_1	[s]	Mean period in the wave spectrum
T_p	[s]	Peak wave period
T_z	[s]	Zero crossing period
V_A	[m/s]	Advance velocity
w	[-]	wake fraction
Δ	[kg]	Weight displacement
η_0	[-]	Open water efficiency
η_H	[-]	Hull efficiency
η_M	[-]	Mechanical efficiency
η_R	[-]	Rotative efficiency
η_T	[-]	Total efficiency
ξ_A	[m]	Wave amplitude
λ	[m]	Wave length
∇	$[m^3]$	Volume displacement
ω	[rad/s]	Wave frequency
ρ	$[kg/m^3]$	Water density
σ_{AW}	[-]	Non dimensional added resistance

MCR	Maximum continuous rating
RAO	Response Amplitude Operator
TEU	Twenty-foot equivalent unit, a measure used for cargo capacity for
ULCC	Ultra Large Crude Carrier, more than 320 000 dwt.
VLCC	Very Large Crude Carrier, 160 000 - 319 999 dwt.
	container vessels

Summary

In the recent years the greenhouse effect in the atmosphere has become much stronger because of emissions of greenhouse gases on the earth. One of these gases is CO_2. This may come from combustion of fossil fuel. The international shipping fleet emitted 1046 million tons of CO_2 in 2007, which corresponds to 3.3% of all CO_2 emission in the world. The increase intensity of the greenhouse effect leads to global warming, which can affect the human life heavily. Ice melts, sea level increase, lands will disappear in the water, lead to heat waves, starving people, more widespread of infections, and etc. Because of this there have to be a reduction of these greenhouse gases soon. The ship fleet is expected to grow in the coming years, so the only way to reduce the emissions is to manage a strong reduction for each vessel. There have been many ideas around this, and one up and coming is Slow Steaming. This is that the vessel is reducing the velocity, which corresponds to reduced necessary break power, which may reduce the emissions. One ship operator which have tried out the slow steaming concept is The A.P. Møller Mærsk group. They have slowed down the speed on some of their container vessels from 25 knots to 20 knots (slow steaming) and also tried out 12 knots (super slow steaming). They have by reduced the speed to the half, reduced the fuel consumption and greenhouse gas emissions by 30%. But to compensate for reduced service frequency there are two options: Increase cargo capacity of the vessels or put in additional vessels on the route. Both options are reducing the profit, both environmental and economical.

In this master thesis there has been performed a case study to look closer to the power prediction when reducing the velocity. Three vessels have been analyzed: a VLCC, a chemical tanker and a container vessel. These have been analyzed in the hydrodynamic workbench ShipX. A route from Le-Havre in Europe to Charleston in America has been applied in ShipX. Since waves are important in break power predictions due to added resistance, both summer season and winter season have been analyzed. The resistance was predicted by the empirical methods Holtrop 84, while the added resistance was calculated by using Gerritsma & Beukelman's method. For each velocity and each vessel was it calculated an optimal propeller (Wageningen B-series). As expected the break power increased exponential for increasing speed for all three vessels in calm water condition, summer season and winter season. But when I looked closer to an added factor, which is the proportion between break power respectively in summer/winter season over calm water, this was largest for low speeds and decreased when the speed was increased. This means relatively the wave contribution of necessary break power is largest for low speeds. An example of this is that for four to six knots with the container vessel, the break power in calm water had to be multiplied by 2.2 (120% increase) to get real break power in summer waves. The added factor for 24 knots was only 1.21 (21% increase).

When it comes to optimum speed for a vessel, realistic weather conditions have a strong influence here. In realistic weather both size of waves and direction of waves are varying. If the ship is traveling in small waves, the optimum speed will be much higher than if it's going in rough sea states. There is also big difference if there is head sea, beam sea or following sea. Other factor for finding an optimum speed for a vessel is economic (profit versus costs), value and durability of cargo, demand of transportation, engine performance and etc.

1 Introduction

In the recent years there has been a major focus on environment, especially emissions of greenhouse gases as CO_2. Despite the international shipping is small in the big picture, it emitted 1046 million tons of CO_2 in 2007, which represent 3.3% of total CO_2 emissions in the world. It is expected that the international shipping fleet will increase in the future, while scientists say the greenhouse gas emissions must decrease in the future, to prevent the global warming to do too much damage. Because of this the maritime industry has to start to think about reducing emissions from the fleet. There have been done a lot of work about this topic recent years, where researchers, scientists, ship owners, classifications societies, politicians and ship designers have presented ways of reducing the emissions. Measures that have been discussed are radical change of within ship design (like Rolls-Royce Wave Piercing Design, Ulstein X-bow and the new STX design), natural gas as main fuel source, wind assisted propulsion, discussion about nuclear powered ships, carbon capture and storage on ships and finally slow down the vessels to reduce the emissions and at the same time save some costs.

Reducing the velocities, also known as slow steaming, is one of the solutions several parts believe on. There have been done some studies on slow steaming for container vessels, but most of them have been done for calm water conditions. This is a condition which very rarely occurs. It is important to include the waves in the analyses, preferably realistic weather conditions, and look how much the wave influences on the power prediction for varying velocities.
It is also important to consider that if today's vessels are slowing down, they are travelling outside the velocity range that they are designed for. This also includes the engines. The performance of the engines will also change when using this for a lower load than what it is designed for.
In this Master thesis will I tell a little about environmental issues, like greenhouse effect and global warming and introduce you to the concept Slow Steaming. The main assessment in this Master thesis is to do a case study where I look at a container vessel, a VLCC and a chemical tanker, how the power prediction varies if the vessels slow down, how much the waves influence on the necessary break power to maintain the planned speed. To give an analysis about this I will use Marintek's hydrodynamic workbench, ShipX. I have planned a route between Europe and America, and used wave statistics for the Atlantic Ocean in summer and winter season. At the end I will take a look at how realistic weather influences the optimum speed for a vessel.

The hypothesis for the case study is that the wave influence on necessary power of the tankers and container vessel will be relatively largest for low speeds, while it will decrease with increasing vessel velocity.

2 CO_2 emissions

In the recent years there has been a major focus on the environment, especially emissions of greenhouse gases as CO_2. Despite that maritime transportation is small in the big picture, it emitted 1046 million tons of CO_2 in 2007, which corresponds to 3.3% of the world's total emissions. CO_2 are one of the gases which contribute to strengthen the greenhouse effect. The greenhouse gsses forms a layer in the atmosphere which absorbs thermal radiation from the earth surface, and re-radiated in all directions. This is the greenhouse effect. There is both a natural greenhouse effect and a human contribution caused by burning fossil fuels. Because of this, the temperature on the earth will increase. In Figure 1 can you see graphically how the greenhouse effect works.

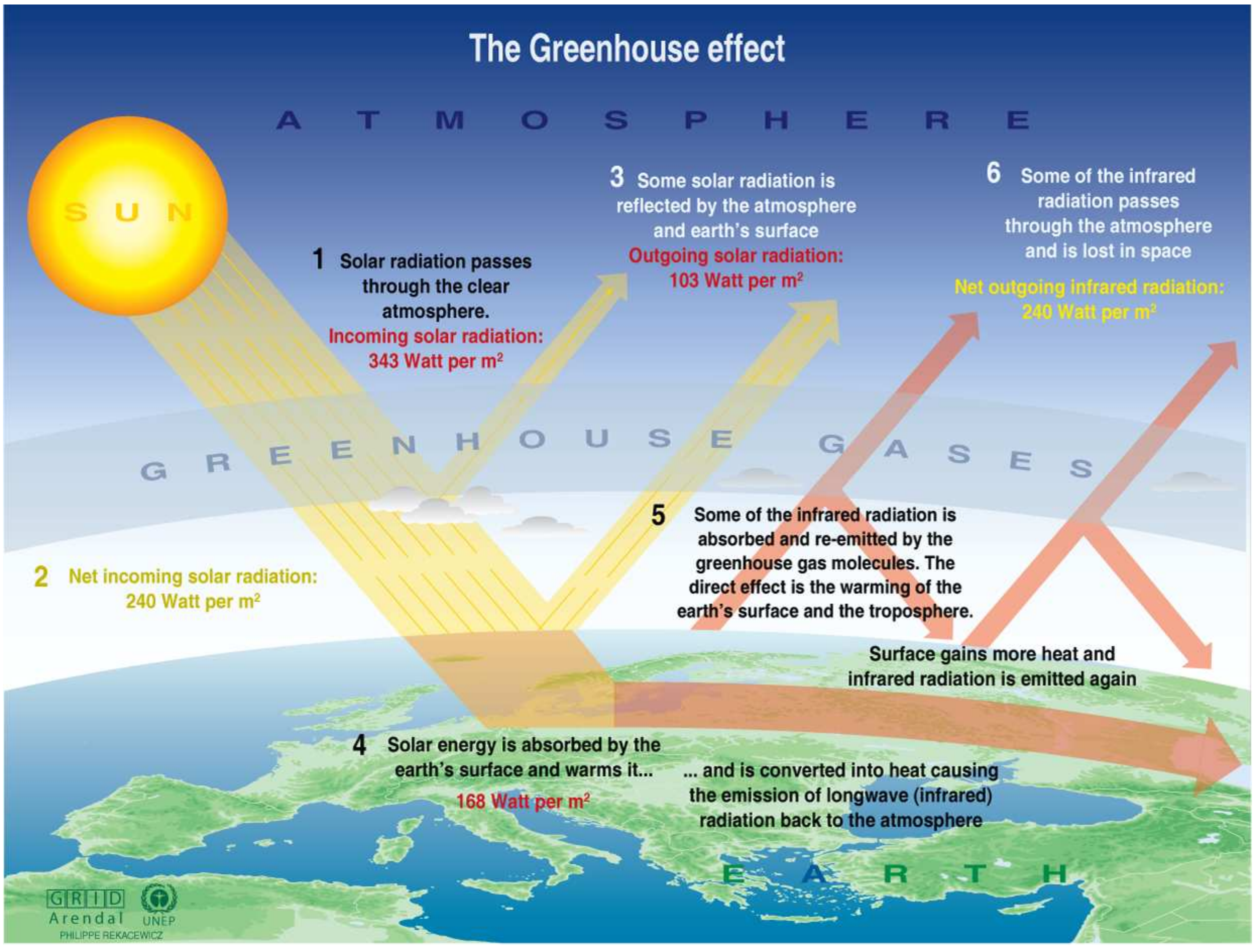


Figure 1- The Greenhouse effect [Ref. 12]

There are many possible consequences of the greenhouse effect, emission-rate of greenhouse gases keeps going like predicted. Natural Resources defense council made a list of some of these [Ref. 13]

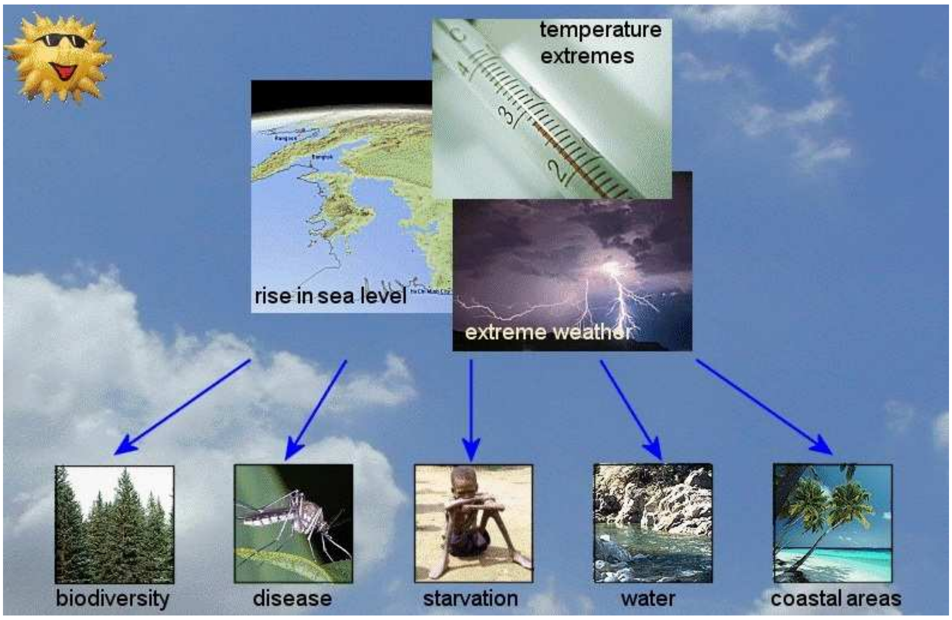


Figure 2- Some consequences of global warming [Ref. 14]

The global warming might have consequences in the weather pattern around the world. Warmer climate on the earth leads to warmer water in the oceans. This means that the oceans pump more energy into tropical storms, making them stronger and potentially more destructive. Warmer temperatures will also increase the probability of drought. Increased evaporation in the summer and fall could also increase the risk of wildfire. The rise in temperature increases the energy of the climatic system, and can lead to heavier rainfall in some areas.

There might also be health related consequences. A rise in the global average temperature might result in more frequent and severe heat waves. This might lead to greater number of heat-related deaths. Global warming could also increase the smog pollution and intensify pollen allergies and asthma. It could also result in aggravate local air quality problems, as already is a problem in many cities. The temperature rise in addition to drought, deluges and ecosystem disruption have contributed to more like malaria, dengue fever and diarrheal illnesses. This is the greatest problem for people living in poverty. A warmer atmosphere can hold and dump more water, and can contribute to more dangerous intense weather events. An example of this is the hurricane Katrina, which stroke New Orleans very hard in 2005. It forced 1,7 million people to evacuate, and lead to deaths and long-term health problems for 200 000 residents.

A warmer climate doesn't only affect us humans. It also affects the animals and the wildlife on the earth. The rise in temperatures is expected to disrupt ecosystems, pushing to extinction those species that cannon adapt. A comprehensive assessment of this risk concluded that more than 1 million species could be obliterated by 2050 if the current trend continues. An example on a wildlife problem caused by global warming, are that some polar bears are drowning because they

Figure 3- Problems with ice melting [Ref. 15]

have to swim longer distances to reach the ice floes.

Another consequence of the rise in temperatures, are an increase the speed of the melting of glaciers and ice caps, and cause early ice thaw on rivers and lakes. According to NASA the polar ice cap is melting with 9 percent per decade. Since the 1960s the arctic ice thickness has decreased with 40 percent. As a result of the melting of glaciers, ice caps, partial melting of the West Antarctic and Greenland ice caps, and a thermal expansion of the oceans, the sea-level is expected to increase. This may lead to loss of coastal wetlands and barrier islands, and a greater risk of flooding in coastal communities. In the past century the sea level has already risen by ten to twenty centimeter. The Intergovernmental Panel on Climate Change predicts that the sea levels could rise by twenty-five to sixty centimeter by 2100. Greenland consists of ten percent of the total global ice mass on the earth. If all ice on Greenland melts, the sea level might rise by up to 6.4 meters.

3 Slow steaming

In times when there are much focus on the environment and emissions, combined with high fuel prices and recently done with a financial crisis, the shipping industry starts to think in new ways to reduce the fuel economy and emissions. In today's market, the demand of fast transportation has lead to a much higher speeds on these transportations vessels than maximum fuel efficiency [Ref. 16]. One strategy there have been some discussions about lately is slow steaming. This is a strategy for long distance transportation, particularly for the containerships. The reason for this is that they travels with high velocity (around 25 knot), and despite the containerships represent just 4% of the world ship fleet they stands for 22% of the fuel consumption and CO_2 emissions in the fleet. Slow steaming is that the vessels reduce the velocity from 25 knots (design speed) to around 20 knots. They have also discussed to take this strategy even further, and introduce super-slow steaming. Then they reduce the speed from 25 knots to around 12 knots. By doing this they reduce the fuel consumptions and CO_2 emissions even more.

By looking on the largest containerships (like the largest containership, Emma Maersk, in Figure 4), with a design speed on 25 knots, they need around 70.000 kW to travel at this speed. By introducing the slow steaming strategy, and reducing the speed to 20 knots, the main engine will require only 50% of this power. [Ref. 17]

Figure 4- Emma Maersk, the world's largest container ship [Ref. 18]

The largest container ship operator and supply vessel operator in the world, The A. P. Moller - Maersk group, introduced both slow steaming and super-slow steaming for their container vessel during the recession. They were doing this for several reasons: To reduce emissions, cut costs and to absorb capacity. They want to become an environmental friendly ship operator, in addition to the economical profit of doing it. Since Maersk reduced the speed to the half, these vessels have reduced the fuel consumptions and green house gas emissions by 30%. By doing this they become a role model to save the environment and costs have been greatly reduced. [Ref. 16]

But even if international shipping industry represents 3,3% of worlds total emission [Ref. 1] and the container vessels travels with a high speed (higher than maximum fuel efficiency), shipping at design speeds is far more efficient than road travel, mile per mile. Shipping a ton of toys from Shanghai to northern Germany chums out lower emissions than the truck-ride south to Berlin afterwards [Ref. 19]

CEO in Maersk Line, Eivind Kolding said to "The journal of commerce [Ref. 20]:
"It is better for our customers, better for the environment, and better for our business"
"*While some customers have complained about longer inventory time -- in essence, with Maersk Line ships as floating warehouses -- the analysis is that slow steaming helps prevent bottlenecks on terminals"*

When the financial crises stroke the hardest, the slow-steaming did another favour to the international shipping industry. Then it didn't just save energy and reduced the emissions, it also took containers out of circulation. By doing this, they stopped the rates from tail-spinning, in times when the demand after container transportation decreased so the shipping companies had to fight for the few contracts and had problems with filling up the ships. In fact, slow steaming absorbed 4.1% of the fleet at one point. This helped to balance the supply and demand.

