The Impact of EEDI on VLCC Design and CO2 Emissions

Jack Devanney
Center for Tankship Excellence, USA, djw1@c4tx.org

Abstract

This paper studies the impact of EEDI on VLCC CO2 emissions. Our numbers indicated that, under reasonable assumptions, imposition of EEDI will result in a slight increase in VLCC operational CO2 emissions. Even under an unrealistically optimistic set of assumptions, the Phase 2 CO2 reduction is less than 3%. In contrast, we find that a $50 per ton CO2 bunkers tax will reduce VLCC CO2 emissions by more than 6% over a market cycle.

Keywords

EEDI, VLCC; CO2 Emissions; Slow steaming

1 Summary

1.1 Background

The International Maritime Organization (IMO) is on the verge of enacting an amendment to MARPOL which would require all new large ships to meet an Energy Efficiency Design Index (EEDI). This is an attempt to reduce CO2 emissions from ocean transportation. This paper considers the impact of this legislation on one ocean transportation sector, Very Large Crude Carriers (VLCC's), and estimates the resulting reduction in CO2 emissions from these ships. These estimates are compared with those generated by a policy of imposing a fuel carbon tax (or an equivalent cap-and-trade permit price) on these ships.

EEDI is defined by MEPC.1/Circ.681.[2] While the formula is complex, for VLCC's it basically boils down to the ratio of fuel consumed at 75% installed power to speed at that power.

IMO has yet to finalize the mandated decrease in EEDI; but the discussion has focused on the following reduction schedule.

Phase 1	Phase 2	Phase 3
2013	2018	2023
10%	25%	35%

These reductions will be from a *baseline* that is determined by fitting a power law regression to the existing fleet. Due to biases in this ad hoc procedure, the EEDI of a current standard VLCC is about 9% above this baseline.[8][1] In other words, newbuilding VLCC's will be required to have an EEDI which is 19% below current designs in 2013, 36% below current in 2018, and 47% below current in 2023.

1.2 Conclusions

There are essentially only two ways a VLCC designer can meet these EEDI requirements:

1. Reduce the fuel required at 75% installed power by employing fuel saving technology not already in use. We estimate that a reasonable upper bound on the reduction in EEDI that can be achieved with such measures is 9%. Moreover, almost all these measures have negative abatement cost and will be implemented by VLCC owners in their newbuildings ***whether or not EEDI is imposed***.
2. Reduce installed power. Unlike most mandated vehicle efficiency requirements such as CAFE, speed is not fixed. An automobile maker cannot meet his CAFE by testing his car at 40 mph rather than 55. But EEDI allows and encourages this. Very roughly, VLCC speed goes as the one-third power of installed power. So the expectation is that a 30% reduction in installed power will results in approximately a 10% reduction in speed at that power, and a 20% reduction in the EEDI ratio. We shall see that it is not quite that simple,

Far more importantly,

a) Reducing EEDI does not guarantee a like reduction in actual CO2 emissions.
b) In fact, it does not guarantee any reduction.

Our figures indicate that, under reasonable assumptions, ***imposition of EEDI will result in slight increase in VLCC operational CO2 emissions***, while imposing a heavy burden on society in market cost and safety. Even under an unrealistically optimistic set of assumptions, the Phase 2 CO2 reduction is less than 3%. These numbers are based on comparing a no EEDI newbuilding, fitted with

---

[1] Like most things EEDI, these numbers are rubbery and constantly changing. There are proposals to correct this bias.

energy saving measures that are economic at current bunker prices, with an EEDI-compliant newbuilding.

Why is EEDI is so ineffective in reducing VLCC CO2 emissions?

The answer is two fold:

1. EEDI does not limit CO2 emissions. EEDI effectively limits installed power. But at current and expected bunker prices, a non-EEDI VLCC owner/term charterer uses all his installed power only in a full boom, or about 10% of the ship's life. So for the great bulk of her life, a non-EEDI ship uses little or no more power than an EEDI compliant ship
2. In limiting installed power, EEDI induces owners to use smaller bore, higher RPM engines which means that the EEDI-compliant VLCC will consume more fuel than the non-EEDI ship when the market is not in boom, which is most of the time.

In contrast, we find that VLCC owners will respond to a $50 per ton CO2 bunkers tax by reducing speed in all but booms and thereby reducing VLCC CO2 emissions by more than 6% over a market cycle. Unlike EEDI, a tax (or an equivalently priced cap-and-trade) will apply to all VLCC's, including those already trading.

There is good reason to believe that the same analyzes applied to smaller tankers and bulk carriers will arrive at very similar conclusions. With the demise of the conference system, the same thing is true of containerships, with the important caveat that liner owners will be limited to a discrete set of slow steaming speeds if they wish to main schedule frequency. Certainly, such analyzes should be performed before a final decision is made on EEDI.

2 "True" Efficiency Improvements

The CTX has conducted a survey of what might be called the "true" efficiency improvements because they attempt to reduce fuel consumption without reducing speed.[4]

We rejected several possibly economic measures as imprudent, including:

Contra-rotating propellers Contra-rotating props require complex epicyclic gearing and bearings. They are inherently far less reliable than a standard VLCC shaft and propeller, and would be a maintenance nightmare. No prudent owner could spec contra-rotating props on a single screw tanker.

Reducing lightweight The EEDI formula includes a cargo capacity term. For VLCC's, it is deadweight. By reducing lightweight the designer can increase deadweight on the same displacement and reduce his EEDI. Unfortunately, VLCC hull structures are already over optimized, resulting in frequent fatigue cracking and short lived vessels. Nonetheless, EEDI will put additional pressure on the VLCC designer to take chances in this area.

We rejected a number of ideas that have been around for decades, on the grounds that they have never been able to demonstrate a significant reduction in fuel consumption.

We rejected a number of possible fuel savings measures on some combination of economics, feasibility, or low availability. This category includes solar, kites, and other wind energy devices. Even if a VLCC owner invests in such measures, he cannot reduce his conventional installed power since energy from these sources is not always available.

We rejected a couple of promising measures as unproven including hull cavity.

We realized that our designer will have to cope with the Tier II NOX requirements which will cost him 2 to 3 g/kWh or about 1%.

On the other hand, it is true that the massive, post-2005 increase in bunker prices has resulted in a number of measures which were not economic at $200 per ton Bunker Fuel Oil (BFO) now being economic at $450 per ton BFO. But when we added them up, rejecting those we regarded as imprudent or unproven, we were hard pressed to produce more than a 9% saving in EEDI.

About half of this savings was due to Waste Heat Recovery (WHR). With an investment of about 1.3 million dollars, it is possible to extract enough energy from a VLCC's cooling water and main engine exhaust to drive a 1000 kW generator, and meet a VLCC's normal at sea electric power requirements. The overall fuel savings is of the order of 4%. At current BFO prices, these WHR systems have a payback period of less than 2 years for a VLCC, and owners are flocking to install advanced WHR. In August, 2010, Wartsila counted 81 big ships including 33 VLCC's that have ordered Wartsila's version of WHR.[1]

A number of these now economic measures (for example, electronically controlled engines, variable pitch turbo-chargers, and multi-speed pumps) result in a substantial improvement in VLCC fuel efficiency at low loads, but have little or no impact on the ship's EEDI which is based on 75% MCR. Perhaps the single most important recent technological development is the ability of VLCC main engines to operate well below 50% load continuously and do it quite efficiently. This major change is ignored by EEDI.