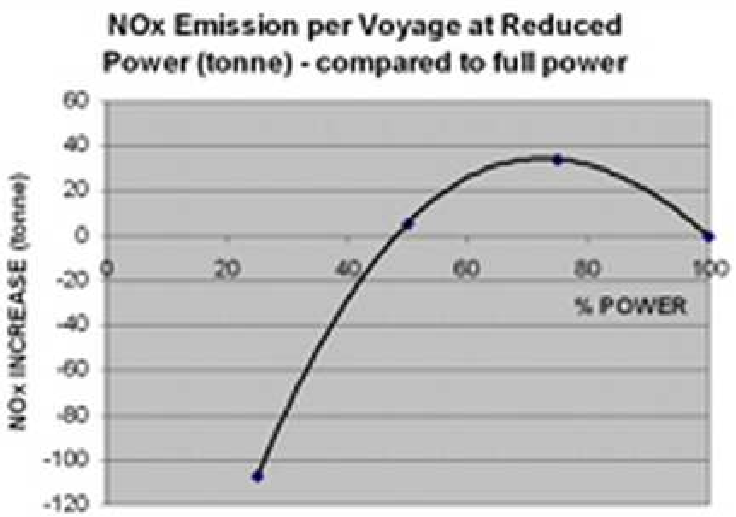


Figure 5- NOx emissions at reduced power [Ref. 21]

As every other discussion, there are both pros and cons. Lloyds Register is one part that has dismissed the slow steaming concept [Ref. 27] Today's container vessel are designed and built for operating at around 25 knots. This includes both the ship design and engines. When these vessels are slow steaming they have to be more closely monitored to avoid loss of engine performance over time, fuel quality and lubrication oil consumption when moving below 20 knots. As the voyage time increases, the fuel savings would be less. The largest fuel savings will be for the first percents speed loss. As the speed is further decreased, the fuel savings will be less. It is also said that when the speed is slowed in this way, the NO_X-emissions will increase (see Figure 5). The vessels will also experience waste engine capacity and higher capital costs from unused power potential. Other areas it would affect is losses in heat recovery systems, turbocharger and propeller efficiency. The hull and propellers would also have more problems with fouling. Marine engines and their attached propellers are generally optimized for 85% of maximum RPM. When the vessels are slow steaming, they are operating at around 70% MCR. Even new electronically controlled engines have significant drop in efficiency because of this. Poor combustion results in soot deposits that retard the boiler performance, and increases the fire risk. To compensate for the lower load of the main engines, the fuel consumption of the auxiliary engines will increase to supplement loss of heat recovery capability, the lubricating oil consumption will increase, and the noise and vibration level may also increase. This may risking safe, reliable ship operations and comfort on the vessel.

When a shipping company introduce slow steaming on their cargo routes, the service frequency decreases, as the transportation time between the harbours increases. To compensate for this, there are two scenarios. You can see the CO_2 reductions against speed reduction in Figure 6.
-Scenario one: The vessels can carry more containers to meet constant container demand.
-Scenario two: Additional ships are added to the route to serve existing demand.

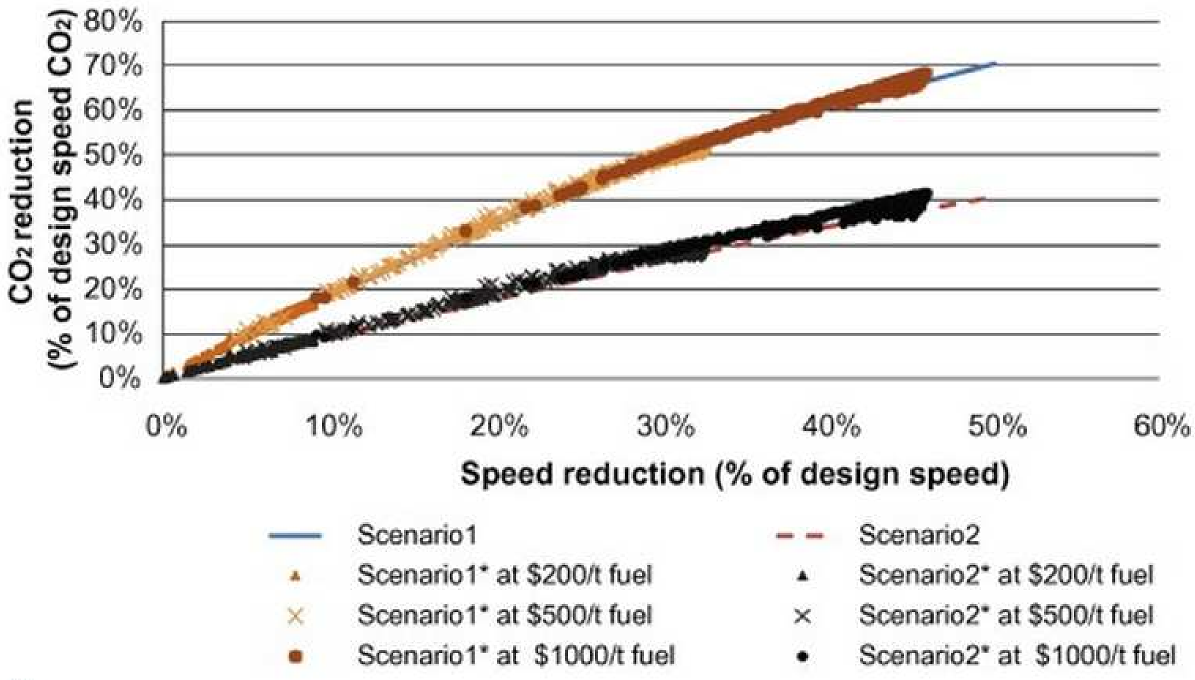


Figure 6- CO2 reduction against speed reduction [Ref. 2]

The first scenario is hard to go for when the shipping companies are using the same vessels as before. To go for this first scenario the vessels have to be designed for this, but at this point it is too risky to do this. It is expected that within few years IMO will regulate the CO_2 emission, and maybe at that time it would be more safe to go for scenario one. Now, the shipping companies have added an extra container vessel to the route, and in this way they can meet the existing demand. GLG Research has looked closer to the slow steaming concept, and found some limitations to this [Ref. 22]. On the route between Asia and Europe, the shipping companies are going from an eight vessel fleet to nine vessels route if slow steaming. In this way the entire transportation loop are slowed down, which are resulting in greatly fuel savings. But this 9th vessels offset is only valid with a very high fuel price. GTG Research stated that there is a limit how far the slow steaming concept can be taken. If the speed is reduced much more than this limit:
-The net fuel savings diminishes as combustion efficiency suffers
-Cargo limitations come into play, as the greater transit time become unacceptable to perishable and time-sensitive
-The main engine maintenance and the risk of main engine casualty increases.

4 ShipX

ShipX is a very helpful and popular hydrodynamic workbench, developed by MARINTEK (Norwegian Marine Technology Research institute)[Ref. 3]. It is a common platform to use for ship design analyses. The main aim of ShipX is that input should be given once during the design process.

The structure of ShipX is module-based, with a main program *ShipX workbench* working as a user interface. From here the user can load the plug-ins he prefers to use. This is smart way of using programs, since the companies may just buy the plug-ins they need, and save some money instead of buying unnecessary plug-ins. Another good reason for this plug-in structure is that the requirements to the computer aren't too high.

When using ShipX, the database browser will always be showing. There you can see an overview over the active fleet with the different properties of the ships. In addition to the properties to the ships there is a category where the user can set some common settings, like properties of seawater, tank water, shell plating and preferred units.

4.1 Ship Speed & Powering

With this plug-in the user can predict performance, resistance and speed loss due to waves for both conventional and high speed vessels [Ref. 4]. It is designed to be a tool where both calm water calculations and speed loss calculations are performed with a minimum amount of input data. The speed loss for vessels in waves consists of two types of speed loss: Voluntary and involuntary speed loss. Voluntary speed loss is due to the captain reduces the thrust for safety/comfort-reasons, while involuntary speed loss is due to increase in total resistance and that the propeller thrust decreases. There are three speed loss components considered in the calculations here:
-Added resistance in waves
-Thrust loss due to ship motions in waves
-Wind resistance

To calculate the speed loss due to waves, we need to do the calm water calculations. Inputs we need to do this are the hull-, propulsion- and resistance data. When we have done this we just need the added resistance and Response Amplitude Operator (RAO). To find this we have to use the plug-in Vessel Response (VeRes).

An important part of the calm water calculation is to find the resistance. In Ship Speed and Powering plug-in there are many ways to do this. The most common ways to do this for conventional displacement vessel is:
-Specify residual resistance coefficient (Cr) curve
-Holtrop 84
-Hollenbach 98
-Specify total ship resistance (Rt) curve
Both Cr-curve and Rt-curve can be found by model-tests or by solving it numerically.

4.1.1 Performance prediction

It is important to predict the performance to the vessels, like thrust, rate of revolution, engine power required and total efficiency. When you have the total resistance R_T of the vessel and the thrust deduction factor t, you can find the required propeller thrust as:

$$T = \frac{R_T}{1-t}$$

Further can you find the advance velocity from the ship velocity V and the wake fraction w:

$$V_A = V(1-w)$$

The program finds the advance coefficient J from the open water diagram to the propeller, and then you can find the rate of revolution by using this, advance velocity and diameter of the propeller D:

$$RPM = \frac{60 * V_A}{J * D}$$

And you can calculate total efficiency:

$$\eta_T = \eta_0 * \eta_H * \eta_R * \eta_M$$

Where η_0 is open water efficiency, η_H is the hull efficiency, η_R is the rotative efficiency and η_M is the mechanical efficiency.

When you have the advance coefficient J, the total efficiency P_E can be calculated, and required engine power P_B at a given speed can be found:

$$P_B = \frac{P_E}{\eta_T}$$

Where effective power is defined as:

$$P_E = R_T * V$$

4.1.2 Speed loss theory and methods

Speed loss calculations require a big set of input data: We need the resistance in calm water, the added resistance, the propeller and engine properties, and also the wave spectrum if the calculations are based on irregular sea states.

The added resistance R_{aw} is extra resistance in addition to the calm water resistance. It is often presented in a non-dimensional form σ_{aw}:

$$\sigma_{aw} = \frac{R_{aw}}{\rho * g * \zeta_a^2 * B^2/L}$$

Where ζ_a is the wave amplitude, B is beam – and L is length in waterline.

The added resistance is often divided in two components: Added resistance due to reflection of waves and added resistance due to ship motions. The reflection-component decreases when the wavelength ship length ration increases, and the ship motion component increases when λ/L -> 1, and decreases when λ/L > 1. You can see this relation in Figure 7.

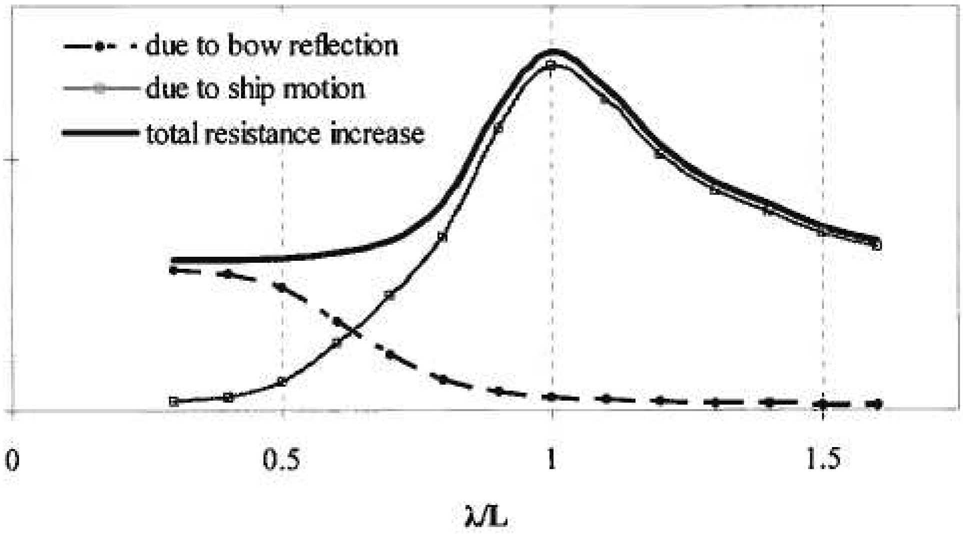


Figure 7- The two components of added resistance, and total resistance increase [Ref. 4]

When the vessel enters waves, the propeller efficiency may decrease. There are many reasons for this. When a ship moves in waves, the submergence of the propeller changes. This may lead to ventilation and cavitations. If the motions are extreme, parts of the propeller may go out of the water, and will result in a significant drop in thrust and torque. In addition will the blade section use some time to build up the lift again after it has been out of the water, a phenomenon called Wagners effect. When parts of the propeller are out of water, the thrust and torque are reduced with a factor approximate equal to the relative loss in wetted propeller disc area.

When the vessel is approaching waves, we have to correct the open water diagram. For regular waves we have to find the thrust diminution factor β, which is developed by Faltinsen et al. Since coupled relations between instantaneous values of revolutions, immersion, thrust, torque and speed for a ship moving through waves are hard to determine, we choose to use a time average over the wave periods for thrust, torque and resistance. We then have this relation for thrust and torque:

$$K_T = \bar{\beta} * K_{T0}$$
$$K_Q = \bar{\beta}^m K_{Q0}$$

Where m is a constant between 0.8 and 0.85.
We can also find the relationship between propeller shaft immersion h and radius of the propeller R in regular waves:

$$\frac{h}{R} = \frac{h_0}{R} + \frac{s_a * \sin(\omega t)}{R}$$

Where h_0 is the propeller shaft immersion in calm water, s_a is the relative vertical motion amplitude between the ship and free surface at propeller position and t is time.

For irregular waves it is assumed to be long crested waves and narrow band process. The wave spectrum are divided into successive parts for each sea states, each such element of the wave spectrum consists of a regular wave set with an amplitude ζ_a and circular frequency ω. For each regular wave part we find one value for the amplitude of the relative motion s_a. In addition to this we use a mean value of β & β^m and obtaining $\bar{\beta}(s_a)$ and $\bar{\beta}^m(s_a)$. By using this we can find $\bar{\beta}$ and $\overline{\beta^m}$:

$$\bar{\beta} = \int_0^\infty p(s_a)\bar{\beta} ds_a$$
$$\overline{\beta^m} = \int_0^\infty p(s_a)\overline{\beta^m}\, ds_a$$

Where $p(s_a)$ is the probability density function for the amplitude of the relative motion described by a Rayleigh distribution.

For regular waves the speed loss calculation consists of the thrust reduction and combining this with tabulated values for ship resistance, propeller thrust and engine characteristics to find the forward speed where the resistance and thrust are in equilibrium. This is done by an iterating process where the difference are calculated of nominal speed, then decreased or increased according to this force difference, and then calculating the force difference again. By doing this until the difference it within a small margin, the program can find the correct vessel speed in waves, and find out the speed loss from the nominal speed.

To find the speed loss in irregular waves, we have to use the same assumptions as we did in correction of open water diagram. By using Lounget-Higgins joint probability density function:

$$f(\xi,\eta) = \left(1 + \frac{\nu^2}{4}\right)\frac{1}{\sqrt{2\pi\nu}}(\frac{\xi}{\eta})^2 e^{-\frac{\xi^2}{2}[1+\left(1-\frac{1}{\eta}\right)^2\frac{1}{\eta^2}]}$$

Where $= \frac{\xi_a}{\sqrt{m_0}}$, $= \frac{T}{\bar{T}}$, $\bar{T} = 2\pi\frac{m_0}{m_1}$ and the spectral width parameter $\nu = \sqrt{\frac{m_0 m_2}{m_1^2} - 1}$
By finding these parameters, we can find the speed loss in a given sea state by solving for the weighted average of the speed losses for each regular wave component (by using the probability density function as weight):

$$\overline{V_{loss}} = \iint_0^\infty V_{loss}(\xi,\eta) f(\xi,\eta) d\xi d\eta$$

4.1.3 Simplifications and limitations

There isn't any engine model in Ship Speed & Powering, so it will underestimate the speed loss in waves due to increase resistance. Since we are dealing with empirical methods to estimate the characteristics and behaviours, we have to be careful with the results. Don't be sure the results are always reliable. For example details in bulb and bow shape might influence the residual resistance more than 10%, something these empirical methods do not take it into account.

4.2 Vessel Responses (Veres)

Veres can be used to calculate motion responses, global loads and other parameters due to waves [Ref. 5]. The calculations can be done for all the range from zero forward speed to high speed. The study of wave induced vessel responses is important, because it influence both operability of the vessels in seaways and the comfort for the crew. Veres can be applied on both monohulls and catamarans in the whole range of speeds. For low and moderate speeds, with Froude number, Fn, up to 0.3, it can be solved by traditional strip theory, developed by Salvesen, Tuck and Faltinsen. At higher speeds Fn>0.4, the high speed formulation developed by Faltinsen and Zhao can be used. In the Fn range 0.3-0.4, a comparison between the two methods should be carried out.

To optimize the operability of the vessel in seaways, it is important to minimize the motions of the ships. To study this you can use the vessel response plug-in. When we minimize the motions, the loads will decrease and can reduce the steel weight. Another benefit from doing these studies are to increase the comfort and safety for crew and passengers.

The vessel response plug-in is divided into two major calculation parts. A main program used for calculating the transfer functions for motions and loads and perform time simulations. The postprocessor part helps the user with reporting, data presentation and further calculations based on the transfer functions.
Veres is based on linear strip theory. In linear theory, the wave loads and motions are linearly proportional to the wave amplitude, so we can obtain the results in irregular waves simply by adding together results from regular waves of different amplitudes, wavelength and propagation directions. To simplify even more, steady-state conditions are assumed, so there are no transient effects present due to initial conditions. Because of this the linear dynamic loads on the body are harmonically oscillating with the same frequency as the wave loads that excite the body:

$$\omega = \omega_0 + \frac{\omega_0^2 U}{g} \cos \beta$$

Where ω is the frequency of encounter, ω_0 is wave frequency and U is the forward velocity.

Since the potential damping is low, Veres includes viscous damping in order to predict the roll motions. There are three components of viscous damping included in Veres:
-Frictional damping caused by skin friction stresses on the hull
-Eddy damping caused by pressure variation on the naked hull
-Bilge keel damping
The viscous damping terms are non-linear due to quadratic viscous damping terms, and are solved by using iteration technique.

4.2.1 Simplifications, limitations and assumptions

The theory applied in the vessel response plug-in is based on linear, potential strip theory. This means that the program is developed for moderate wave heights inducing moderate motions on the vessels where the length is much larger than breadth and draught. In addition the change in cross-sectional area should be low when moving in longitudinal direction. Because of these simplifications, large ships in large waves will not give too accurate results. However, ship motions obtained by the program show good correlation with experiments even at wave conditions which are outside the limits of the theory. Some other assumptions are that transient effects due to initial conditions are not accounted for, hydro elastic effects are not accounted for, assumed to be a linear relation between the responses and the incident wave amplitude, the vessel is assumed to be slender and the vessel is symmetric about the centreline.

Because of the slender ship assumption we reduces the three dimension problem may be reduced to a set of two dimensional problems along the hull. This will save a lot of computational time. The disadvantage of this is that three dimensional effects are neglected. Since it is used potential theory to calculate hydrodynamic forces, which will not account for viscous effects. However viscous effects should be accounted for in roll, since potential damping is low. This is done by empirical formulas.

5 The case study

5.1 The models

5.1.1 KVLCC2

Maritime & Ocean Engineering Research Institute (MOERI) have developed two different variants of VLCC (Very Large Crude Carrier) tankers, KVLCC1 & KVLCC2 [Ref. 23]. The first variant has more V-shaped stern frame lines. The second variant, which is included in my study, has more U-shaped stern frame-lines. In Figure 8 you can see the shape of this tanker.

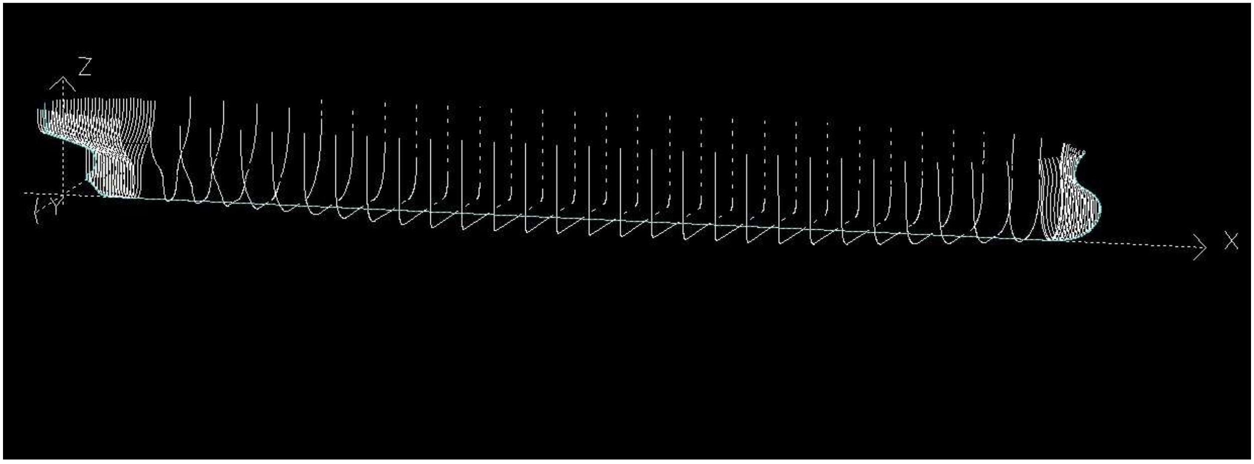


Figure 8- The KVLCC2 (From ShipX)

The main characteristics of the KVLCC2 for design waterline can you see in Table 1.

Table 1- Main characteristics of KVLCC2

Characteristics	
Length between perpendiculars (LPP)	333.50 m.
Length overall (LOA)	320.00 m.
Breadth overall (B_{max})	58.00 m.
Moulded depth (D)	28.00 m.
Mean draught (T)	20.80 m.
Volume displacement (∇)	312 693.30 m^3

5.1.2 R3D Chemical tanker

Here is a figure of the R3D chemical tanker (Figure 9):

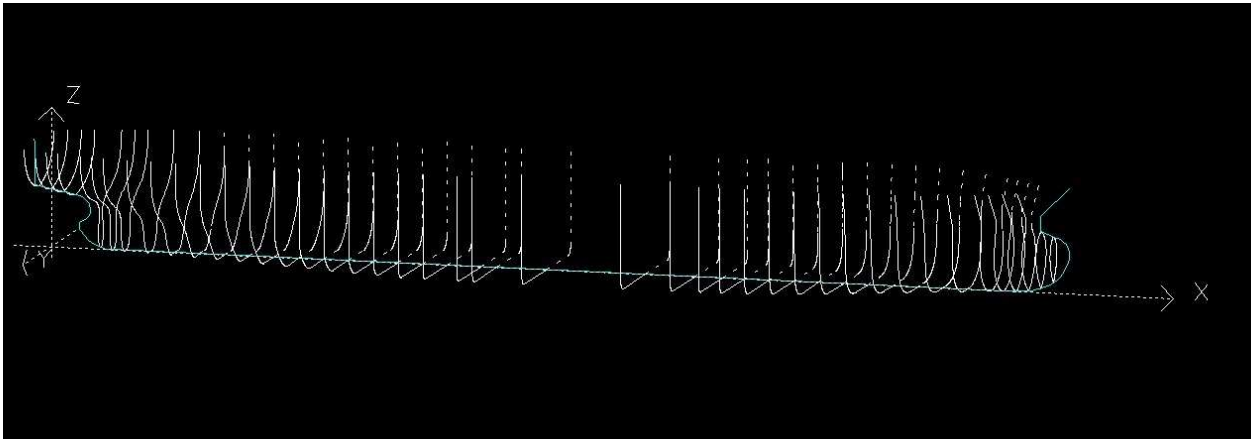


Figure 9- The R3D chemical tanker (From ShipX)

The main characteristics for design waterline can you see in Table 2:

Table 2- The main characteristics for the R3D chemical tanker

Characteristics	
Length between perpendiculars (LPP)	183.11 m.
Length overall (LOA)	175.00 m.
Breadth overall (B_{max})	32.20 m.
Moulded depth (D)	18.50 m.
Mean draught (T)	10.60 m.
Volume displacement (∇)	46 664.79 m^3

5.1.3 R3D Container vessel

You can see a figure of the R3D container vessel in Figure 10:

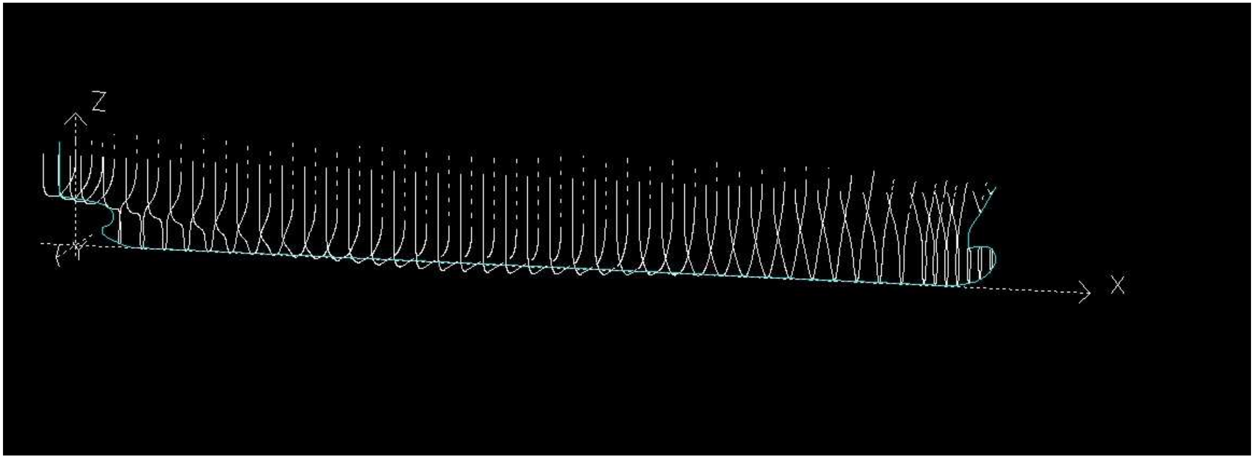


Figure 10- The R3D container vessel (From ShipX)

The main characteristics for the design waterline can you see in Table 3:

Table 3- The main characteristics for the R3D container vessel

Characteristics	
Length between perpendiculars (LPP)	244.32 m.
Length overall (LOA)	233.00 m.
Breadth overall (B_{max})	32.20 m.
Moulded depth (D)	26.00 m.
Mean draught (T)	11.00 m.
Volume displacement (∇)	47 213.79 m^3

5.2 The route

One of the first assignments I had to do to in this master thesis was to find a common route for container vessels and tankers. I had to find wave data for this route, find out how far it was between the ports and so on. After some searching I found one typical route is between Europe and America. I decided to analyze the vessels between Le Havre in France to Charleston in South Carolina. Le Havre was the first and is the biggest container port in France [Ref. 24]. It is accommodating 60% of traffic in containers and 40% of export oil. Charleston port is placed in South Carolina, has a deep water port, so it is no problem to handle container ships and tankers [Ref. 25]. In Figure 11 can you see how I have planned the sailing route, and how it goes through four different wave areas (Area 16, 17, 23 and 24).

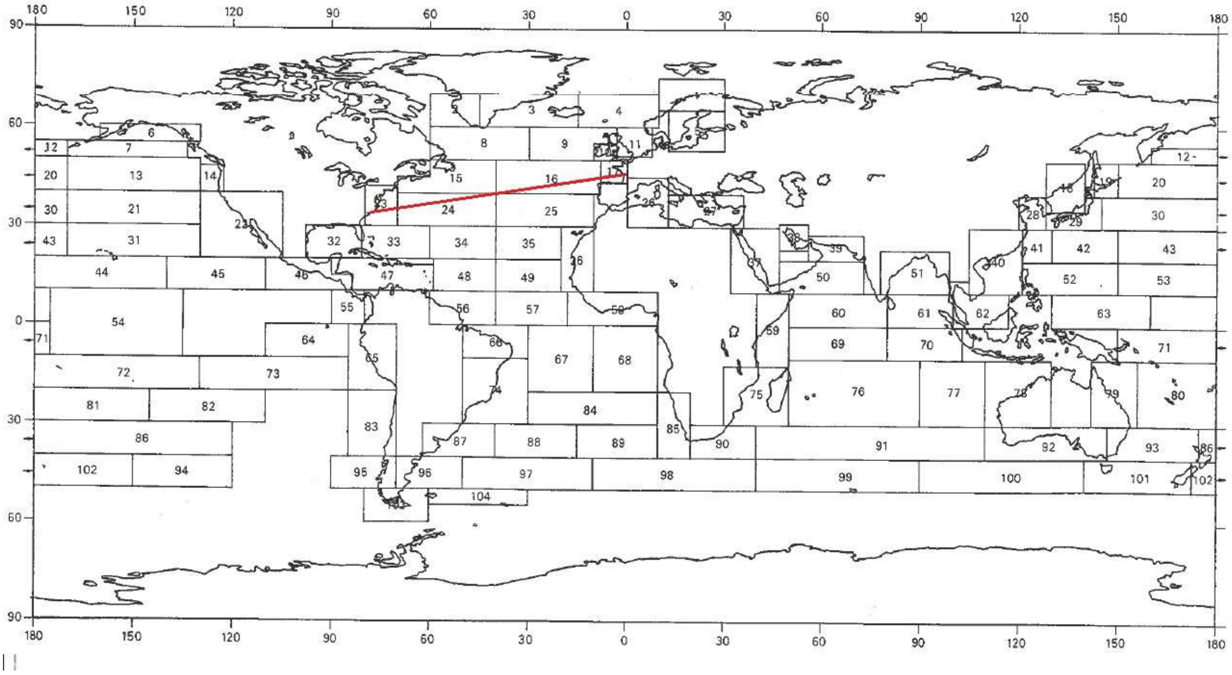


Figure 11- The planned route between Le Havre and Charleston [Ref. 6]

The distance between Le Havre and Charleston, South Carolina, is 6700 km = 3618 nautical miles. The route is showed in Figure 11 by a red line. By using the map and a ruler, I found out how to divide the route into the four wave areas. In Table 4 can you see how big parts in each area.

Table 4- Distances in each area, collected from Global wave statistics

	Distance on map	[-]	Parts [%]	In full scale	[-]
Distance from Europe to America				3618	Nm
Distance on map	6	Cm	100		
Distance in area 16	2.4	Cm	40	1447.2	Nm
Distance in area 17	0.6	Cm	10	361.8	Nm
Distance in area 23	0.7	Cm	11.7	422.1	Nm
Distance in area 24	2.3	cm	38.3	1386.9	Nm

5.3 Waves and wave data

As mentioned did I collect the wave data from the book "Global Wave Statistics", compiled and edited by British Maritime Technology Limited [Ref. 6]. By using the map showed in Figure 11 I found out my route will go through four of the Area subdivisions in the North Atlantic. This was area 17, 16, 24 and 23. For each area we can find scatter diagrams for annual period and for each season. For each period the scatter diagrams are divided in 8 different directions (North, North East, East, South East, South, South West, West and North West). In addition there are a scatter diagrams which sums up all directions. After recommendations from Marintek, because of the work load, I chose to use the scatter diagram for each direction, and let ShipX distribute the waves around the vessels.

The data in Global Wave Statistics are collected by ships around the world have reported visual observations of wave height, period and direction. This has been done since 1949. Wind speed and directions and wave heights in a coarse code have been reported since 1854. All this data have been collected by World Meteorological Organization (WMO). The British Maritime Technology Limited have used this data, and made statistics of them. The first version of this wave statistics was published in 1967 and covered 50 sea areas involving about a million sets of visual wave observations. Now the seas around the world are divided in 104 subdivisions, and the statistics are more precise. The scatter diagrams given in this book are reporting the middle value of the range.

When ShipX are supposed to make waves in the hydrodynamic analysis, it needs to make a wave spectrum from the wave data input. There are two choices here: JONSWAP and Pierson-Moskowitz (PM). Since JOSWAP are short for JOint North Sea Wave Project, it is based on waves in the North Sea. Pierson-Moskowitz spectrum however is based on data from the North Atlantic, just where this route goes.

First we consider spectrums on this form [Ref. 11]:

$$S(\omega) = \frac{A}{\omega^5}\exp\left[-\frac{B}{\omega^4}\right]$$

These spectrums are valid for fully developed sea states at open oceans, and consist of one top with a steep front for low frequencies. You can see this in Figure 12.

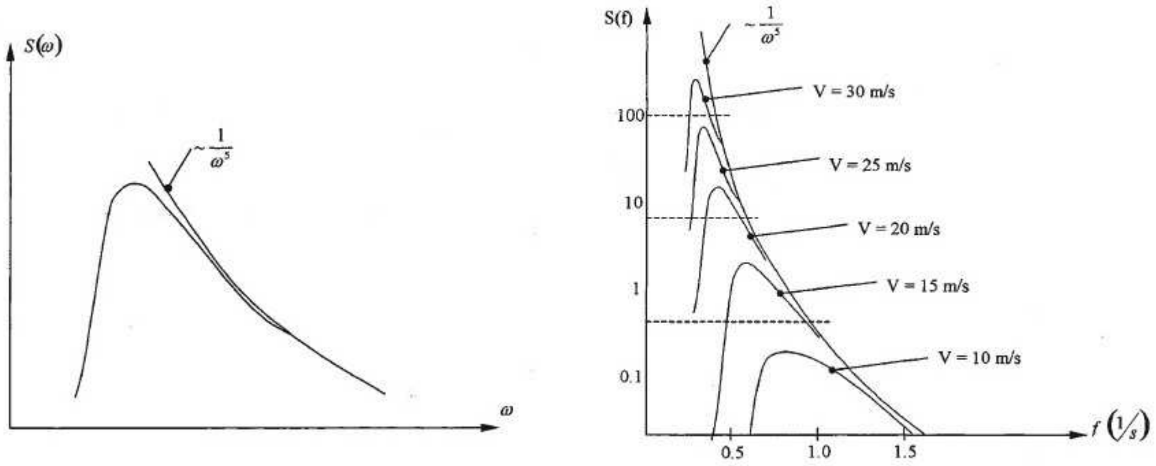


Figure 12- Pierson-Moskowitz spectrum, to the right the spectrum for increased wind speed U [Fig. 5.6 & 5.7 from ref. 11]

To get the Pierson-Moskowitz spectrum we have to define A and B:

$$A = 0.0081 * g^2$$

$$B = 0.74 * \left(\frac{g}{U}\right)^4$$

$$S(\omega) = \frac{0.0081 * g^2}{\omega^5} exp\left[-\frac{-0.74 * \left(\frac{g}{U}\right)^4}{\omega^4}\right]$$

where g is the gravitation constant (acceleration) and U is the wind speed 19.5 meter above the sea surface. From Figure 12 we can see that a PM spectrum is set up such that the curve will go against $\frac{1}{\omega^{-5}}$ when $\omega \rightarrow \infty$. In the right figure above we can see how the Pierson-Moskowitz develops for increasing U.

In this analysis it has been used scatter diagrams for June to August, and December to February for area 16, June to August and December to February for area 17, June to August and November to March for area 23, and June to August and December to February for area 24. By using these I have divided it in one analysis for summer season and one analysis for winter season. To make the analysis input progress easier, ShipX have a route input function. There can the user state which scatter diagrams that will be included in the analysis, and how long distance the vessel will go in each area.

In Appendix A3-A10 can you see the scatter diagrams I have used in my analysis, how the scatter diagram input for ShipX should be set up in A1, and in A2 how the route input should be set up.

5.4 The analysis

5.4.1 Resistance prediction

When performing a Ship Speed and Powering analysis in ShipX, there are five different ways to calculate the resistance for the vessel:

- Artificial neural network
- Specify C_R curve
- Holtrop 84
- Hollenbach 98
- Specify ship resistance (R_T) curve

For this analysis the empirical resistance prediction methods was the most useful. After some discussion with my supervisor, we decided to use Holtrop 84 resistance prediction method in this analysis. This because it gives valid and conservative results in resistance prediction.

This method is described by Knut Minsaas and Sverre Steen in the "Ship Resistance" compendium [Ref. 8]. It is based on regression analysis of approximate 300 ships with varying dimensions and form coefficients. Holtrops method is a bit outdated, since it was based on ships in 1984. So the user has to be careful and critical to the resistances. The total resistance coefficient is formulated as:
$C_T = C_F(1+k) + C_{APP} + C_W + C_B + C_{TR} + C_{BTO} + C_A$
where subscript T, F, App, W, B, TR, BTO and A stands for total, friction, appendages, wave, bulb, Transom stern, thrusters openings and correlation. k is the form factor.

The formula used to find the wave resistance R_w is this:
$R_w = k_4 * k_5 * k_6 * \Delta * \rho * g * exp[k_7 * F_N^d * k_8 * cos(\lambda * F_N^{-2})]$
Where $k_{4\text{-}8}$ are constants, Δ is volume displacement, ρ is the water density, g is gravity-acceleration, F_N is Frouds number and λ is approximately:
$\Lambda \approx 1,446 * C_P - 0,03*(L/B)$
where C_P is prismatic coefficient, L is length in waterline and B is Breadth.
Resistance due to bulb is:

$$R_B = 0{,}11 * \exp[-3 * P_B^{-2}] * F_{NI}^3 * A_{BT}^{1{,}5} * \frac{\rho * g}{1 + F_{NI}^2}$$

where F_{NI} are Froude's number based on immersion, A_{BT} is transverse bulb area, and P_B is defined as:

$$P_B = 0{,}56 * \frac{\sqrt{A_{BT}}}{T_F - 1{,}5 * h_B}$$

T_F is draught at forward perpendicular and h_B is distance to the centre of gravity of the bulb area above the keel.