A common feature of just about all the measures that make sense is that they will be implemented without any regulation.[2] In the jargon, they have *negative abatement cost*, meaning that the owner's

---

[2] As will be new, still unproven technologies that turn out to be truly effective. Perhaps the number 1 candidate in this category is air cavity.

bottom line will be improved by investing in them in his newbuildings. Most of them are already being implemented.

The problem for our VLCC designer is that, if you add up all the prudent, proven measures you are talking at most a 9% improvement in fuel consumption at 75% installed power, the EEDI design point.[3] This just gets him down to the Baseline. For the great bulk of his reduction in EEDI, he will have to reduce installed power.

3 VLCC Slow-steaming

3.1 Background

Before we can estimate the impact of mandating a reduction in installed power, we must understand *slow-steaming*. The relationship between EEDI and tanker CO2 emissions is an indirect one. The amount of CO2 emitted by a VLCC (or any ship) depends ***not*** on the fuel consumption at installed power (or 75% of installed power), but on the power that the owner/term charterer actually uses and the fuel consumption at that power. The power that a VLCC owner/term charterer will actually use depends on three things:

1. the current VLCC spot rate,
2. the owner's/term charterer's current fuel cost,
3. the ship's speed/consumption curve.

In any market situation (spot rate and bunker cost), the owner/term charterer will adjust the ship's steaming speed to maximize his daily net earnings, or equivalently for the term charterer, minimize his unit cost of transportation.[4]

As Figure 1 shows, the VLCC market, an example of nearly textbook competition, is extremely volatile. The spot rate can vary by a factor of ten in a matter of months. At the bottom of the market, the owner will barely be paying his fuel bill. In a full scale boom, the entire $100,000,000 ship can be paid off in a dozen voyages.

The spot market cannot go below the owner's *Layup Rate* for any length of time. The Layup rate is the rate below which the owner is better off laying up his VLCC, rather than continuing to trade. In Worldscale terms, the VLCC lay-up rate is usually in the very high 20's.

In the very long run, the spot rate must average the *Required Freight Rate (RFR)*. The RFR is the spot rate the owner would have to average over the ship's life in order to just break even on his investment, including his opportunity cost of capital. If over the very long run, the market averaged a spot rate higher than RFR, this would attract more investment in VLCC's and depress the rate. If over the very long run, the market averaged a spot rate less than RFR, then capital would move out of the VLCC market raising the rate.

The VLCC Required Freight Rate over the last two decades is a bit of a moving target for several reasons, but mainly because the newbuilding price of a VLCC is constantly changing. When the shipbuilding market is very strong, the price of a VLCC can be double that when the yards are desperate for business. But once again, over the long-run, the average newbuilding price has to be somewhere near the yards' present valued cost of building the ship, or we'd have capital continually flowing into or out of shipbuilding. A reasonable estimate of the average VLCC RFR over this period is WS62 +/- 5 Worldscale points. See Appendix A. As Figure 1 shows, the actual average average was WS63.2. In short, the actual average spot rate is about where we would expect it to be.

3.2 Spot Rate Profile

Figure 2 is a histogram showing the fraction of the time the market spent at each spot rate, between 1989 and 2009 inclusive. For the purposes of this diagram, we broke the rates down into 10 Worldscale point intervals. As Figure 2 shows, the market spends most of its time between the Layup Rate (usually in the high twenties) and RFR (usually in the low sixties) with occasional spikes much higher in booms. For this 21 year period, the market was above WS 100 about 9% of the time and at or below the RFR about 70% of the time, a highly skewed distribution. During a boom, rates can easily be 3 or 4 times the RFR, which means the market must spend a lot of time below RFR to compensate.

Table A shows the actual numbers. The column labeled "Standard" is the *market rate profile* which we used in averaging CO2 emissions over a market cycle. In this profile, all rates above WS100 are considered to be full boom, and mapped to WS200. Our Standard rate profile is a reasonable approximation to the observed rates below WS100; but is intentionally biased upward, that is, in favor of the lower powered, EEDI compliant ship above WS100. The Standard profile has an average Worldscale of 70.9, comfortably above a newbuilding RFR, even for $620 bunkers. More importantly, in any market above WS100, it artificially speeds up the non-EEDI BASE ship more than the EEDI compliant ship — which is often already at or near max speed at WS110 — improving the lowered powered ships' advantage in emissions at the high end of the market.

---

[3] greenship.org, a group that generally takes an optimistic view of the potential for vessel emissions reductions, studied a 35,000 ton bulk carrier to which they fitted just about every device applicable, and ended up with a 7% decrease in CO2 emissions.[9]

[4] It is well known that both the real owner in the spot market and a term charterer face essentially the same speed optimization problem. See for example [3, Apprendix B] for a proof. Henceforth, I will shorten the klunky "owner/term charterer" to "owner" with the understanding that, for a term chartered tanker, the term charterer is the effective owner.

Table A. Actual and Standard Rate Profiles

World scale	Observed fraction	Standard fraction
20	0.012	0.00
30	0.067	0.08
40	0.230	0.20
50	0.163	0.20
60	0.230	0.20
70	0.056	0.06
80	0.056	0.06
90	0.052	0.05
100	0.044	0.05
110	0.020	
120	0.028	
130	0.008	
140	0.020	
150	0.004	
180	0.008	
200	0.000	0.10
240	0.004	

4 The BASE Route and Ship

4.1 Standard Route

In order to estimate VLCC CO2 emissions over a market cycle,

1. we must first figure out what the owners will do as a function of the spot rate,
2. then, using our market rate profile, combine these numbers to obtain his average CO2 emissions over a market cycle.

We will perform these calculations for a standard (no EEDI) VLCC and a standard route. We will them study various EEDI compliant variations of the standard ship on the same route.

The particulars of the route we will use for all our calculations are shown in Table 1. The route is Fujairah to Ras Tanura to Yokohama to Fujairah via Malacca both ways. The ship was bunkered for the round trip at Fujairah. For these parameters none of the loadlines nor the Malacca draft requirement is limiting. The cargo limiting restriction is arrival draft at Yokohama. This route is reasonably representative of most VLCC voyages. The SFC adjustment corrects for overly optimistic book (manufacturer) SFC figures mainly due to an unrealistically high fuel Net Calorific Value (NCV).

The cargo value (about \$80 per barrel) and interest rate (5%) are used to compute the in-transit inventory carrying cost. Currently, oil companies tend to be rather cavalier about inventory carrying cost, for the most part ignoring them. This might be semi-forgivable when one is dealing with a difference of a day or two in loaded leg time. But since we will be dealing with a very wide range of vessel speeds, we really don't have this luxury. Therefore, our VLCC steaming speeds will be set to minimize the charterer's total cost of transporting a ton of oil including his inventory carrying costs.