This method requires the after body form and ship propulsion system to be specified. Experience from Marintek shows that calculations with bulb (C_B) gives strange results, and the results varies strongly with different geometries of the bulb. Because of this should bulbous effects applied with care. Often would you get better prognosis when you are skipping the bulb in the calculations.

Since the assignment in this master thesis was to look close the slow steaming concept, and not examine a specific ship, there is not included appendages and thruster openings in this analysis. This may affect the resistance of the vessel, but not so much that it affect the slow steaming trend.

5.4.2 Vessel response in waves

The theory used in the VEssel RESponse (VERES) is based on linear, potential, strip theory [Ref. 5]. This means there are some limitations and restrictions in the program to get valid results:

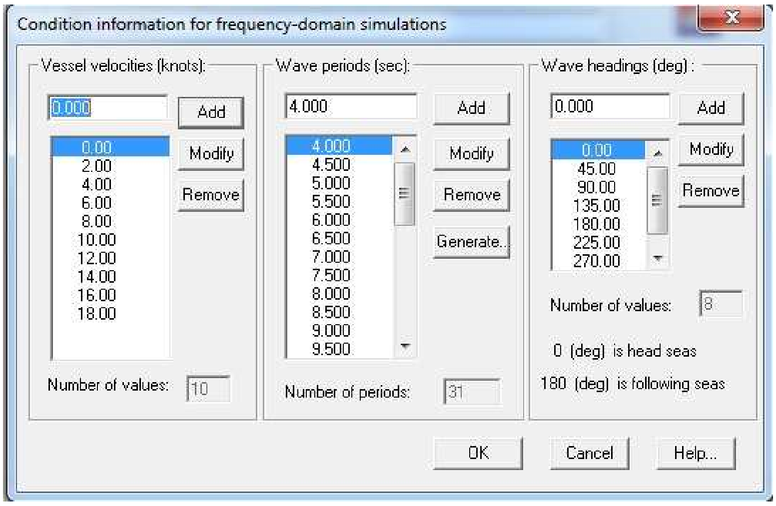
- It is developed for moderate wave heights and moderate ship motions
- The length must be much larger than the beam and draught
- The change in cross-sectional areas as a function of longitudinal position should be slow

As mentioned, the Vessel Response analyses are done by using 2D strip theory formulation. This is developed by Salvesen, Tuck and Faltinsen.
To calculate the added resistance in waves, there is to different approaches available in ShipX [Ref. 5]:

-Gerritsma & Beukelman
-Pressure integration

The method of Gerritsma & Beukelman is derived from energy considerations and the resulting equation gives the added resistance in terms of quantities that are relatively insensitive to how well the local flow around the ship is resolved. On the other hand, the direct pressure integration method needs accurate values for the flow variables along the water line and on the ship hull. Gerritsma & Beukelman is based on the generalized approach of Loukakis and Sclavounos [Ref. 5]. They have extended the method to oblique waves and so the calculations are no longer restricted to head sea. This method is known to give conservative estimates of the added resistance. The pressure integration method is the most accurate results for head to beam sea with Froude numbers over approximately 0.2. After I found this information about the added resistance methods available in ShipX in the Veres theory manual [Ref. 5], I decided to use the Gerritsma & Beukelman method.

The last thing we have to do before we can run a Veres run is to describe the wave environment. Here the user has to insert information about different vessel velocities, wave periods and wave headings. You can see the condition information box in Figure 13. The wave periods should be chosen so the range is enough to make the wave spectrums in the Ship Speed & Powering analysis. Here the user also has to specify which wave heading he wants to use for the speed and power analysis.


Condition information for frequency-domain simulations

Vessel velocities (knots): 0.000
0.00
2.00
4.00
6.00
8.00
10.00
12.00
14.00
16.00
18.00
Number of values: 10

Wave periods (sec): 4.000
4.000
4.500
5.000
5.500
6.000
6.500
7.000
7.500
8.000
8.500
9.000
9.500
Number of periods: 31

Wave headings (deg) : 0.000
0.00
45.00
90.00
135.00
180.00
225.00
270.00
Number of values: 8

0 (deg) is head seas
180 (deg) is following seas

Figure 13- The condition information description from ShipX Veres UI

The user also has to fill in some vessel descriptions, as the radii of gyrations. For this ship models, all the information was already inserted, except for the Radius of gyration in roll (r_{44}). In the Veres Manual, it is stated that the radius of gyration in roll should be in the range 0.30*B - 0.45*B. I chose to use these values for the three models:
- KVLCC2: 23.2 m. (0.4*B)
- Chemical tanker: 12.88 m. (0.4*B)
- Container vessel: 12.88 m. (0.4*B)

5.4.3 Ship Speed and Powering analysis

5.4.3.1 Transverse projected area

One substantial parameter when it comes to Ship Speed and Powering analysis is the Transverse (front) projected area. This is the area the wind force works on (in the front). Both tankers and container vessel do have a large area in front over the water line. Tankers are often wide, with some height between the sea level and the gunwale, and have a high and wide superstructure. When it comes to the container vessel, there they have stacked containers high in the air, and creating a very big transverse projected area because of that. It was hard to find a comparison ship for the tankers, where the front projected area was stated, so I had to find some pictures of typically oil tankers and chemical tankers, where I used the same proportions for the superstructures.

Figure 14- Some VLCC comparison ships [Ref. 28 – 31]

First we need some information about the hull (Table 5):

Table 5- Principal hull data for KVLCC2

Data	Value
Breadth (B)	58.00 m.
Draught (T)	20.80 m.
Depth (D)	28.00 m.

First we have to find the area projected area of the hull. This is how much area the hull has over the sea surface:

$$AF1 = B * (D - T) = 58.00 * (28.00 - 20.80) = 417.60\ m^2$$

Then we have to find the front projected area of the superstructure. As mentioned I used same proportions as some comparison VLCC ships. Then I compared this with the breadth for KVLCC2. You can see how I did this in Figure 15.

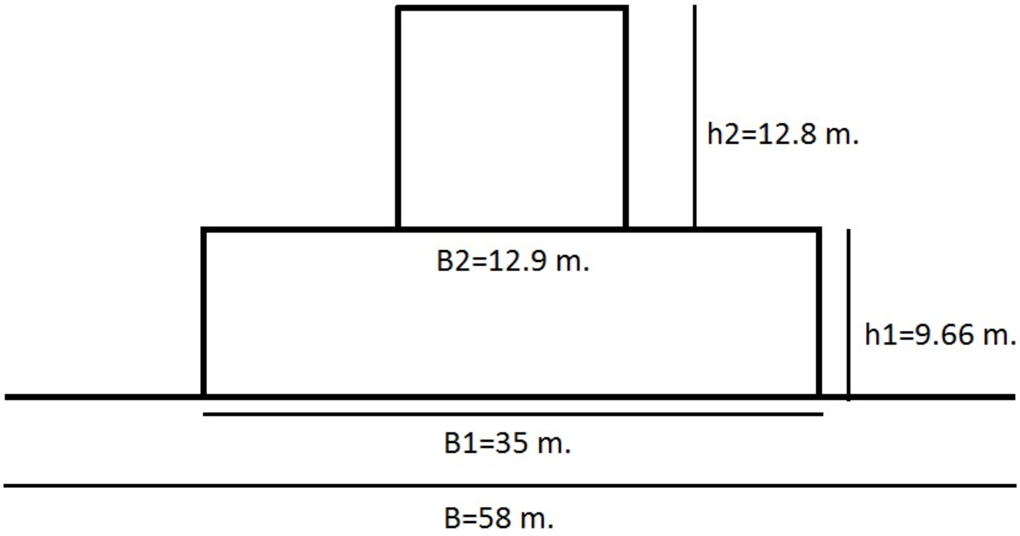


Figure 15- Dimensions on the superstructure on the KVLCC2

Then it was possible to find the transverse projected area for the superstructure:

$$AF2 = (35.00 * 9.66) + (12.90 * 12.80) = 503.22\ m^2$$

Total transverse projected area for the KVLCC2 will then be:

$$AF = AF1 + AF2 = 417.60\ m^2 + 503.22\ m^2 = 920.80\ m^2$$

For the R3D chemical tanker I had to do it the same way. The principal hull data for this vessel can you see in Table 6:

Table 6- Principal hull data for R3D chemical tanker

Data	Value
Breadth (B)	32.20 m.
Draught (T)	10.60 m.
Depth (D)	18.50 m.

The transverse projected hull area, between the sea surface and the gunwale is so large in this case:

$$AF1 = B * (D - T) = 32.20 * (18.50 - 10.60) = 254.38\ m^2$$

For the superstructure on the chemical tanker I did it some easier. I estimated this as a rectangle, with breadth equal to 25 m. and the high equal to 12 m. Then would the transverse projected area for the superstructure be:

$$AF2 = B1 * h1 = 25.00 * 12.00 = 300.00\ m^2$$

Finally can we get the complete transverse projected area for the chemical tanker:

$$AF = AF1 + AF2 = 254.38 + 300.00 = 554.38\ m^2$$

When I was supposed to find the transverse projected area for the container vessel, I used a comparison ship in *Maneuvering Technical Manual* [Ref. 9]. In Table 7 you can see the dimensions of this comparison ship and the R3D Container ship:

Table 7- Dimensions of comparison ship and the R3D container ship

	Comparison ship	R3D container vessel
Length between perpendiculars (Lpp)	194.51 m	233.00 m
Breadth (B)	30.50 m	32.20 m
Draught (T)	11.60 m	11.00 m
Transverse projected area	857.06 m^2	1030 m^2

Since the breadth is almost equal, the draught is almost equal, the only severe difference is the length of the ships. Longer ship means higher superstructure. Since the exact value for the transverse projected area is not too important to find, we assumes a approximately transverse projected area are the area for the comparison ship multiplied with the scale between the two ships.

5.4.3.2 Speed loss analysis

To perform the speed and powering analysis, I used scatter diagrams for summer and winter season. For each season I used scatter diagrams for four different wave areas. Instead of performing one run for each area, the ShipX has a route-function where the user can specify which scatter diagrams that will be included in the run, where they are saved, and how long distance the vessel is sailing in each area. In Appendix A2 can you see how the route-input should be set up.

When it comes to wind resistance, the Ship Speed and Powering estimates this. By using the transverse projected area, some wind coefficient depending on what kind of vessel it is dealing with and the formula under to find the wind speed, this plug-in computes the wind resistance. The formula to find the wind speed is like this:

$$V_{wind} = \sqrt{\frac{9.81 * Hs}{0.21}}$$

where Hs is the significant wave height.

For a cargo vessel, the wind resistance coefficient, C_x will vary as a function of wind direction like this:

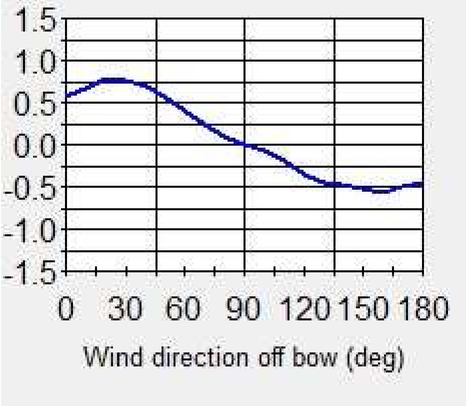


Figure 16- Wind resistance coefficient as a function of wind direction (From ShipX)

5.4.3.3 Propulsion data

For all three vessels did I use the Wageningen B-series propeller, with fixed pitch, and every propeller have four blades. Wageningen B-series is perhaps the most extensive and widely used propeller series. It is a general purpose, fixed pitch, non-ducted propeller that is used extensively for design and analysis [Ref. 4]. The propeller diameter for each propeller is designed due to the different speeds in calm water, by using the optimum propeller wizard.

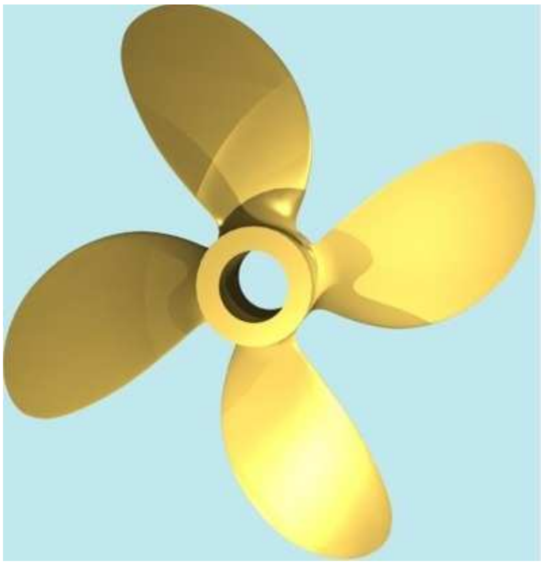


Figure 17- Wageningen B-series propeller [Ref. 26]

When using the optimum propeller wizard, we can find the optimum propeller diameter for a given speed by inserting some data:
-Design power (for that given speed)
-Rate of revolutions (RPM)
-Design speed
-Gear/shaft losses in %
-Number of propellers
-Number of blades

Then can the wizard use Burrills formula to estimate Blade area ratio, A_e/A_0, and then find the optimum propeller diameter. Burrills formula will also check that cavitation is avoided. When the propeller diameter changes, it will increase/reduce the available speed for the same power as before, so the user have to go through the wizard again. This is an iteration process until the really optimum propeller diameter is reached. How the optimum propeller diameter varies as a function of the speed for the different vessels will be shown in the Result chapter.

5.4.4 Results

In this master thesis, one of the assignment was to analyse three different vessels, a VLCC tanker, a chemical tanker and a container vessel, with varying speed, in calm water, with summer waves and winter waves (2 different season conditions). In addition it has been performed an optimization of the propeller for each vessel for each speed. In this chapter I will present the optimal propeller diameter for each speed, the performance prediction for varying speed, both in tables and diagrams. In the next chapter will there be a discussion around the results in this analysis.

5.4.4.1 KVLCC2

The optimal diameter for the propeller is estimated for calm water conditions. It is done this way because I don't think it is realistic for a ship to change propellers when it goes from one season to another. The optimal diameters, optimal pitch ratios (P/D), Blade Area Ratios (A_e/A_0) and propulsion efficiency η_D for the KVLCC2, as a function of speed, can you find in Table 8 and in Figure 18:

Table 8- The optimal propeller data for KVLCC2

Design speed	Optimal diameter	P/D	A_e/A_0	η_D
4 knots	2.95 m.	0.6	0.439	0.325
6 knots	3.562 m.	0.6	0.514	0.377
8 knots	4.07 m.	0.6	0.556	0.416
10 knots	4.52 m.	0.6	0.592	0.445
12 knots	4.868 m.	0.62	0.642	0.466
14 knots	5.173 m.	0.655	0.717	0.481

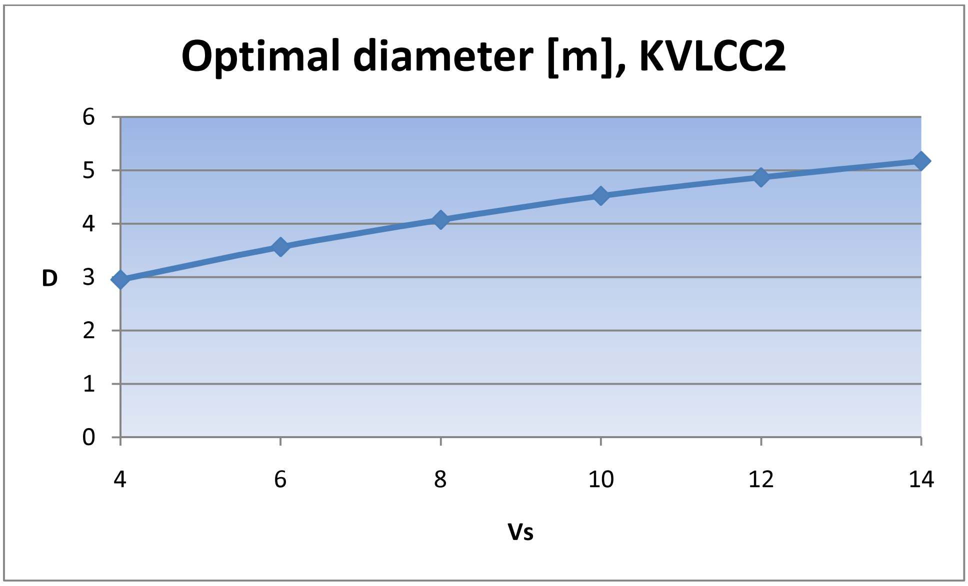


Figure 18- The optimal propeller diameter for KVLCC2 against the speed

The optimal propeller diameter was further used in the calm water analysis, where I studied the power requirement for different speeds. This is the way most previous studies on slow steaming have been done. In Table 9 and in Figure 19 can you see how much break power the tanker need for different speeds.

Table 9- Break power in calm water as function of speed for KVLCC2

Vessel speed	Break power
4 knots	1054 kW
6 knots	2876 kW
8 knots	5807 kW
10 knots	10125 kW
12 knots	16148 kW
14 knots	24247 kW

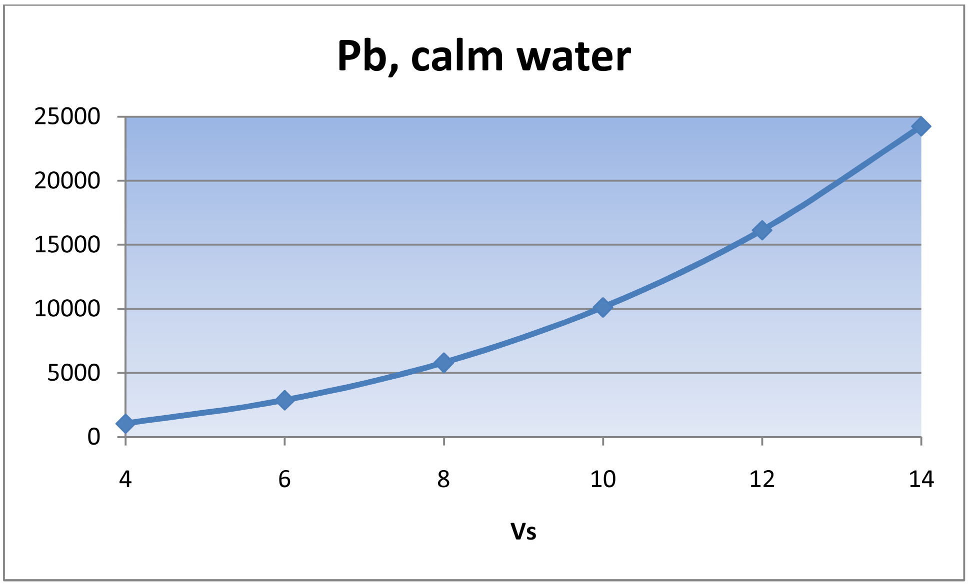


Figure 19- Break power in calm water as a function of speed for KVLCC2

But calm water is a very rare condition for a ship in traffic. The most of the time the ship have to move in waves, which varies from season to season. That is why I have both analyzed the three vessels in summer waves and winter waves. First I will show the results for the KVLCC2 in summer waves. In Table 10 and Figure 20 you can see necessary break power in summer waves as a function of the speed.

Table 10- Break power in summer waves, as a function of speed for the KVLCC2

Vessel speed	Break power
4 knots	2328 kW
6 knots	5421 kW
8 knots	9709 kW
10 knots	15503 kW
12 knots	23605 kW
14 knots	33865 kW

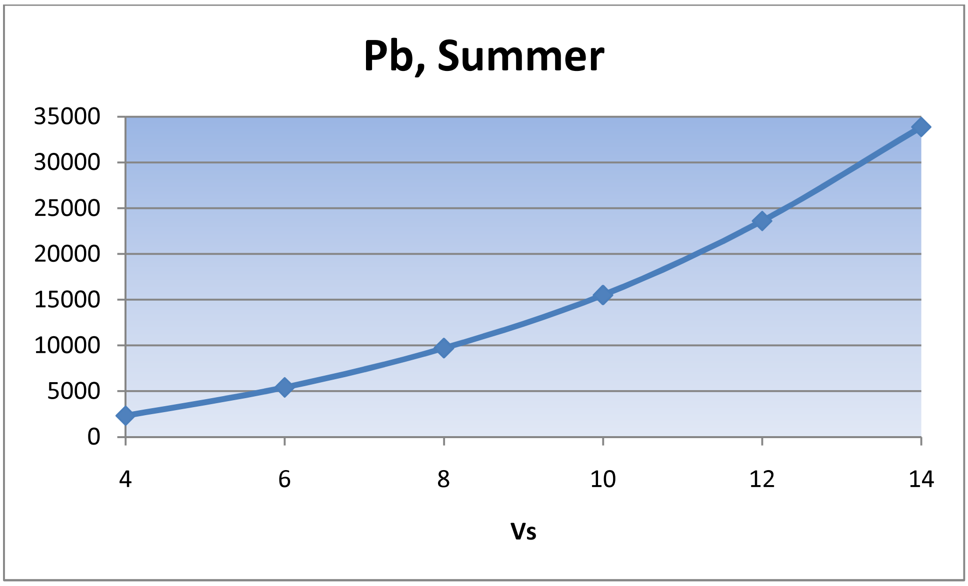


Figure 20- Break power in summer waves, as a function of speed for the KVLCC2

Then can we see how much break power needed in winter waves for the KVLCC2 in Table 11 and Figure 21:

Table 11- Break power in winter waves, as a function of speed for the KVLCC2

Vessel speed	Break power
6 knots	5101 kW
8 knots	10960 kW
10 knots	18961 kW
12 knots	29879 kW
14 knots	42514 kW

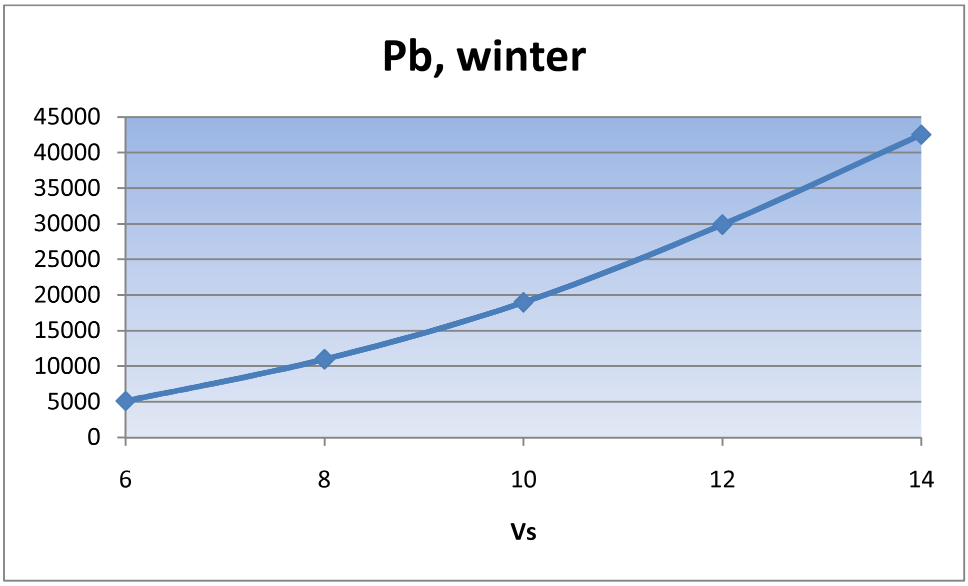


Figure 21- Break power in winter waves, as a function of speed for the KVLCC2

The Ship Speed and Powering plug-in for ShipX had problems to estimate break power for less than six knots in winter waves. When the break power was increased the program estimated an unrealistic high speed for the vessel.

5.4.4.2 Chemical tanker

Then can we look at the optimal diameters, optimal pitch ratios (P/D), Blade Area Ratios (A_e/A_0) and propulsion efficiency η_D for the chemical tanker in Table 12 and in Figure 22:

Table 12- The optimal propeller diameter data for chemical tanker

Design speed	Optimal diameter	P/D	A_e/A_0	η_D
6 knots	2.516 m.	0.619	0.353	0.455
8 knots	3.009 m.	0.637	0.427	0.507
10 knots	3.395 m.	0.662	0.489	0.541
12 knots	3.738 m.	0.69	0.55	0.564
14 knots	4.076 m.	0.716	0.61	0.577
16 knots	4.418 m.	0.746	0.698	0.579

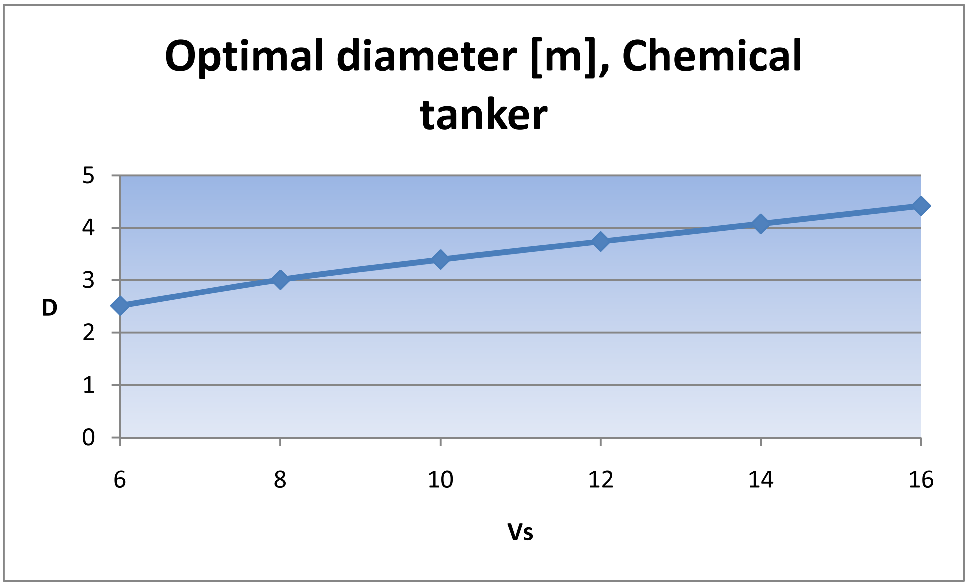


Figure 22- Optimal diameter for R3D chemical tanker against the speed

This information did I use further in the power prediction analyses. The chemical tanker was first analyzed in calm water condition, as reference when performing analyses with waves. In Table 13 and Figure 23 can you see how the break power increases with the speed:

Table 13- Break power in calm water, as a function of speed, for the chemical tanker

Vessel speed	Break power
6 knots	707 kW
8 knots	1473 kW
10 knots	2641 kW
12 knots	4348 kW
14 knots	7023 kW
16 knots	11507 kW

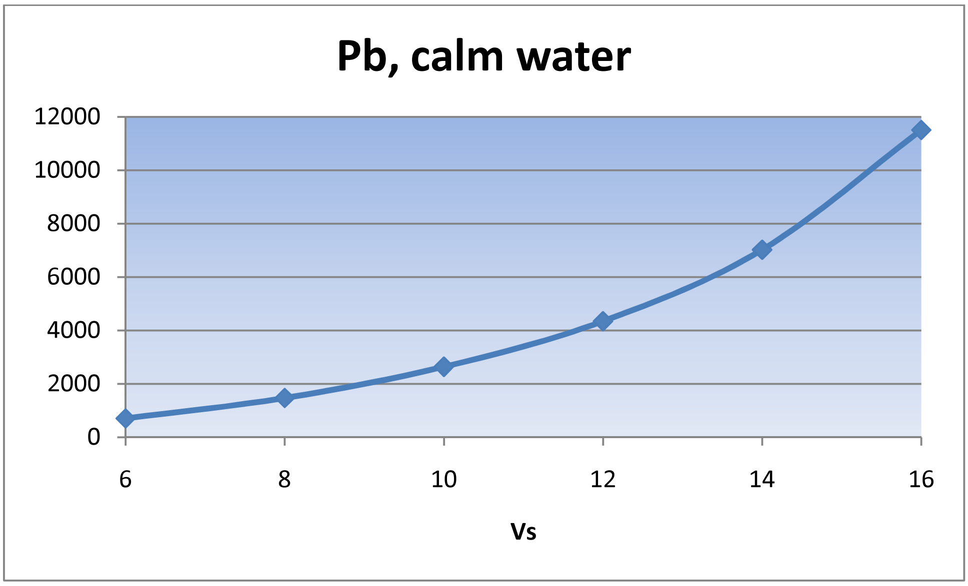


Figure 23- Break power in calm water, as a function of speed, for the chemical tanker

In Table 14 and Figure 24 can you see the break power as a function of speed for summer waves:

Table 14- Break power in summer waves, as a function of speed, for the chemical tanker

Vessel speed	Break power
6 knots	1064 kW
8 knots	2346 kW
10 knots	4182 kW
12 knots	6780 kW
14 knots	10584 kW
16 knots	16533 kW

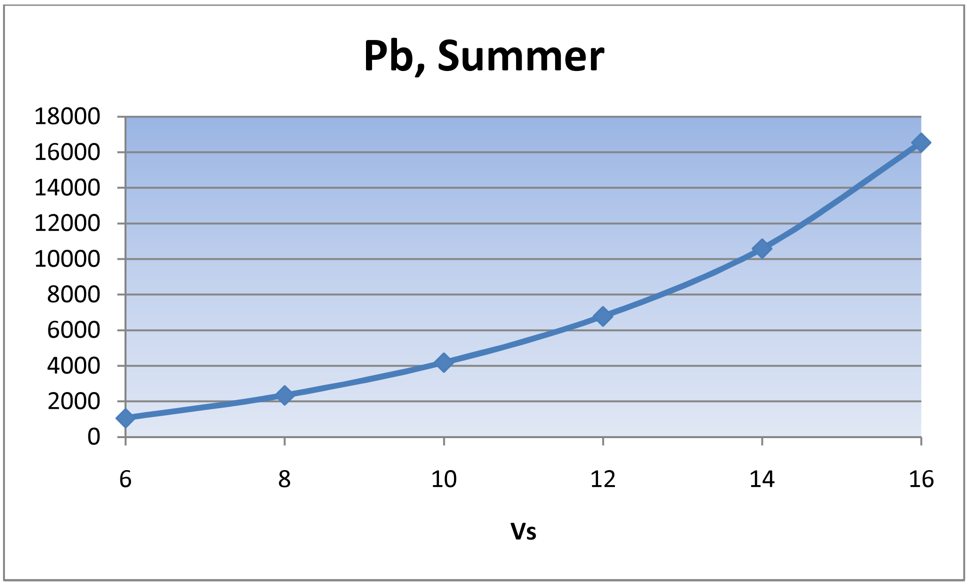


Figure 24- Break power in summer waves, as a function of speed, for the chemical tanker

For the chemical tanker in winter waves, can you find necessary break power in Table 15 and Figure 25:

Table 15- Break power in winter waves, as a function of speed, for the chemical tanker

Vessel speed	Break power
6 knots	357 kW
8 knots	2063 kW
10 knots	4499 kW
12 knots	8259 kW
14 knots	14183 kW
16 knots	23489 kW

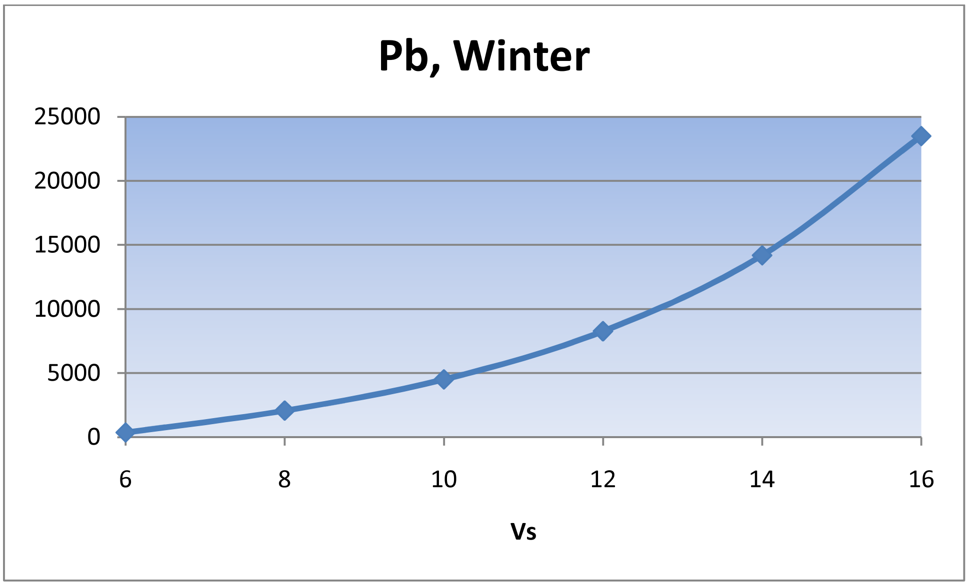


Figure 25- Break power in winter waves, as a function of speed, for the chemical tanker

5.4.4.3 R3D Container vessel

At last can we look at the optimal propeller diameters D, the optimal pitch ratios (P/D), blade area ratios (A_e/A_0) and propulsion efficiency η_D for the container vessel in Table 16 and Figure 26:

Table 16- The optimal propeller data for container vessel

Design speed	Optimal diameter	P/D	A_e/A_0	η_D
4 knots	2.094 m.	0.6	0.303	0.423
6 knots	2.725 m.	0.6	0.384	0.494
8 knots	3.111 m.	0.626	0.438	0.531
10 knots	3.431 m.	0.659	0.491	0.559
12 knots	3.701 m.	0.693	0.539	0.579
14 knots	3.947 m.	0.726	0.579	0.594
16 knots	4.19 m.	0.758	0.628	0.605
18 knots	4.431 m.	0.791	0.688	0.611
20 knots	4.667 m.	0.83	0.77	0.611
22 knots	4.849 m.	0.883	0.876	0.605

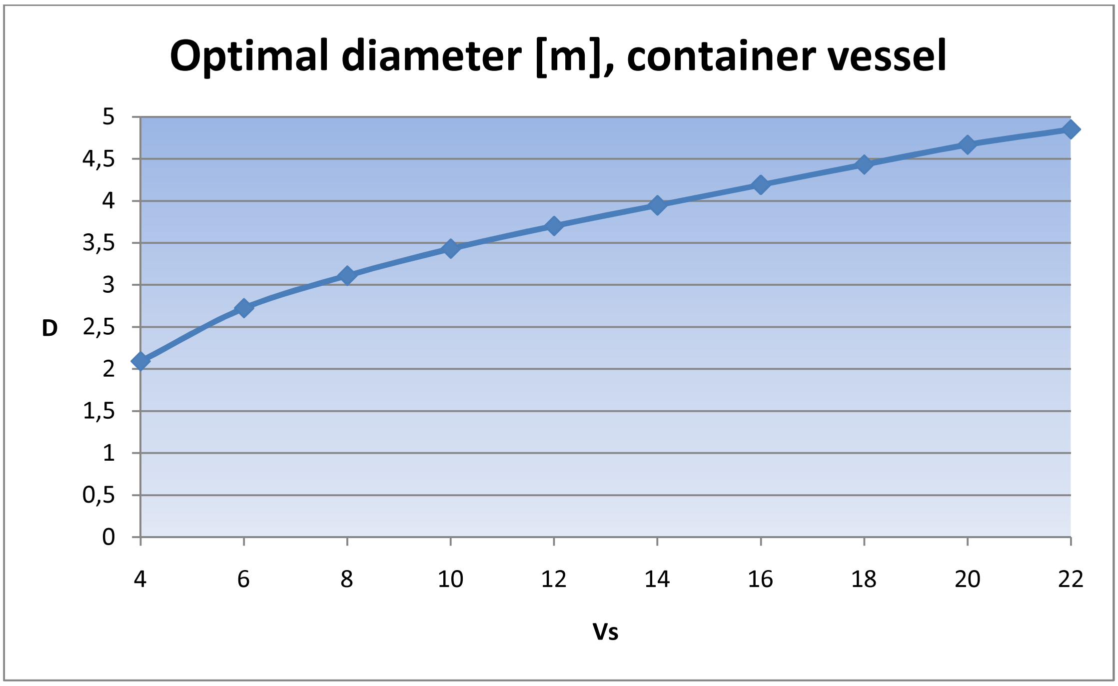


Figure 26- Optimal propeller diameter for R3D container vessel

Break power for the container vessel in calm water condition can you see in Table 17 and Figure 27:

Table 17- Break power in calm water, as a function of speed, for the container vessel

Vessel speed	Break power
4 knots	237 kW
6 knots	663 kW
8 knots	1392 kW
10 knots	2492 kW
12 knots	4047 kW
14 knots	6168 kW
16 knots	9058 kW
18 knots	13015 kW
20 knots	18524 kW
22 knots	26261 kW
24 knots	37831 kW