We also made some test runs in which we set inventory carrying cost to zero. The ***relative*** differences between the non-EEDI and EEDI ships were almost unchanged. The main effect of including inventory carrying costs is to speed both ships up on the loaded leg at the bottom of the market. Within reason, whatever you assume about inventory carrying costs will not change our bottom line conclusions about the effectiveness of EEDI for VLCC's.

4.2 Standard Ship

Fortunately, for our purposes, almost all VLCC's are very similar. The single most important characteristic of a VLCC from a CO2 point of view is the loaded and ballast speed/fuel consumption curves. The speed/fuel curves in turn are based on three curves:

1. The hull resistance curve, which determines the amount of power the hull requires as a function of speed.
2. Propulsive efficiency curve which determines the fraction of the main engine power that is converted to thrust to drive the hull.
3. The engine Specific Fuel Consumption (SFC) curve which determines the amount of fuel the engine needs to produce a given amount of power.

4.2.1 Hull form

In all our calculations, we kept the hull form constant. The hull we used is that studied by Min et al.[7] In the Min paper, our hull form is labeled Extreme V. It is clearly, the best of the three studied. The design draft (20.95 m) resistance curve of this hull is shown in Figure 3. It is close to cubic up to Froude number of 0.14 (15 knots) above which it turns upward a bit faster than cubic. To convert this design draft curve (wetted surface = 27,271 m2) to loaded and ballast curves, we assumed resistance was proportional to wetted surface and a loaded/ballast wetted surface of 28,500/21,000 m2.

4.2.2 Propulsive efficiency curve

Our base ship uses a four bladed, 9.93 m propeller, with a constant propulsive efficiency (PE) of 0.73. In reality, PE will vary with speed, but for this hull form and propeller, the variation was less than 1% over a range from 40% full power to 100% full power. If the torque characteristics of an engine forces it to use a smaller propeller, we assumed Propulsive Efficiency goes as 0.25 power of diameter. Thus an 8.0 meter propeller will have a Propulsive Efficiency of 0.69.

4.2.3 Specific Fuel Consumption Curve

The base Specific Fuel Consumption Curve we will use is that for the Wartsila 7RTA84T engine. This is a standard seven cylinder engine used by many VLCC owners. It has an MCR (Maximum Continuous Rating) power of 27,516 kW at 76 RPM, at which point it has a book SFC of 168.0 g/kWh. The competitive engines have very similar characteristics. For reasons which will become clear we also studied 6, 5, and 4 cylinder engines with the same bore and stoke. These are essentially the same engine with less cylinders. The 5 and 4 cylinder variants don't actually exist because they would have extremely poor vibration characteristics, but for now we ignore that.

5 VLCC Speed/Fuel Curves

5.1 Speed/Fuel Curves for Existing VLCC's

Putting all our assumptions together, we arrive at the speed/fuel curves shown in Table 2 for existing VLCC's. The ship labeled 7RTA84T-D is a standard 7 cylinder, camshaft controlled VLCC. Most VLCC's currently trading will look pretty much like this ship. The ship labeled 6RTA84T-D is the same ship but fitted with a six cylinder engine of the same make and model. The third and fourth ships are imaginary; they are infeasible due to vibration problems. They were produced by simply removing additional cylinders from the same engine. All four designs use the same propeller. In all four cases, the ***book*** SFC at MCR is 168.0 g/kWh.[5]

According to Table 2, the 7 cylinder ship has a poorer fuel consumption below about 14 knots loaded than the lowered powered ships as the SFC starts to climb with lower load. The 7 cylinder ship is also very limited as to how slow it can go. This is misleading. For a modest investment, the owner of the 7 cylinder ship can do everything the lower powered ships can do, including the vibrationally challenged 5 and 4 cylinder ships. To do this he must invest in a cylinder cut out system (less than $30,000) and variable pitch or multiple turbo-charger fans (about $150,000). He can pay for this with a savings of 400 tons of fuel. At that point, he will be able to have the best of all worlds picking out the best SFC for each power in Table 2. And unlike the four and five cylinder engines, he will not have a vibration problem. The momentarily unused cylinders are in effect balancers. The resulting ship is shown in the rightmost column. This ship is also a decent approximation for an electronically controlled VLCC fitted with a complete set of slow-steaming mods. Despite the big improvement over the unmodified leftmost ship at low load, our BASE VLCC has the same EEDI, 2.54. Akiyama and Tagg came up with an EEDI of 2.53 for their standard VLCC which is a slightly smaller ship.[8] So this appears to be a reasonable number for existing VLCC's.

5.2 The Base Speed Fuel Curves for Newbulding VLCC's

When we take advantage of additional Waste Heat Recovery (about 4% reduction) and assume other true improvements in efficiency amounting to 5% in total, we obtain the following newbuilding counterparts to the ships in Table 2. The ship on the right will be our BASE newbuilding VLCC, the ship that would be built with no new regulation. This ship has an EEDI of 2.32, well above the Phase 1 requirement of 2.09.

6 Phase 1 EEDI

6.1 Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 1 reduction is 10% resulting in a required EEDI of 2.09. A glance at Table 3 reveals that our BASE 7 cylinder ship is illegal, but the six cylinder ship just meets the proposed Phase 1 requirement.

Tables 4 and 6 show the slow-steaming tables for these two ships for an assumed bunker cost of $465 per ton, about the current market price. Both ships were placed on our standard Ras Tanura-Yokohama route. These tables display the owner's optimal average (loaded/ballast) steaming speed as a function of spot rate, the resulting round trip fuel consumed, the owner's net earnings in $/day term charter equivalent, round trip voyage time, cargo per trip, and the barrels per day delivered.

These numbers were computed using the MFIX package which was the standard voyage analysis software used by Hellespont Shipping between 1995 and 2002 in operating their fleet of VLCC's and ULCC's. This program optimizes loaded and ballast speed in half-knot increments, so the speed-up can be a little jumpy.

The column on the right shows the tons CO2 emitted per ton per day cargo delivered. This column adjusts the fleet size to achieve the same tons per day delivered; but does ***not*** adjust CO2 emissions for the additional Build/Repair/Scrap emissions, nor the CO2 produced by flying more crews around, extra cargo evaporation, etc, associated with slower speed and a bigger fleet.

Comparing Tables 4 and 6, below WS80, both ships are going the same speed, so there is no difference. Between WS90 and WS140, the more fuel efficient (at these speeds) 7 cylinder ship speeds up a bit faster, and the 6 cylinder ship produces 1 to 2% less CO2 per ton delivered per period. Between WS140 and 190, the lowered powered ship is going as fast it can, and the difference is about 4%. The higher powered ship still has one gear left, which it

---

[5] This is a manufacturer figure based on a fuel NCV that doesn't exist, optimistic ambient and NOX conditions. We will correct for this in the actual voyage calculations.

uses as WS200. At WS200 and above, the difference is about 6%. Table B summarizes this comparison. Under our Standard spot rate profile, over a market cycle a fleet of the BASE ships would average 1.238 tons of CO2 per ton per day delivered; a fleet of the 6 cylinder ships would average 1.226 tons of CO2/TPD. Despite our rate profile being intentionally biased toward the lowered powered ship, we end up with a 1% reduction in VLCC CO2 emissions due to Phase 1 EEDI. Due to the tenuous connection between installed power and power actually used, a 10% reduction in EEDI results in little reduction in operational CO2 emissions over a market cycle.