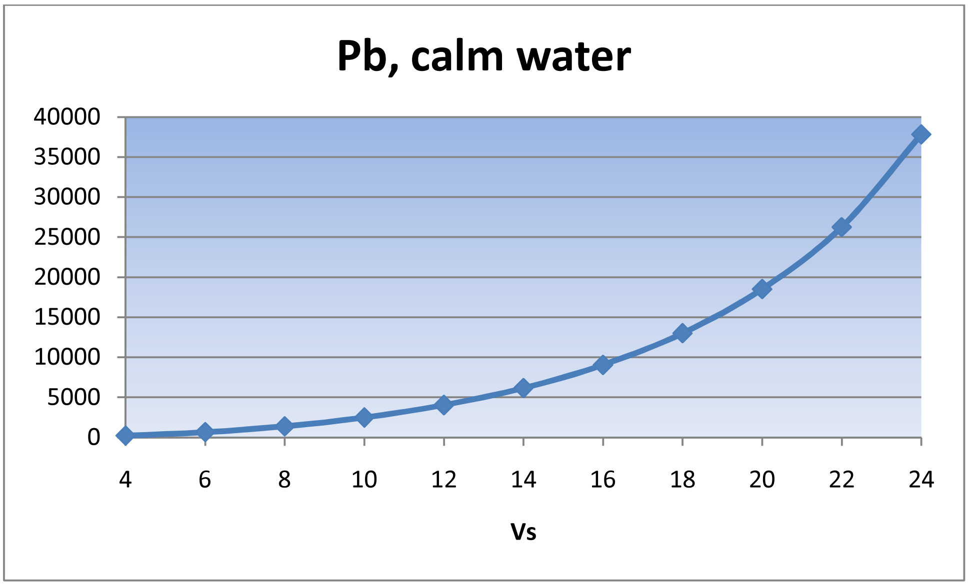


Figure 27- Break power in calm water, as a function of speed, for the container vessel

When we adds summer waves on the container model, the increase in break power as a function of speed can be found in Table 18 and Figure 28:

Table 18- Break power in summer waves, as a function of speed, for the container vessel

Vessel speed	Break power
4 knots	527 kW
6 knots	1464 kW
8 knots	2705 kW
10 knots	4307 kW
12 knots	6453 kW
14 knots	9314 kW
16 knots	12976 kW
18 knots	17837 kW
20 knots	24338 kW
22 knots	33170 kW
24 knots	45862 kW

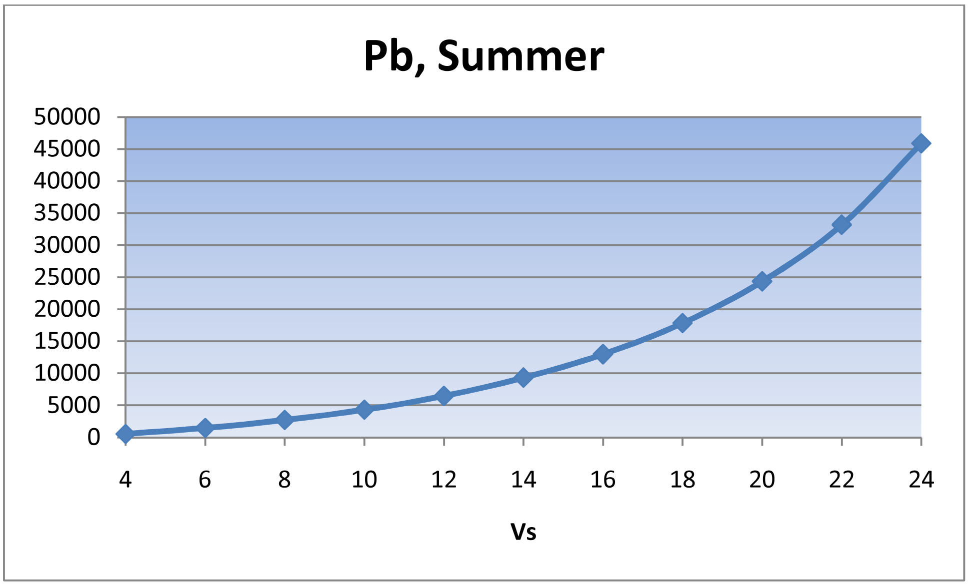


Figure 28- Break power in summer waves, as a function of speed, for the container vessel

And finally when we add the winter waves on the container vessel, the break power will be like shown in Table 19 and Figure 29:

Table 19- Break power in winter waves, as a function of speed, for the container vessel

Vessel speed	Break power
6 knots	622 kW
8 knots	2179 kW
10 knots	4337 kW
12 knots	7007 kW
14 knots	10645 kW
16 knots	15463 kW
18 knots	20958 kW
20 knots	30020 kW
22 knots	41259 kW
24 knots	57225 kW

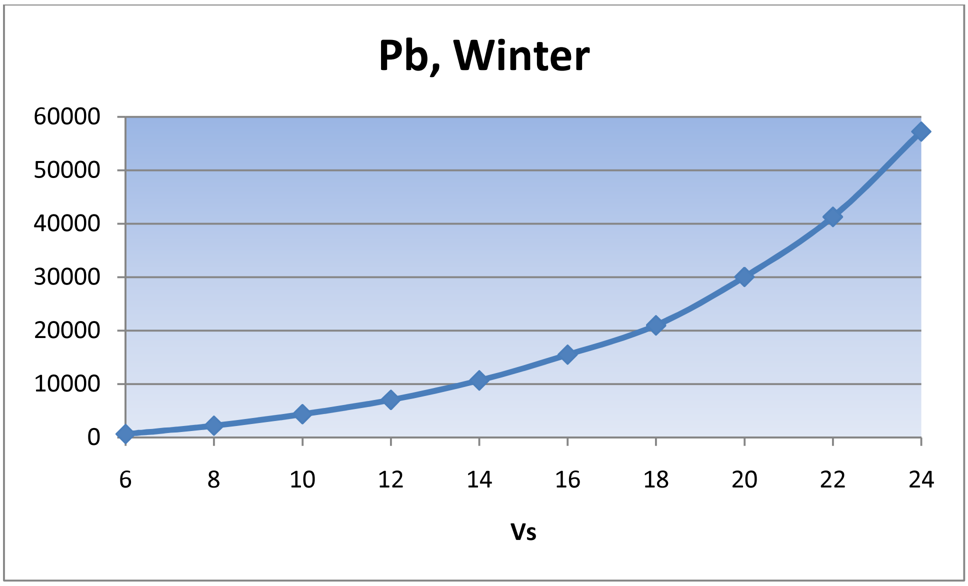


Figure 29- Break power in winter waves, as a function of speed, for the container vessel

ShipX did also have some problems on this vessel to estimate necessary break power for a vessel speed less than 6 knots.

5.4.5 Discussion of the results

In this chapter will there be a closer look on the results found in previous chapter, and a little discussion around them.

5.4.5.1 KVLCC2

If we look at the power predictions for the KVLCC2 for the different speeds, we can see why the biggest reduction in fuel and emissions is for the first knots speed reduction. This is because the increase in break power increases exponential. We can see this in Figure 30, where the diagrams show how the break power decreases (in percent of break power at 14 knots) as a function of the speed:

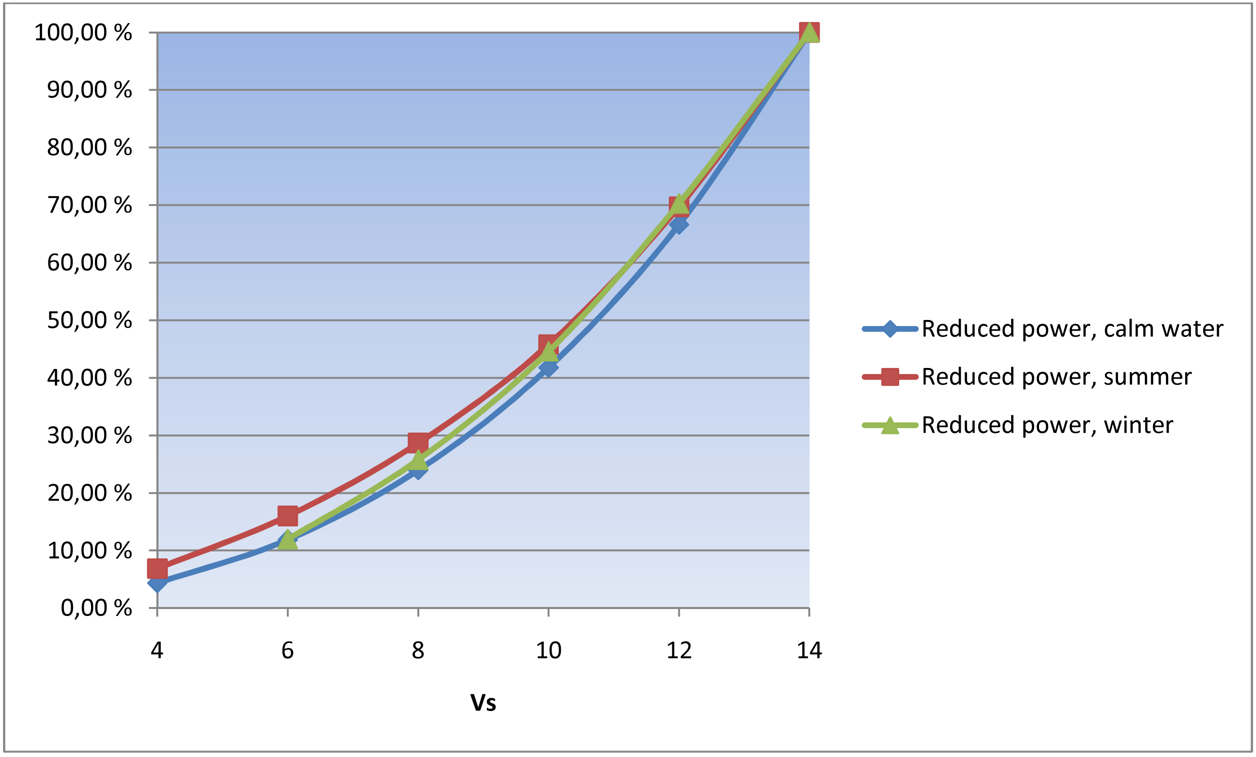


Figure 30- Reduction in break power as a function of speed, for the KVLCC2

If the tanker slows down from 14 knots to 12 knots, the vessel needs just respectively 67%, 70% and 70 % of the break power for calm water condition, summer condition and winter condition. If we go further down, if the tanker slow all the way down to eight knots, the vessel needs just respectively 24%, 29% and 26% of the maximum break power.

When we compare the power predictions for calm water, the vessel in summer waves and the tanker in winter waves, we can see there are some strange results for low speed. At six knots, the vessel requires more break power in summer waves, than in winter waves. This is a problem which comes again for the other vessels too. In Figure 31 can you see the three different break power diagram compared to each other. Then can you see how the waves influence on the performance of the tanker.

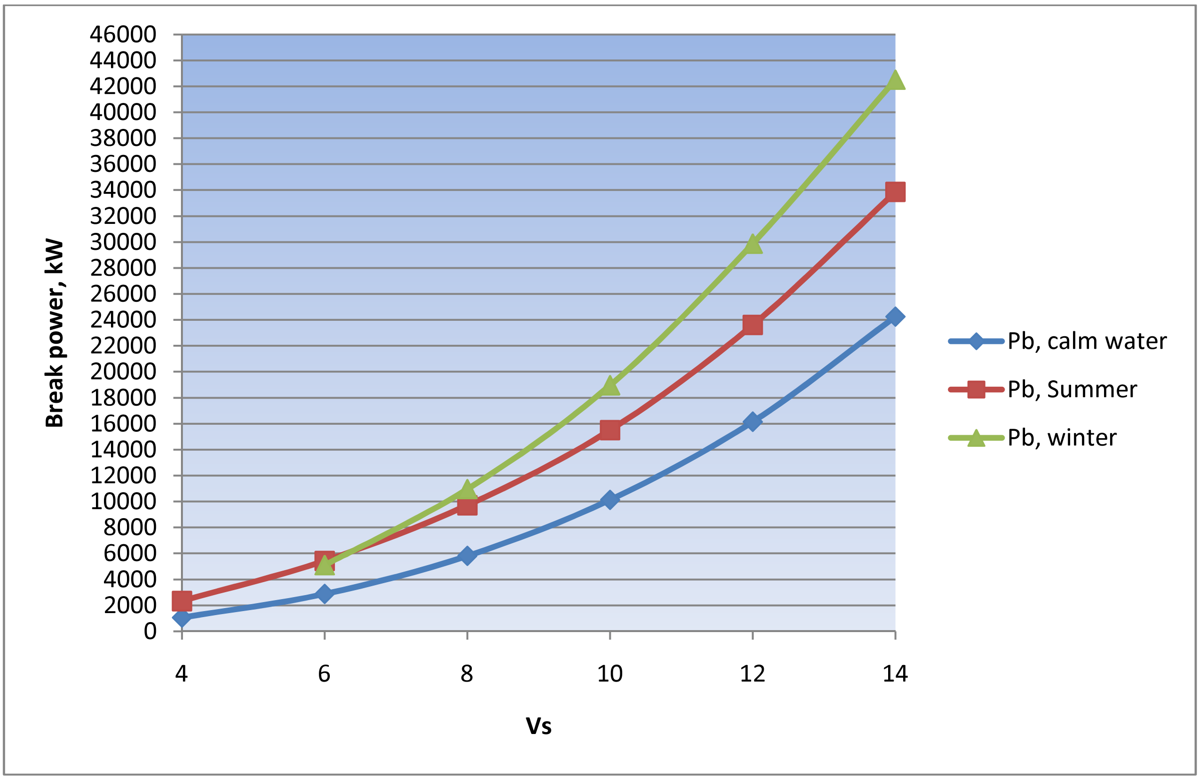


Figure 31- Break power for the three different conditions, as a function of speed, for the KVLCC2

From this figure can we see that the waves influence a lot on the power predictions, and we can say that to assume calm water condition in a slow steaming study will not give quite realistic results. Further can we see how the ratio between the break power in summer/winter waves against the calm water results in Figure 32. It has been used this ratio in here:

$$Added\ factor(summer) = \frac{Break\ power\ in\ summer\ waves}{Break\ power\ in\ calm\ water}$$

$$Added\ factor(winter) = \frac{Break\ power\ in\ winter\ waves}{Break\ power\ in\ calm\ water}$$

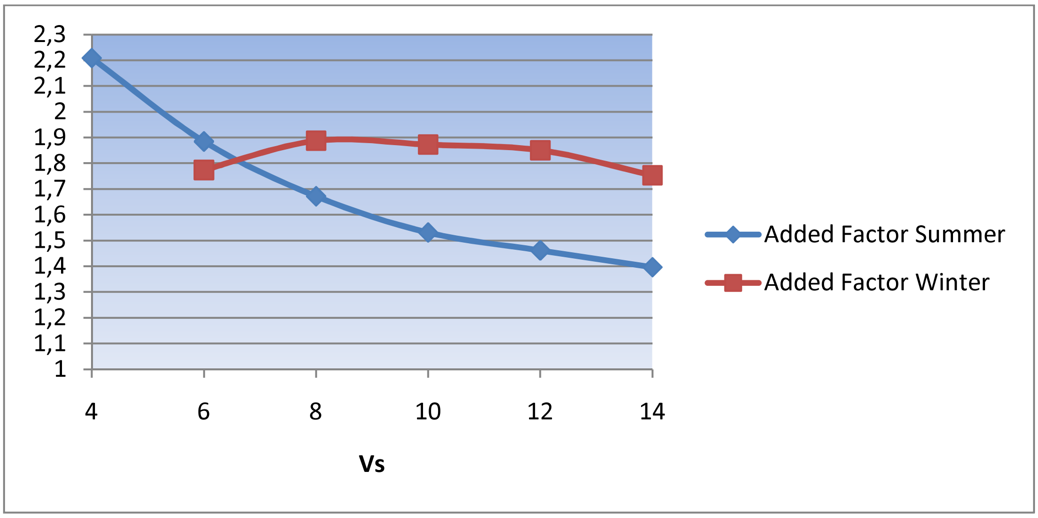


Figure 32- Added factor for the two different seasons, against speed for KVLCC2

In the summer season can we see that the calm water condition assumption is most wrong for low speed. When the tanker moves in four knots, the calm water break power has to be multiplied with a factor on 2.2 to get the break power in realistic conditions. The added factor decreases when the speed increases, and at 14 knots the waves represents just 40% of the break power required. When it comes to the winter waves, it doesn't decreases in the same way. As mentioned, the result for six knots looks a bit strange. This figure do agree with that statement. For the other predictions, the added factor decreases just a little bit, not moving to far away from an added factor equal to 1.8-1.9.

5.4.5.2 R3D Chemical tanker

For the chemical tanker the trend is the same, the break power increases exponential when the speeds increases. In Figure 33 the reduction in break power, as percent of maximum break power (for 16 knots), as a function of the speed is shown:

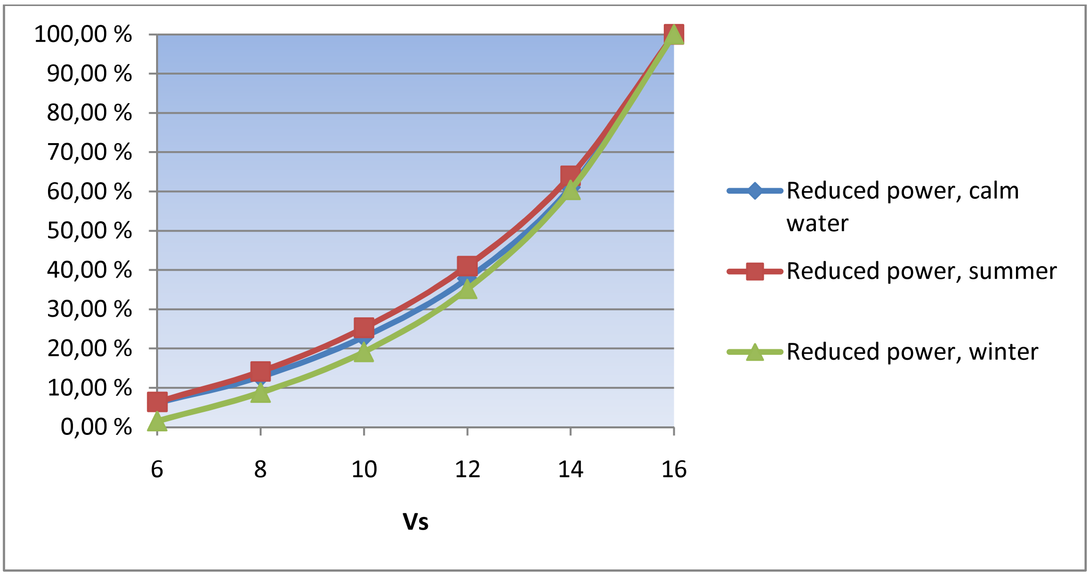


Figure 33- Reduction in break power as a function of speed, for the R3D chemical tanker

From this figure can we see that if the tanker slows down from 16 knots to 14 knots, the necessary break power will be reduced to respectively 61%, 64% and 60% for calm water condition, in summer waves and in winter waves. If the vessel slows down more, to eight knots, the break power will be reduced to 13%, 14% and 9%. According to this the biggest reduction in break power when reducing the speed is for winter waves

In Figure 34 can we see the diagrams for break power against speed, where the three different conditions are compared to each other.