Table B. Phase 1 Percent Reduction in CO2, BASE vs 6 cylinder ship. BFO=$465

WS	Avespd BASE	Avespd 6CYL	Ratio CO2	% Diff.
30	10.25	10.25	1.0000	-0.0
40	10.74	10.74	1.0000	-0.0
50	11.19	11.19	1.0000	-0.0
60	11.97	11.97	1.0000	-0.0
70	13.20	13.20	1.0000	-0.0
80	14.24	14.00	0.9820	-1.8
90	15.00	14.75	0.9846	-1.5
100	15.49	15.25	0.9948	-0.5
110	15.99	15.49	0.9732	-2.7
120	16.25	15.94	0.9903	-1.0
130	16.49	15.94	0.9747	-2.5
140	16.72	16.17	0.9762	-2.4
150	16.83	16.17	0.9632	-3.7
160	16.83	16.17	0.9632	-3.7
170	16.83	16.17	0.9632	-3.7
180	16.83	16.17	0.9632	-3.7
190	16.83	16.17	0.9632	-3.7
200	16.97	16.17	0.9427	-5.7
Average	1.238	1.226		-1.0

When we throw in the seven cylinder ship's superior heavy weather performance, and the fact that in a boom we would need 4.4% more six cylinder ships to move the same amount of oil and thus 4.4% more B/R/S emissions, the difference in CO2 emissions is in the noise. It is also obvious from these tables, that, over a market cycle, the seven cylinder engine is on average operating at a considerably lower percent of MCR which means a substantial decrease in main engine failures.

Finally, this 1% difference in CO2 applies only to the ships that will be built under Phase 1. The regulation does not apply to existing ships; so the great bulk of the fleet will be unaffected for over ten years.

6.2 Slow-steaming curves for $620 BFO cost

If you repeat these analyses for a BFO cost of $620 per ton, you will find that the difference in CO2 emissions from the two ships over a market cycle is even smaller than for $465 BFO cost. See [4] for the details. As rates improve, both ships speed up more slowly. The lowered powered ship does not reach its speed constraint until WS180. Below WS110, there is no difference; between WS110 and WS200 the difference is about 2%, and it is not until you get to WS270, that we see the both-ships-at-full-speed 6% difference. Using our Standard spot rate profile, the BASE ship averages 1.161 tons of CO2/TPD, the EEDI compliant ship 1.152, a difference of 0.8%.[6]

6.3 The Impact of a $50 per ton CO2 Carbon Tax

A far more interesting comparison is to match the slow steaming curve for the BASE ship at $465 bunkers, Table 4, with the slow steaming curve for the same ship at $620 bunkers, Table 5, as Table C does. If the $150 difference in owner's fuel cost is caused by a $50 per ton carbon tax (or equivalent cap-and-trade permit price), what we are looking is how a VLCC owner would react to a $50 per ton CO2 carbon emissions price, assuming no EEDI.

Table C. Percent Reduction CO2, $50/ton CO2 tax BASE ship at $465 versus $620 BFO cost

WS	Avespd 465	Avespd 620	Ratio CO2	% Diff.
30	10.25	9.98	0.9854	-1.5
40	10.74	9.98	0.9472	-5.3
50	11.19	10.50	0.9307	-6.9
60	11.97	10.74	0.9197	-8.0
70	13.20	11.74	0.8965	-10.4
80	14.24	12.24	0.8865	-11.3
90	15.00	13.24	0.9094	-9.1
100	15.49	14.00	0.9224	-7.8
110	15.99	14.50	0.9141	-8.6
120	16.25	15.25	0.9301	-7.0
130	16.49	15.49	0.9262	-7.4
140	16.72	15.75	0.9290	-7.1
150	16.83	15.99	0.9297	-7.0
160	16.83	16.49	0.9678	-3.2
170	16.83	16.49	0.9678	-3.2
180	16.83	16.72	0.9867	-1.3
190	16.83	16.72	0.9867	-1.3
200	16.97	16.83	0.9787	-2.1
210	16.97	16.83	0.9787	-2.1
220	16.97	16.83	0.9787	-2.1
230	16.97	16.83	0.9787	-2.1
240	16.97	16.83	0.9787	-2.1
250	16.97	16.83	0.9787	-2.1
260	16.97	16.83	0.9787	-2.1
270	16.97	16.97	1.0000	-0.0
Average	1.238	1.161		-6.2

At WS30, the owner will go nearly the same speed at both BFO costs, so there is only a 1.5% difference in CO2 per TPD. However, the owner speeds up more slowly in the face of $620 BFO cost than he does for $465 BFO.[7] Between WS50 and WS150,

---

[6] The RFR and the long run average of the spot rates will be about 5 Worldscale points higher (assuming the same flat rate as we have) for $620 bunker cost than for $465 bunker cost. This is one of the reasons we biased our Standard profile toward the high end.

[7] The long-run average Worldscale rate will be about 5 WS points higher in a $620 BFO cost world than a $465 BFO cost world. To be totally correct we should compare, say, WS50 and $465 BFO with WS55 and $620 BFO; but, as Table C shows, it wouldn't make that much difference.

which is where the market spends almost all its time, the difference in adjusted CO2 emissions is about 8%. Above that the difference starts falling but is still around 2% at WS250. It is not until the market gets to WS270 or above that the owner will steam as fast at $620 BFO as he does at $465.

If we assume our Standard spot rate profile, we find that, over a market cycle, the ship averages 1.238 tons CO2/TPD at $465 BFO and 1.161 at $620, a difference of 6.2%.

It is extremely important to focus on how the bunkers tax achieves this reduction. Below about WS130 — in other words almost all the time — the non-EEDI compliant ship with the tax (Table C) is steaming ***more slowly*** than the Phase I EEDI compliant ship without the tax (Table B). ***It is only in full boom that the non-EEDI ship with tax steams faster than the Phase I EEDI compliant ship without the tax***. But this is exactly what we want for it avoids wastefully expending resources on additional ships, just to handle a boom.[8]

6.4 Summary

Speed reduction is not a **measure** as most vessel CO2 emissions studies would have us believe. ***It is*** **a reaction**. It is the owner/term charterer's reaction to the current spot rate, his bunker cost, and his speed-fuel curve. At current and likely bunker prices, a well-designed VLCC will be operating at maximum speed only in a full scale boom, less than 10% of the ship's life. Most of the time, the ship will be operating at a percentage of full power, often much less than full power.

EEDI affects this reaction indirectly by reducing the owner's max speed The net effect over a market cycle is that the Phase 1 EEDI requirement will reduce VLCC operational CO2 emissions by 1% or less for the ships that are actually affected by this regulation while at the same time increasing the amount of resources society must devote to the VLCC sector, and reducing safety.

An increase in bunker cost affects the owner's reaction directly. This could be accomplished most simply and most efficiently by a carbon based bunkers tax. Over a market cycle, a $50 per ton CO2 BFO tax would reduce VLCC CO2 emissions by more than 6% and it would apply to the entire fleet, and it would do so without EEDI's expensive and pernicious side-effects.

So far throughout this analysis we have been acting as if society's goal were to minimize CO2 emissions. In fact, the goal is (or at least should be) minimizing the sum of the societal cost of CO2 plus all the other costs associated with moving the oil. The six cylinder ship will have a market cost which is about 1.2 million dollars less than the 7 cylinder, a savings of about 1.3% in initial cost. But as we have seen we will need about 4% more of them, so the 7 cylinder ship has a clear superiority here. This of course is why almost all existing VLCC's have the power they do. By forcing owners to buy less power than they would have, we are forcing the world to devote more scarce resources to building VLCC's. Any intelligent regulatory policy would take this into account.

7 Phase 2 EEDI

7.1 Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 2 reduction is 25% resulting in a required EEDI of 1.74. A glance at Table 3 reveals that our imaginary 5 cylinder ship is illegal, but the 4 cylinder would easily meet the EEDI requirement. Unfortunately, neither of these engines have acceptable vibration characteristics. To meet the EEDI requirement with a 6 cylinder engine, the owner will have to go down to a 650 mm bore cylinder. The engine we will use for Phase 2 is a MAN 6S65ME with an MCR of 17,220 KW at 95 RPM. This increase in RPM will reduce the propeller diameter from the BASE ship's 9.9 m to about 7.1 m. This will result in about an 8% loss in propulsive efficiency. On top of this, the smaller bore engine has a 3 g/KW-hr (2%) disadvantage in SFC.

Table 7 shows the fuel consumption curves for this engine for 6 through 3 cylinders. As usual we examine vibrationally infeasible engines to study the impact of cylinder cutout. This engine still does not quite meet the Phase 2 EEDI requirement. Therefore he will have to derate the engine slightly to an MCR of 16,500, resulting in the fuel consumption curve at the far right.[9]

Table 8 show the slow-steaming table for this ship for a bunker cost of $465 per ton. If we compare this ship with the non-EEDI BASE ship from Table 4, we obtain Table D.

These numbers are biased in favor of the lower powered ship. They are calm water numbers plus a 15% sea margin for both ships. In reality, in heavy weather the low powered ship's performance will deteriorate more rapidly than the higher powered ship's. The low powered ship will suffer a larger speed reduction due to prop cavitation and limited

---

[8] In jargon, the marginal social value of VLCC capacity is at least 10 times higher in a boom than a slump. A tax adjusts efficiently to this changing valuation. EEDI does not. For a more complete discussion, see [5].

[9] The owner could have drastically derated the six cylinder 840 mm bore engine to meet the EEDI requirement. This would give him a slightly better SFC curve and more importantly avoid the loss in propulsive efficiency. But to do so, he would have to purchase a 23,000 kW engine and "throw away" some 6,000 KW. This would increase his initial cost by at least 1.4 million dollars. Owners are not in the habit of buying power they can't use. Almost all owners will go the cheaper route. Drastic derating is explored further in Section 9.

torque; but also that larger reduction will be from a smaller base. A 2 knot reduction from 13 knots will increase voyage time by 18%. A 2 knot reduction from 15 knots will increase voyage time by 15%.

Table D. Phase 2 Percent CO2 Reduction
BASE ship vs 6S65ME at $465 BFO cost

WS	Avespd BASE	Avespd 6S65	Ratio CO2	% Diff.
30	10.25	9.50	1.0269	+2.7
40	10.74	9.97	1.0392	+3.9
50	11.19	10.39	1.0461	+4.6
60	11.97	11.19	1.0480	+4.8
70	13.20	12.24	1.0136	+1.4
80	14.24	13.25	1.0340	+3.4
90	15.00	13.49	1.0083	+0.8
100	15.49	13.72	1.0029	+0.3
110	15.99	13.93	0.9939	-0.6
120	16.25	13.93	0.9701	-3.0
130	16.49	14.12	0.9758	-2.4
140	16.72	14.12	0.9571	-4.3
150	16.83	14.12	0.9444	-5.6
160	16.83	14.12	0.9444	-5.6
170	16.83	14.12	0.9444	-5.6
180	16.83	14.12	0.9444	-5.6
190	16.83	14.12	0.9444	-5.6
200	16.97	14.12	0.9242	-7.6
Average	1.238	1.263		+2.0

But assuming calm water, below WS100, the BASE ship puts out less CO2 thanks to its more efficient propeller and engine. At WS110 and above the BASE ship is steaming faster than the Phase 2 ship, and the CO2 balance shifts in favor of the speed limited, lower powered ship. At WS200, an all-out boom, a fleet of EEDI-compliant VLCC's produces 8% less operational CO2 than a fleet of BASE ships. In this situation, we need 18% more EEDI-compliant ships to move the same amount of oil.

If we apply our Standard spot rate profile to this comparison, we find that a fleet of the non-EEDI ships averages 1.238 tons CO2/per ton per day delivered; the EEDI compliant ships average 1.263. The overall effect of EEDI Phase 2 at this bunker price is to ***increase*** VLCC CO2 emissions by about 2%.

Gratsos et al argue that at least 2.15 tons of CO2 are produced per ton of ship steel in the building and scrapping process.[6] If we assume a VLCC lightweight of 43,000 tons and a 25 year ship life, then building/scrapping emissions are about 3.4% of operational emissions. With these numbers, an 18% larger fleet is equivalent to a 0.6% increase in operational emissions.

7.2 Slow-steaming curves for $620 BFO cost

We repeated these analyses for $620 bunkers.[4]. Once again the higher bunker price shifted the numbers in favor of the BASE ship. Both ships speed up more slowly at higher BFO cost, extending the Worldscale range over which the more fuel efficient, higher powered ship produces less CO2. In all markets except an all-out boom, the non-EEDI fleet emits less CO2 than the Phase 2 fleet. Assuming the Standard spot rate profile, the non-EEDI BASE fleet averages 1.161 tons CO2/TPD; the EEDI compliant fleet 1.180.

7.3 Summary

- The Phase 2 EEDI regulations will not result in any noticeable decrease in operational VLCC CO2 emissions over a market cycle. In fact, it is likely that the net effect will be to increase VLCC operational CO2 emissions slightly. The fuel savings due to forcing the owner to go slower in booms are balanced by the inefficiencies associated with a much smaller than optimal power plant for this sized ship. These are calm water numbers. In heavy weather, the balance shifts further in favor of the non-EEDI ship.
- The Phase 2 regulations will eventually result in a 18% larger fleet. The resulting increase in building/scrapping emissions will be equivalent to about another 0.6% increase in operational emissions.
- The Phase 2 regulations will require that just about 18% more of the world's resources be devoted to VLCC transportation, great news if you are a shipyard.
- The Phase 2 regulations will increase our exposure to VLCC casualties by 18% even before we account for the fact that the EEDI compliant ship will be less maneuverable, less able to get out of trouble than the non-EEDI ship.