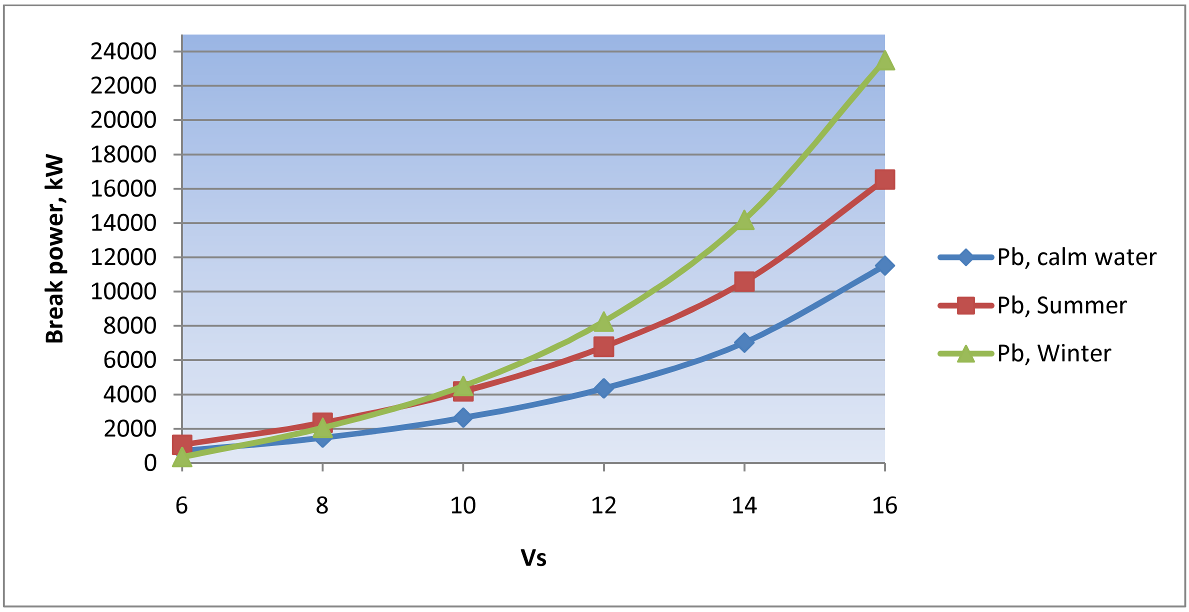


Figure 34- Break power for the three different conditions, as a function of speed, for the chemical tanker

From these results can we see that there is something strange for the lowest speed in winter waves. For calm water conditions in 6 knots the break power is 707 kW, while for the vessel in winter waves in 6 knots, the break power is 357 kW. If we look on the added factor for summer condition and winter condition in Figure 35, we can easier see the problems at low speed.

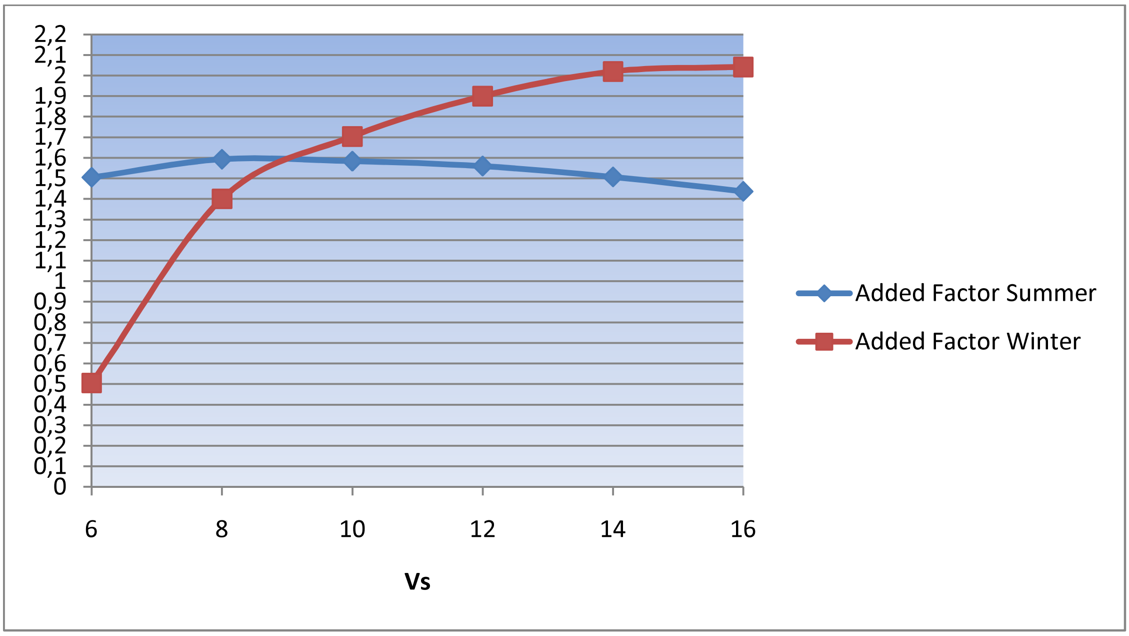


Figure 35- Added factor for the two different seasons, against speed for chemical tanker

We can see for summer waves, the added factor will decrease for increasing speed. But the shape of the added factor in winter waves as a function of speed looks strange. For six knots, the added factor is 0.5, increasing to 1.4 for eight knots, and increasing all the way. For 16 knots the added factor is 2.04. In summer waves the vessel acts like stated in the hypothesis, that the waves gives a larger increase in necessary power for low speed than higher speed.

5.4.5.3 R3D container vessel

Also for the container vessel, the winter waves give strange results for slow speed. If we look at six knots in winter waves, the needed break power is lower compared with calm water condition. This means that the wave contribution is bigger from aft than head sea. For calm water its needed 663 kW, while for the vessel in winter waves, it is needed 622 kW. We can see this in Figure 36.

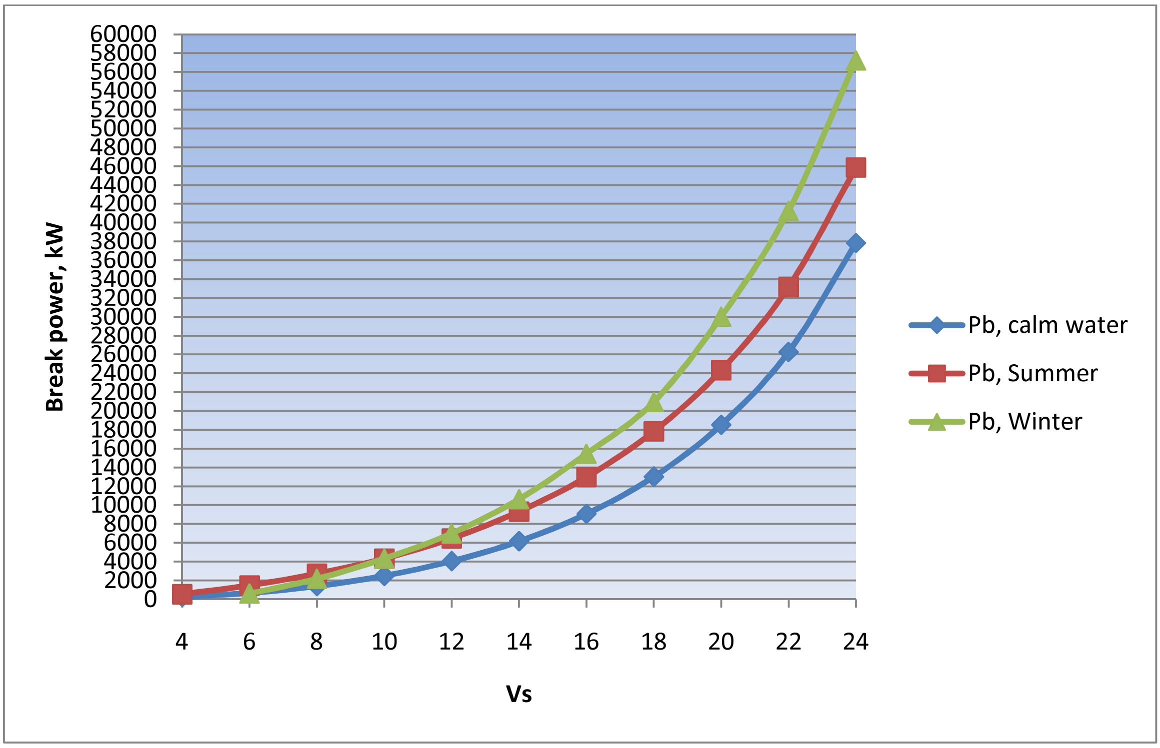


Figure 36- Break power for the three different conditions, as a function of speed, for the container vessel

We can further look on how the break power decreases in percent of full throttle as a function of the sailing speed in Figure 37.

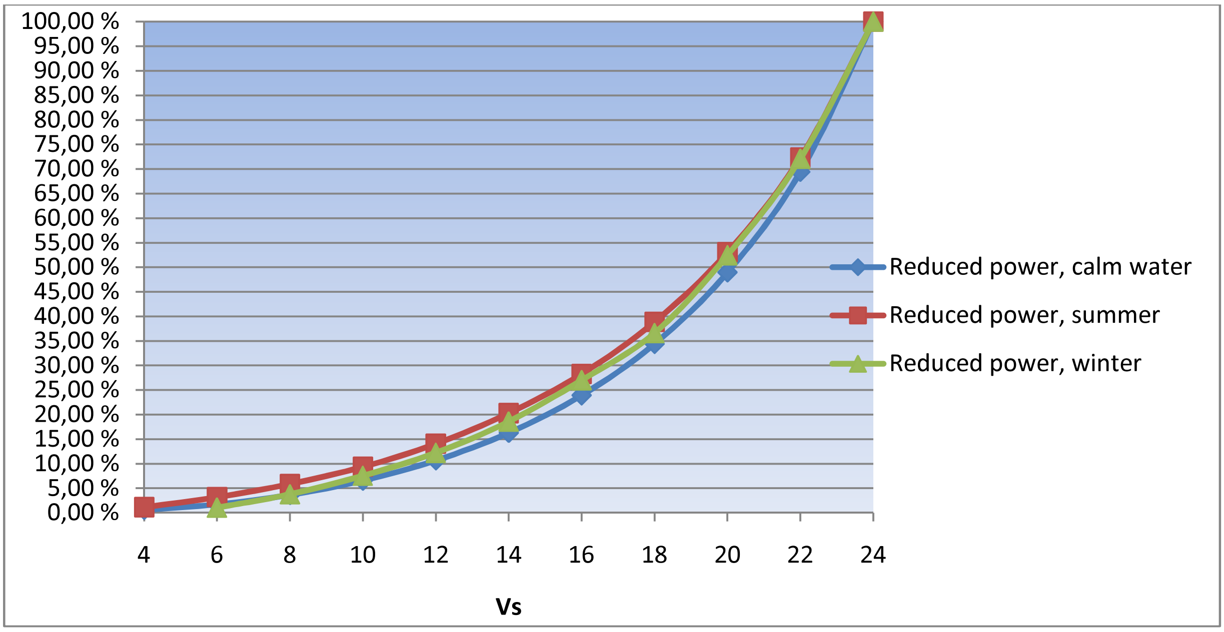


Figure 37- Reduction in break power as a function of speed, for the R3D container vessel

From this figure can we see that if the vessel slows down from 24 knots to 20 knots, the break power decreases down to respectively 49%, 53% and 52% for calm water condition, in summer waves and in winter waves. If the container vessel slows further down to 12 knots, the break power decreases 11%, 24% and 12%.

In Figure 38 can you look at the added factor for the two different seasons for the container vessel.

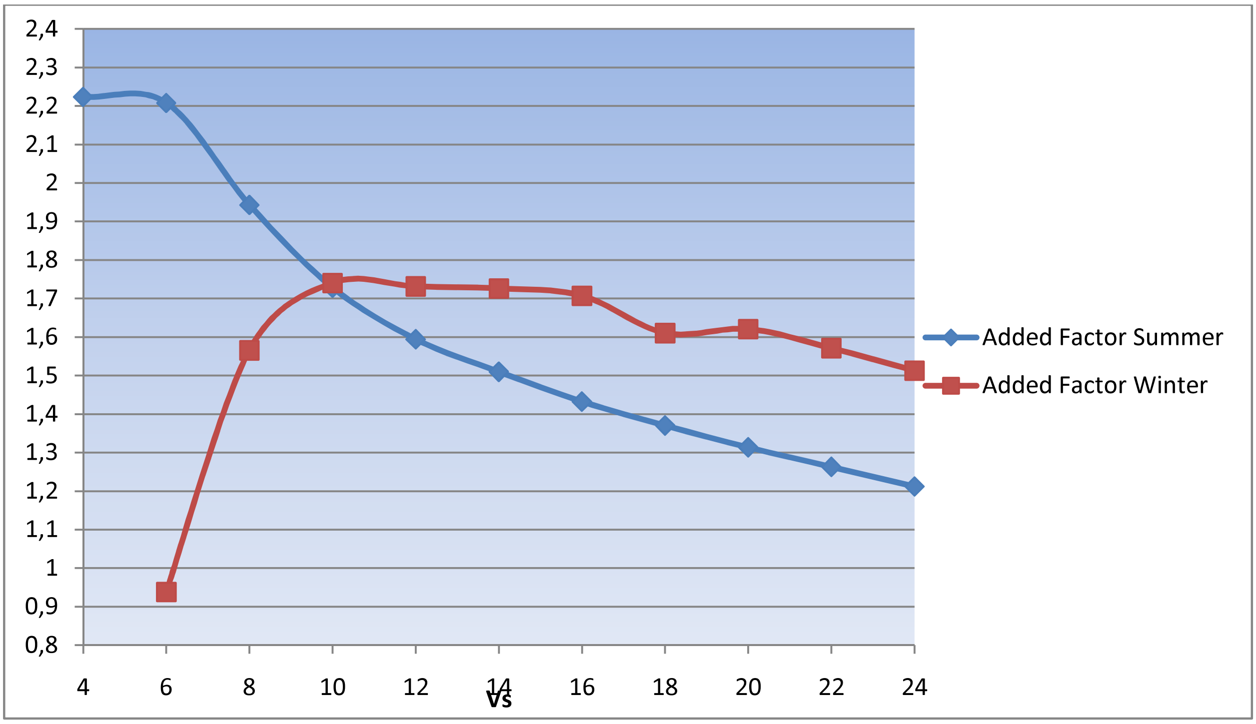


Figure 38- Added factor for the two different seasons, against speed for container vessel

In this figure the strange results for low speeds in winter waves are more evident. The added factor for six knots is 0.94, which gives a speed bonus when adding waves on the vessel. But added factor for summer waves follows the same trend as mentioned in the hypothesis, that the added factor will decrease when increasing the speed. If we neglect the results for six and eight knots in winter waves, the added factor in winter waves will also decrease when increasing the speed, but not so rapidly as summer waves.

6 Realistic weather conditions influence optimum speed

From the results in the case study in chapter five could we see that the waves have a huge influence on the resistance and the break power for vessels like tankers and container vessels. If the engineers find an optimum speed for a vessel in calm water it would give a false result, since it very seldom is moving in calm water. The problem with adding waves is that waves in realistic weather conditions change in both strength and directions. In Figure 39 can you the container vessel moving in 20 knots, and how the Break power increases for increasing significant wave height.

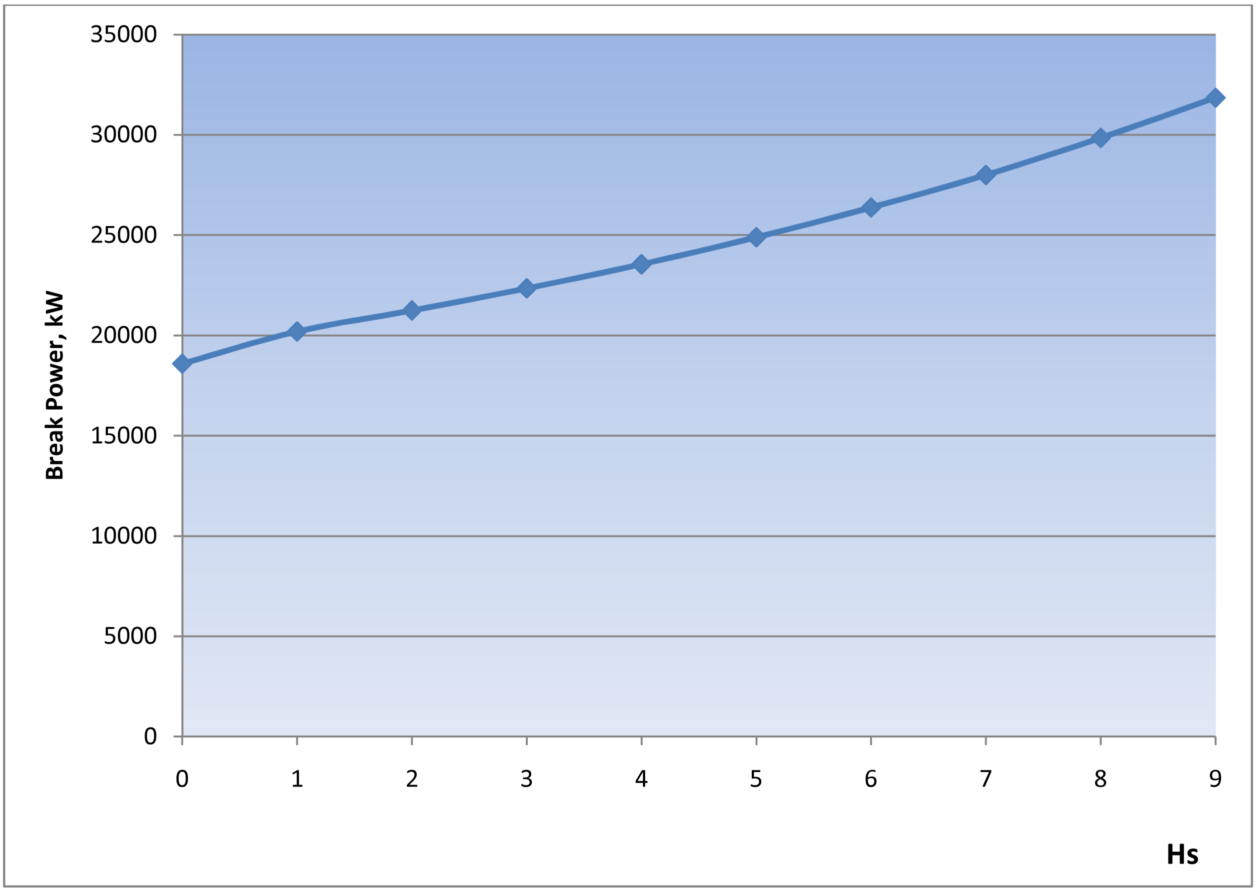


Figure 39- Break power against increasing Hs for the R3D container vessel maintaining 20 knots

Out of this figure we can see the necessary break power to maintain 20 knots are strongly dependent on the significant wave height. For one meter Hs the needed brake power is 20200 kW, while if the vessel is moving in 7 meter Hs the brake power is equal to 28000 kW. This is an increase of 38 percent.