8 Phase 3 EEDI

8.1 Slow-steaming curves for $465 BFO cost

The proposed VLCC baseline EEDI is 2.32, and the proposed Phase 3 reduction is 35% resulting in a required EEDI of 1.51. To meet the EEDI requirement with a 6 cylinder engine without throwing away a lot of power, the owner will have to go down to a 600 mm bore cylinder. The engine we used for Phase 3 is a MAN 6S60ME with an MCR of 14,280 KW at 105 RPM. According to MAN, this engine has the same SFC curve as the 650 mm bore engine, but the increase in RPM and consequently smaller propeller will result in a 4% loss in propulsive efficiency relative to the 650 mm bore machine.

Even with the reduction in bore, this engine normally rated does not meet the required EEDI of 1.51. The owner will have to derate the engine to an MCR of about 13,200 kW. ***Phase 3 will require VLCC owners to cut installed power in half.***[10]

---

[10] Simple prudence dictates that the impact of halving installed power on heavy weather performance and maneuverability should be studied by a properly equipped sea keeping program prior to imposition of EEDI.

The details of these Phase 3 calculations can be found in the CTX report.[4]. Table E summarizes the $465 BFO results. This ship is so under-powered that at WS90, she is already going as fast as she can. This ship's engine will be pushed hard. The Phase 3 VLCC fleet will need to be 29% larger than the BASE fleet to move the same amount of oil in a boom. And that's in calm water. This ship will have lousy heavy weather performance. If we apply our Standard spot rate profile to these numbers, the non-EEDI BASE fleet averages 1.238 tons of CO2 per ton per day delivered; the EEDI-compliant fleet averages 1.259.

Table E. Percent CO2 Reduction,
BASE ship vs 6S60ME at $465 BFO cost

WS	Avespd BASE	Avespd 6S60	Ratio CO2	% Diff.
30	10.25	8.97	1.0453	+4.5
40	10.74	9.38	1.0660	+6.6
50	11.19	9.89	1.0437	+4.4
60	11.97	10.97	1.0545	+5.4
70	13.20	11.84	1.0293	+2.9
80	14.24	12.35	1.0078	+0.8
90	15.00	12.82	1.0044	+0.4
100	15.49	12.82	0.9816	-1.8
110	15.99	12.82	0.9464	-5.4
120	16.25	12.82	0.9237	-7.6
130	16.49	12.82	0.9092	-9.1
140	16.72	12.82	0.8918	-10.8
150	16.83	12.82	0.8799	-12.0
160	16.83	12.82	0.8799	-12.0
170	16.83	12.82	0.8799	-12.0
180	16.83	12.82	0.8799	-12.0
190	16.83	12.82	0.8799	-12.0
200	16.97	12.82	0.8611	-13.9
Average	1.238	1.259		+1.6

8.2 Slow-steaming curves for $620 BFO cost

We repeated the Phase 3 analyses for $620 BFO.[4]. When you apply our Standard spot rate profile to the resulting numbers, the non-EEDI BASE ship averages 1.161 tons of CO2 per ton per day delivered; the EEDI-compliant vessel averages 1.181.

8.3 Summary

The Phase 3 results followed a now familiar pattern.

- Even assuming calm water, a Phase 3 EEDI compliant VLCC fleet will not produce less CO2 emissions than an non-EEDI fleet, despite the drastic reduction in installed power. In fact, the numbers indicate that, over a market cycle, the net effect of Phase 3 EEDI will be to increase calm water VLCC CO2 emissions by about 2%, even before we adjust for the differences in heavy weather performance.
- The Phase 3 regulations will eventually result in a 29% larger fleet, Using the Gratsos numbers of Section 7, the resulting increase in building/scrapping emissions is equivalent to about another 1.0% increase in operational emissions.
- The Phase 3 regulations will require that at least 29% more of the world's resources be devoted to VLCC transportation.
- The Phase 3 regulations will increase our exposure to VLCC casualties by 29% even before we account for the fact that the dangerously under-powered EEDI compliant VLCC will be less reliable and less maneuverable than the non-EEDI ship.

9 A Saintly VLCC Owner's Response to Phase 2 EEDI

9.1 Saintly Slow-steaming curves for $465 BFO cost

A basic problem with EEDI is that, in mandating a reduction in installed power, we induce VLCC owners to fit a less efficient engine and more importantly a smaller propeller. Suppose we could somehow assume away this problem. Perhaps we have a saintly VLCC owner who decides to purchase the same engine he would have used in the absence of EEDI and derate it as necessary. To meet the Phase 2 requirement, this saint must derate our BASE non-EEDI engine so that the de-rated MCR is 65% of the original. This ship will cost him about 2.5 million dollars more than that assumed in Section 7, but this public spirited individual feels this is a small price to pay to contribute to the reduction in CO2. Perhaps only slightly more plausibly, we suddenly discover a technology that avoids the deterioration in SFC and loss of propulsive efficiency of Sections 7 and 8. Either way we will end up with the Table 3 speed/fuel curve except that the max loaded/ballast speed will be 14.0/15.5 knots. The slow-steaming curve is also the same except for the lower speed limit. Once again see [4] for the details.

Comparing this ship with the BASE un-derated ship, we obtain Table F. Below WS 80 both ships are at the same speed and there is no difference. But at WS80, the derated ship begins hitting her max speed limits. Between WS 80 and WS150, her CO2 per TPD advantage increases to about 14%, and finally to 16% at WS200 when both ships are going full speed.

Applying our Standard rate profile to these numbers, the BASE ship averages 1.238 tons of CO2 per ton delivered per day, the derated ship averages 1.205. Over a market cycle, the derated ship produces 2.7% less CO2 than the non-derated ship.

Table F. Phase 2 Percent Reduction in CO2. BASE vs BASE derated 35%. BFO=$465

WS	Avespd BASE	Avespd DERATE	Ratio CO2	% Diff.
30	10.25	10.25	1.0000	-0.0
40	10.74	10.74	1.0000	-0.0
50	11.19	11.19	1.0000	-0.0
60	11.97	11.97	1.0000	-0.0
70	13.20	13.20	1.0000	-0.0
80	14.24	14.00	0.9820	-1.8
90	15.00	14.49	0.9648	-3.5
100	15.49	14.72	0.9558	-4.4
110	15.99	14.72	0.9215	-7.8
120	16.25	14.72	0.8994	-10.1
130	16.49	14.72	0.8853	-11.5
140	16.72	14.72	0.8683	-13.2
150	16.83	14.72	0.8568	-14.3
160	16.83	14.72	0.8568	-14.3
170	16.83	14.72	0.8568	-14.3
180	16.83	14.72	0.8568	-14.3
190	16.83	14.72	0.8568	-14.3
200	16.97	14.72	0.8385	-16.2
Average	1.238	1.205		-2.7

9.2 Saintly Slow-steaming curves for $620 BFO cost

When we repeated these anaylses for $620 bunkers, we found that both ships go the same speed up to WS100, after which the un-derated ship starts using her superior speed.[4] Applying our Standard rate profile over a market cycle, the BASE ship averages 1.161 tons CO2 per TPD, and the derated ship 1.134, for a 2.4% operational CO2 per TPD advantage. We will require about a 9% larger fleet of the derated ships to move the same amount of crude in a boom.

9.3 Summary

Even if we somehow assume away the inefficiencies associated with a smaller engine and a smaller propeller, a 25% reduction in EEDI will reduce actual VLCC operational CO2 emissions by less than 3%. The failure of a percentage reduction in EEDI to produce anything like the same reduction is CO2 is the product of three factors:

1. EEDI does not limit CO2 emissions. EEDI effectively limits installed power. But at current and expected bunker prices, a non-EEDI VLCC owner uses all his installed power only in a full boom, or about 10% of the ship's life. So for the great bulk of her life, a non-EEDI ship uses little or no more power than an EEDI compliant ship
2. In limiting installed power, EEDI induces owners to use smaller bore, higher RPM engines which means that the EEDI-compliant VLCC will consume more fuel than the non-EEDI ship when the market is not in boom, which is most of the time.
3. When the market is in boom, the only period in which the non-EEDI ship really uses her superior speed, we need more EEDI compliant ships to move the same amount of oil, cutting into the EEDI-compliant ship's advantage in this market, while increasing BRS emissions.

Even if we somehow could make factor (2) disappear, the reduction in actual operational VLCC CO2 emissions would still be about a tenth of the reduction in EEDI. Even under impossibly optimistic set of assumptions, EEDI is a strikingly ineffective means of reducing VLCC CO2 emissions.

As we've seen, under more realistic assumptions, EEDI actually ***increases*** VLCC CO2 emissions slightly. Our saintly owner may only be 2 to 3% better than a non-EEDI tanker, but he is 4 to 5% better than his avaricious, but EEDI-legal competitors. Hopefully, he finds comfort in this.

A VLCC Required Freight Rate

The right way to compute Required Freight Rate is to combine the investment parameters with a market rate profile, allowing the ship to use the optimal speed for whatever market it is currently in. Then adjust the profile so the investment just breaks even, and find the average of that break even profile. The standard and incorrect way to compute RFR is to assume a constant market rate throughout the ship's life, and find that rate for which the investment just breaks-even. We will use this second, incorrect approach both because it is the standard definition of RFR and it is close enough for present purposes.

MFIX has the capability of computing standard RFR's, so we can use the same route, etc that we used in the slow-steaming calculations. The ship we used was our non-EEDI BASE VLCC.[11] For representative financial parameters, we fixed the following:

Yard Terms	10/10/10/0/70
Loan Terms	60 million at 7.7%, 7 years, level
OPEX	$9000 per day
Drydocking	Every 4 years, 45 days, $3,000,000
Inflation	3% per year
Scrap value	$400 per lt-ton, 43,000 ton ltwt

We varied ship price (80, 100, 120) million dollars, ship life (20, 25) years, discount rate (10%, 15%), and fuel price ($465, $620) per ton. Table G summarizes the results.

---

[11] The EEDI compliant ships will have a higher RFR representing the long-run market cost to society of the regulation.

Table G. Representative RFR's

20 year ship life				
	$465/t BFO			$620/t
Price	80mm$	100mm$	120mm$	100mm$
10%	WS54.7	WS59.6	WS64.5	WS67.5
15%	WS60.5	WS67.4	WS74.3	WS75.3

25 year ship life				
	$465/t BFO			$620/t
Price	80mm$	100mm$	120mm$	100mm$
10%	WS53.5	WS57.9	WS62.4	WS65.5
15%	WS59.7	WS66.2	WS72.8	WS74.1

Obviously, you can move these numbers around by varying the parameters, but a reasonable ball park figure for $465/t is high 50's, low 60's.

Since Worldscale is tied to bunker prices with a lag, the $620/t BFO numbers are not really applicable. If BFO cost did move to $620 for a year or so, then the Worldscale flat rate would be adjusted upward, pushing the RFR numbers back down to those we see for current bunker cost.

References

[1] D. Antonopoulos. Whr references — total 81 installations. Technical report, Wartsila, Ship Power Merchant, August 2010.

[2] Marine Environment Protection Committee. Interim guidelines on the method of calculation of the energy design index for new ships. Technical report, IMO, August 2009. MEPC 1/Circ.681, 2009-08-17.

[3] J. Devanney. The impact of bunker prices on vlcc spot rates. Technical report, Center for Tankship Excellence, 2009.

[4] J. Devanney. Detailed studies of the impact of eedi on vlcc design and co2 emissions. Technical report, Center for Tankship Excellence, 2010.

[5] J. Devanney. Eedi, a case study in indirect regulation of co2 pollution. Technical report, Center for Tankship Excellence, 2010.

[6] G. Gratsos, H. Psaraftis, and P. Zachariadis. Life cycle co2 emissions of bulk carriers: A comparative study. *Int. Journal of Maritime Engineering*, 2010. In press.

[7] K. S. Min and J. E. Choi. Study on the cfd application for vlcc hull-form design. In *24th Symposium on Naval Hydrodynamics*, 2003.

[8] Y. Ozaki, J. Larkin, K. Tikka, and K. Michel. An evaluation of the energy efficiency design index for tankers, containerships, and lng carriers. Technical report, ABS/Herbert Engineering, February 2010. Sname/Marine Board Symposium, 2010-02-16/17.

[9] C. Schack. Green ship of the future. Technical report, greenship.org, March 2010. Asia-Pacific Martime Conference, Singapore, March, 2010.

Table 1: Standard route/ship parameters

Summer Dwt	308,000	SDWT draft	22.600
Tons per m	16,980	Tons/m2	64.0
Cargo Cubic	350,000	Less%	2.00
Cargo density	0.85	Cargo value($/t)	600.00
Demurrage($/day)	25,000	Cargo interest	5%
Laytime(hrs)	72	Hrs to owner	48
Cylinder LO g/kWh	1.2	Cylinder LO $/T	1800
Brokers Commis %	1.25	Hotel TPD	10
Consumables(tons)	500	BFO Capacity tons	9,741
SFC Adjustment%	7.4	Speed adjustment	0.0
FUJA port charges	0	FUJA port hours	0
FUJA draft limit	99.9	FUJA port fuel (t)	0
FUJA/RAST miles	506	Sea Margin	15%
RAST port charges	27,000	RAST port hours	48
RAST draft limit	32.0	RAST port fuel (t)	50
RAST/YOKO miles	6593	RAST/YOKO WS FLAT	18.41
YOKO port charges	130,000	YOKO draft limit	20.9
YOKO port fuel (t)	250	YOKO/FUJA miles	6220