Another thing with realistic weather condition is that the waves won't just hit the vessel in the bow (head sea). The waves might come from all directions. To show how the wave direction influences the attainable speed, I did some estimation in ShipX for the container vessel, where the model goes in 20 knots in calm water conditions. Then I generated waves for every 45 degrees, so we can see how the speed varies. The results can you see in Figure 40.

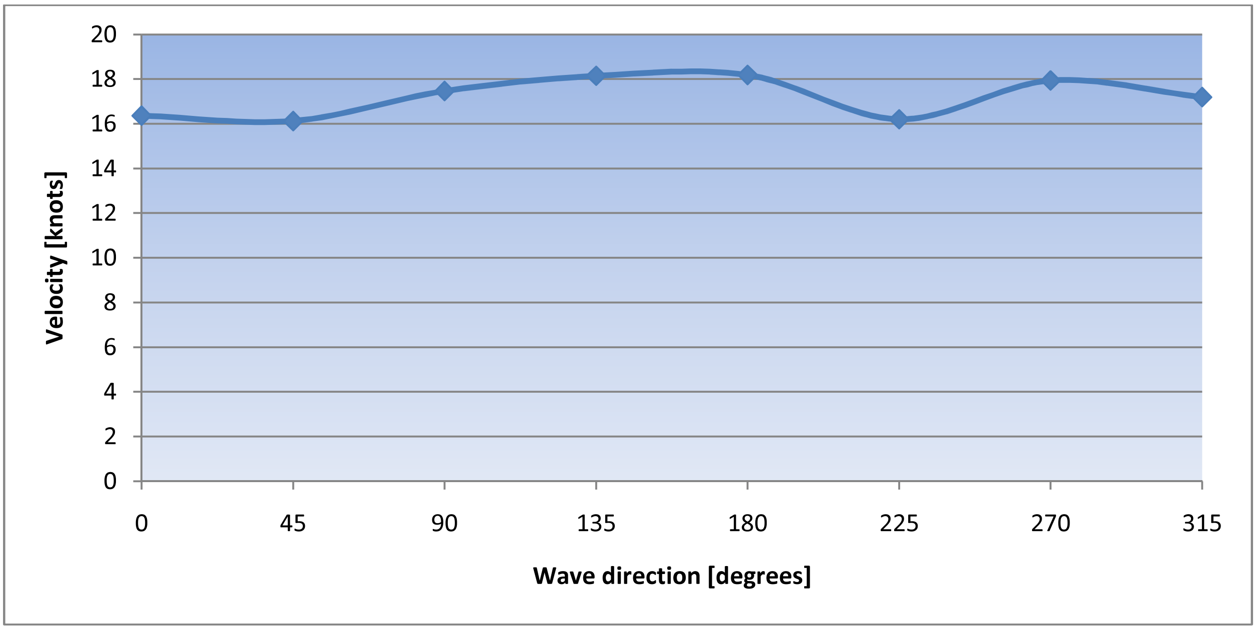


Figure 40- How the velocity varies for different wave directions on the R3D container vessel

Out of this figure we can see the velocity varies between 16 and 18 knots. So this means the wave directions also have a strong influence on the vessel performance in realistic weather conditions.

Since there are so many factors varying when it comes to sea states, the best thing is to use available wave data. Here can you find average sea states for different areas in different seasons, and also statistical data for each directions, and how often that wave direction occurs.

As the results in the case study, in chapter five, showed, for container vessels and tankers, the wave influence is bigger relatively to calm water performance for low speed than for high speeds. For the container vessel the factor we had to multiply the calm water break power with to get the break power in summer waves, for six knots was 2.21, while for 22 knots the factor was equal to 1.26 (From Figure 38).

Economics is one important factor when the ship industry is going to set an optimum speed. This depends on ships, route, engines, other gear and so on. The ship owner has to make enough profit on the transport so he can maintain the business. This will also vary with the fuel price, emission taxes and other taxes. It depends on the demand, how much the customers will pay to let you bring their cargo, if they are in a hurry or the cargo is time sensitive (have to be transported to the marked quick). To look at an example with economy and wave influence, we can use the data from Figure 36 If the payment from the customer makes it doable to go with 3000 kW break power, this corresponds to a speed equal to approximate 23 knots. But we have to take the waves into the account. Then the optimum speed will go down to approximate 20 knots. You can see this in Figure 41

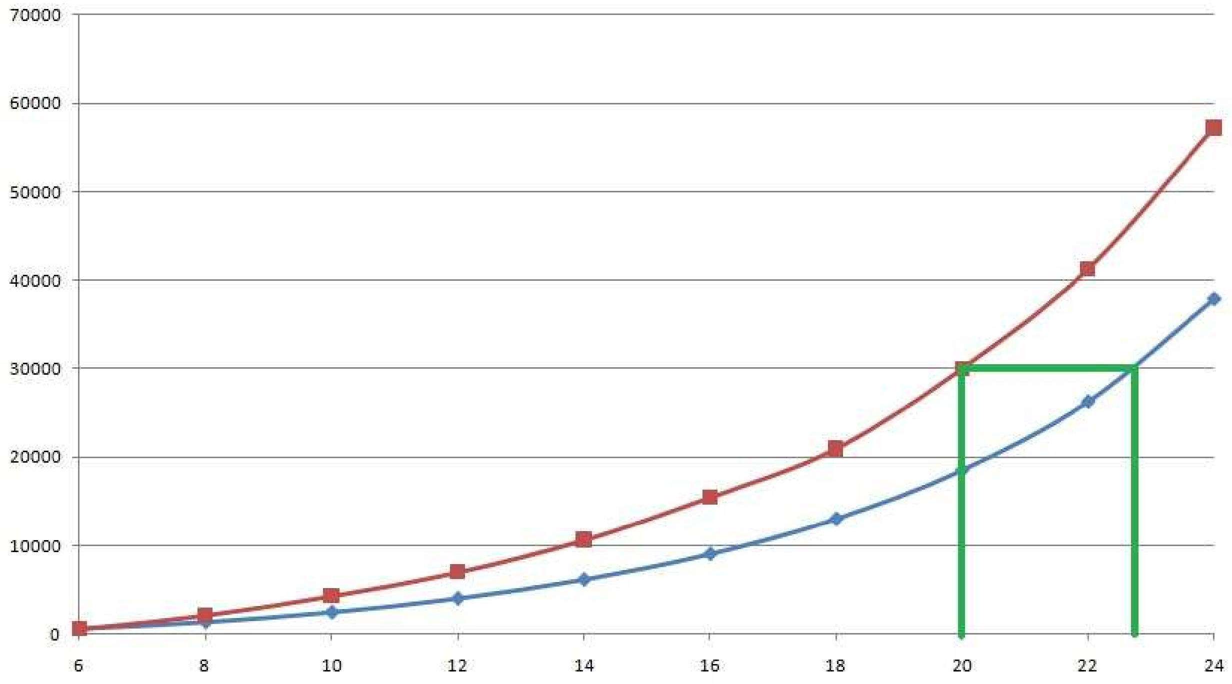


Figure 41- Change in optimum speed for 3000 kW with and without waves for R3D container vessel

From this can you see how the waves influence the design speed when economics are taken into account. The blue line is how break power varies in calm water, while the red line is with waves. The green line shows how the design speed decreases if the economy say 3000kW is the correct power for the trip.

The engine is also a factor which is important. The engine efficiency isn't the same for all of the load range, so somewhere when decreasing the speed, the fuel consumption (including lubrication oil consumption) will increase when decreasing the speed of the vessel (decreasing load on the engine).

7 Conclusion

From statistics and statements from experts we know the increase in intensity of the Greenhouse effect on the Earth is scary. The temperature is increasing, the climate is often acting strange, and people are afraid if the prognosis in the future will be true. This means there have to be a reduction in the greenhouse gas emissions.

There have been performed some analyses before in the Slow Steaming concept, where they often have neglected the waves, and just analyzed the vessels in calm water conditions. In this Master thesis we have seen how important the waves are when it comes to necessary break power. For the R3D container vessel at low speed the break power in calm water had to be multiplied with a factor of 2.2 to get realistic results in waves. From this can we see the assumption of calm water conditions is too rough compared with the reality.

As seen from the case study in this Master thesis, it is needed quite much break power to keep large vessels, like tankers and container vessels in motion, especially for the container ships which have a design speed today at around 25 knots. From the power predictions for reducing the velocity in this study, we have seen the reduction in break power is enormous for the first knots for the container vessels. But we also have seen that if the power is decreased just a little, the emissions of NO_X will increase. In addition will the combustion be more incomplete and more soot will be produced. This means that if the slow steaming should be applied to save the environment, the engines have to be designed for this load, such that the combustion will be completed, so we get a reduction in NO_X emissions in addition to reduction in fuel consumption and CO_2 emissions.

The hypothesis from when I started to work with this Master thesis, that the influence on necessary power of the three vessels would be largest relatively for low speeds, while it would decrease with increasing vessel velocity, was correct.

8 Further work

When it comes to slow steaming there are challenges to work further with. Since the CO_2 emissions have to go down in the future, while the shipping fleet is increasing, something has to be done. Slow steaming is a good way of reducing the emissions (if it is done in the right way).

Since the way ShipX is spreading out the waves for different directions isn't close enough to the reality, it is possible to go closer in the global wave statistics, or newer data, and use the scatter diagrams for the different directions, and corresponding part of occurrence, and use this in the ShipX analysis.

Another change in the analysis can be to use more detailed resistance information for the vessels, such that the power predictions won't give any problems for lower and higher speeds. This has been a problem in this analysis. When I passed a certain velocity for the different vessels, the power predictions was completely crazy. This was because the Holtrop resistance prediction method didn't cover those velocities.

An experimental test about the slow steaming concept may be one assessment for later works, it may be done in connection with a numerical predictions. The resistance results from the experimental test may be used in the numerical methods, instead of the resistance prediction methods.

There can be done some analyses about one kind of ship with varying size, like looking closer to container vessels, from small feeders (with a capacity up to 1000 TEU) to ultra large container vessels (capacity more than 14500 TEU) and see how the trends in necessary power changes. The same can be done with tankers, where the range goes from small tankers to Ultra Large Crude Carriers.

Another assessment that can be done is to look on the difference in behaviour and/or trends for traditional bows compared with the new designs like Rolls-Royces wave piercing design and Ulstein X-bow. For the new designs it might be hard to get good models for the ShipX analyses.

As mentioned in chapter six, the engine performance has a lot influence in design speed for vessels, and how much emissions there will be. One way to go further with this thesis, is to go deeper in engine performance, look on how the efficiency varies with different loads on engine (different speeds for the vessel), how the emissions varies, how the combustion quality varies, alteration in fuel and lubrication oil consumption, etc.

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Appendix

A1 Scatter diagram input for ShipX

Found from Vessel Responses Users' Manual [Ref. 5]

```
DESCRTEXT
IFORM HSTXTYPE NUMHS NUMTX
HS(IHs), IHs = 1, NUMHS
TX(ITx), ITx = 1 NUMTX
do IHs = 1, NUMHS
(PROB(IHs,ITx), ITx = 1, NUMTX)
enddo
```

Variable	Description
DESCRTEXT	Text describing the scatter diagram
IFORM	Type of wave period
	1 - T_p
	2 - T_Z
	3 - T_1
HSTXTYPE	Identifies if the H_s and T_x values are gives as:
	1 - the middle value of range
	2 - the highest value of range
	3 - the lowest value of range
NUMHS	Number of significant wave heights
NUMTX	Number of wave periods
HS	Significant wave heights
TX	Wave period
NPROB	Number of occurrence of a sea state

A2 Route input for ShipX

```
// Line 1. File header
// Line 2. File type (=1) and number of scatter diagrams
// Line 3++. weight factor (route-length in nm) and Scatter diagram file names
delimited by ":"
```

My route input summer:

```
Atlantic Ocean
1 4
1447.2 : C:\routes\\a16s.sea
361.8 : C:\routes\\a17s.sea
422.1 : C:\routes\\a23s.sea
1386.9 : C:\routes\\a24s.sea
```

My route input winter:

```
Atlantic Ocean
1 4
1447.2 : C:\routes\\a16w.sea
361.8 : C:\routes\\a17w.sea
422.1 : C:\routes\\a23w.sea
1386.9 : C:\routes\\a24w.sea
```

A3 Scatter diagram for Area 16, summer season

```
Atlantic Ocean, Area 16, June to August
2       1       8       9
0.5     1.5     2.5     3.5     4.5     5.5     6.5     7.5
3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5
0       0       0       0       0       1       1       0       0
0       0       0       0       1       2       2       1       1
0       0       0       2       4       5       4       2       1
0       0       1       7       15      16      11      5       2
0       0       6       25      44      40      22      9       3
0       2       23      73      95      66      30      10      3
0       9       61      118     99      47      15      4       1
2       16      38      34      15      4       1       0       0
END
```

A4 Scatter diagram for Area 16, winter season

Atlantic Ocean, Area 16, December to February

```
2       1       13      9
0.5     1.5     2.5     3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5    12.5
5.5     6.5     7.5     8.5     9.5     10.5    11.5    12.5    13.5
0       0       0       0       1       1       1       0       0
0       0       0       0       1       1       1       1       0
0       0       0       1       2       2       2       1       0
0       0       0       1       3       4       3       1       1
0       0       0       3       6       7       4       2       1
0       0       1       6       12      12      6       2       1
0       0       3       12      21      18      9       3       1
0       1       7       25      36      26      11      3       1
0       2       16      46      53      30      10      2       0
0       5       33      71      61      27      7       1       0
1       13      56      78      46      14      3       0       0
2       24      52      39      13      3       0       0       0
3       9       8       2       0       0       0       0       0
END
```

A5 Scatter diagram for Area 17, summer season

Atlantic Ocean, Area 17, June to August

```
2       1       7       9
0.5     1.5     2.5     3.5     4.5     5.5     6.5
3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5
0       0       0       1       1       1       1       0       0
0       0       1       2       3       3       2       1       0
0       0       2       8       11      9       5       2       1
0       1       10      27      33      23      10      4       1
0       6       38      79      73      39      15      4       1
1       26      104     136     86      33      9       2       0
6       39      68      46      17      4       1       0       0
END
```

A6 Scatter diagram for Area 17, winter season

Atlantic Ocean, Area 17, December to February

```
2       1       13      9
0.5     1.5     2.5     3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5    12.5
4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5    12.5
0       0       0       0       0       0       1       0       0
0       0       0       0       0       1       1       1       0
0       0       0       0       1       1       1       1       0
0       0       0       0       1       2       2       1       1
0       0       0       1       3       4       4       2       1
0       0       0       2       5       7       6       3       1
0       0       1       4       11      13      10      5       2
0       0       1       9       21      24      15      6       2
0       0       4       20      39      36      19      7       2
0       1       11      42      64      47      21      6       1
0       2       26      72      78      43      15      3       1
0       8       46      75      51      18      4       1       0
2       11      22      15      5       1       0       0       0
END
```

A7 Scatter diagram for Area 23, summer season

```
Atlantic Ocean, Area 23, June to August
2       1       7       8
0.5     1.5     2.5     3.5     4.5     5.5     6.5
3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5
0       0       0       1       1       0       0       0
0       0       1       1       1       1       0       0
0       1       3       5       4       2       1       0
0       4       15      18      12      5       2       0
2       20      55      55      29      10      3       1
10      81      147     105     42      12      2       1
44      125     114     48      12      2       0       0
END
```

A8 Scatter diagram for Area 23, winter season

Atlantic Ocean, Area 23, November to March

```
2       1       10      9
0.5     1.5     2.5     3.5     4.5     5.5     6.5     7.5     8.5     9.5
3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5
0       0       0       0       0       1       1       0       0
0       0       0       0       1       1       1       1       0
0       0       0       1       2       3       2       1       0
0       0       0       2       4       5       4       2       1
0       0       1       5       10      11      7       3       1
0       0       2       12      24      23      13      5       2
0       0       8       33      51      40      19      6       2
0       2       23      73      87      53      20      6       1
0       7       54      107     85      36      10      2       0
1       16      42      37      16      4       1       0       0
END
```

A9 Scatter diagram for Area 24, summer season

```
Atlantic Ocean, Area 24, June to August
2       1       7       9
0.5     1.5     2.5     3.5     4.5     5.5     6.5
3.5     4.5     5.5     6.5     7.5     8.5     9.5     10.5    11.5
0       0       0       1       1       1       1       0       0
0       0       1       2       3       2       1       1       0
0       0       3       7       8       6       3       1       0
0       2       12      25      25      15      6       2       1
0       10      48      76      58      27      9       2       1
3       46      135     140     73      25      6       1       0
11      58      80      44      14      3       1       0       0
END
```

A10 Scatter diagram for Area 24, winter season

Atlantic Ocean, Area 24, December to February

```
2	1	12	9
0.5	1.5	2.5	3.5	4.5	5.5	6.5	7.5	8.5	9.5	10.5	11.5
5.5	6.5	7.5	8.5	9.5	10.5	11.5	12.5	13.5
0	0	0	0	0	1	1	0	0
0	0	0	0	1	1	1	1	0
0	0	0	1	2	2	2	1	0
0	0	0	2	4	4	3	1	1
0	0	1	4	8	8	5	2	1
0	0	2	9	15	13	7	3	1
0	1	7	21	29	21	9	3	1
0	3	18	44	47	28	10	3	1
0	8	41	74	60	28	8	2	0
2	21	71	85	48	16	3	1	0
5	35	59	40	14	3	0	0	0
4	9	6	2	0	0	0	0	0
END
```