Table 2: Speed/Fuel Consumption Curves for Existing VLCC's

```
   LOADED   |   7RTA84T-D   |   6RTA84T-D   |Imaginary 5 cyl|Imaginary 4 cyl|7RTA84T-D  with|
SPEED|POWER |eedi=2.54      |eedi=2.30      |eedi=2.04      |eedi=1.77      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
10.50|  7507|       |       |       |       |       |       |  165.7|   29.8|  165.7|   29.8|
11.00|  8632|       |       |       |       |       |       |  164.0|   34.0|  164.0|   34.0|
11.50|  9863|       |       |       |       |  165.0|   39.0|  162.9|   38.6|  162.9|   38.6|
12.00| 11207|       |       |  165.7|   44.6|  163.6|   44.0|  162.6|   43.7|  162.6|   43.7|
12.50| 12667|  166.2|   50.5|  164.3|   49.9|  162.8|   49.5|  163.4|   49.7|  162.8|   49.5|
13.00| 14303|  164.6|   56.5|  163.0|   55.9|  162.7|   55.8|  165.1|   56.7|  162.7|   55.8|
13.50| 15946|  163.4|   62.5|  162.6|   62.2|  163.5|   62.6|       |       |  162.6|   62.2|
14.00| 17706|  162.8|   69.2|  162.8|   69.2|  165.0|   70.1|       |       |  162.8|   69.2|
14.50| 19626|  162.6|   76.6|  163.9|   77.2|  168.0|   79.1|       |       |  162.6|   76.6|
15.00| 21683|  163.2|   84.9|  165.3|   86.0|       |       |       |       |  163.2|   84.9|
15.50| 23928|  164.6|   94.5|       |       |       |       |       |       |  164.6|   94.5|
16.00| 26326|  166.8|  105.4|       |       |       |       |       |       |  166.8|  105.4|
MCR  SPD/TPD|  16.20|  110.9|  15.40|   95.1|  14.50|   79.2|  13.40|   63.4|  16.20|  110.9|

  BALLAST   |   7RTA84T-D   |   6RTA84T-D   |Imaginary 5 cyl|Imaginary 4 cyl|7RTA84T-D  with|
SPEED|POWER |eedi=2.54      |eedi=2.30      |eedi=2.04      |eedi=1.77      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
11.50|  7268|       |       |       |       |       |       |  166.1|   29.0|  166.1|   29.0|
12.00|  8258|       |       |       |       |       |       |  164.5|   32.6|  164.5|   32.6|
12.50|  9333|       |       |       |       |  165.8|   37.1|  163.1|   36.5|  163.1|   36.5|
13.00| 10539|       |       |       |       |  164.3|   41.6|  162.6|   41.1|  162.6|   41.1|
13.50| 11750|       |       |  165.1|   46.5|  163.0|   46.0|  162.8|   45.9|  162.8|   45.9|
14.00| 13046|  165.8|   51.9|  163.9|   51.3|  162.7|   50.9|  163.8|   51.3|  162.7|   50.9|
14.50| 14462|  164.5|   57.1|  162.9|   56.6|  162.7|   56.5|  165.3|   57.4|  162.7|   56.5|
15.00| 15977|  163.4|   62.7|  162.6|   62.4|  163.5|   62.7|       |       |  162.6|   62.4|
15.50| 17631|  162.8|   68.9|  162.8|   68.9|  164.9|   69.8|       |       |  162.8|   68.9|
16.00| 19398|  162.5|   75.7|  163.7|   76.2|  167.6|   78.0|       |       |  162.5|   75.7|
16.50| 21334|  163.1|   83.5|  165.0|   84.5|       |       |       |       |  163.1|   83.5|
17.00| 23402|  164.2|   92.2|  167.8|   94.2|       |       |       |       |  164.2|   92.2|
17.50| 25667|  165.8|  102.1|       |       |       |       |       |       |  165.8|  102.1|
MCR  SPD/TPD|  17.80|  110.9|  17.00|   95.1|  16.00|   79.2|  14.90|   63.4|  17.80|  110.9|
```

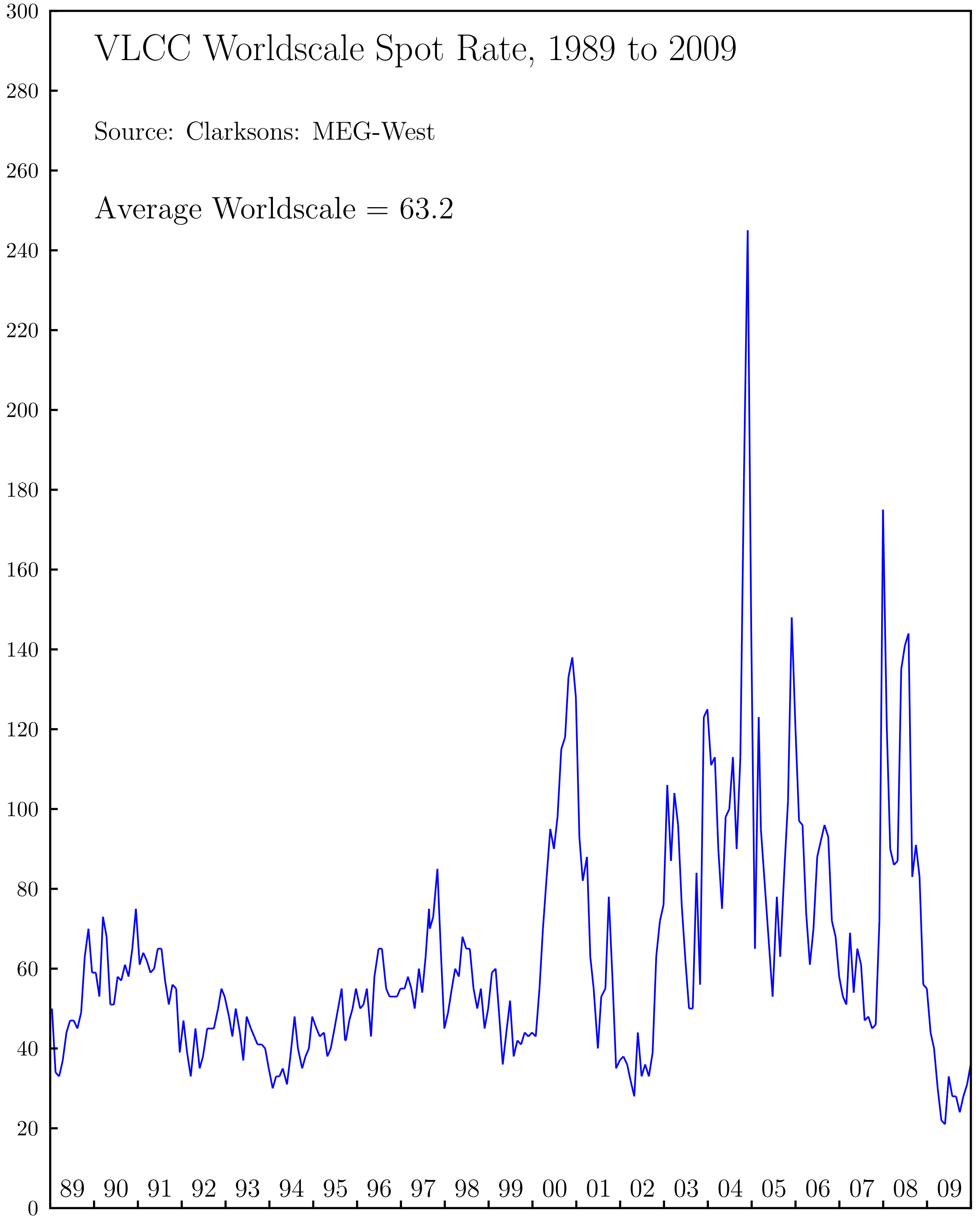

Figure 1: VLCC Spot Rate for the last 21 Years

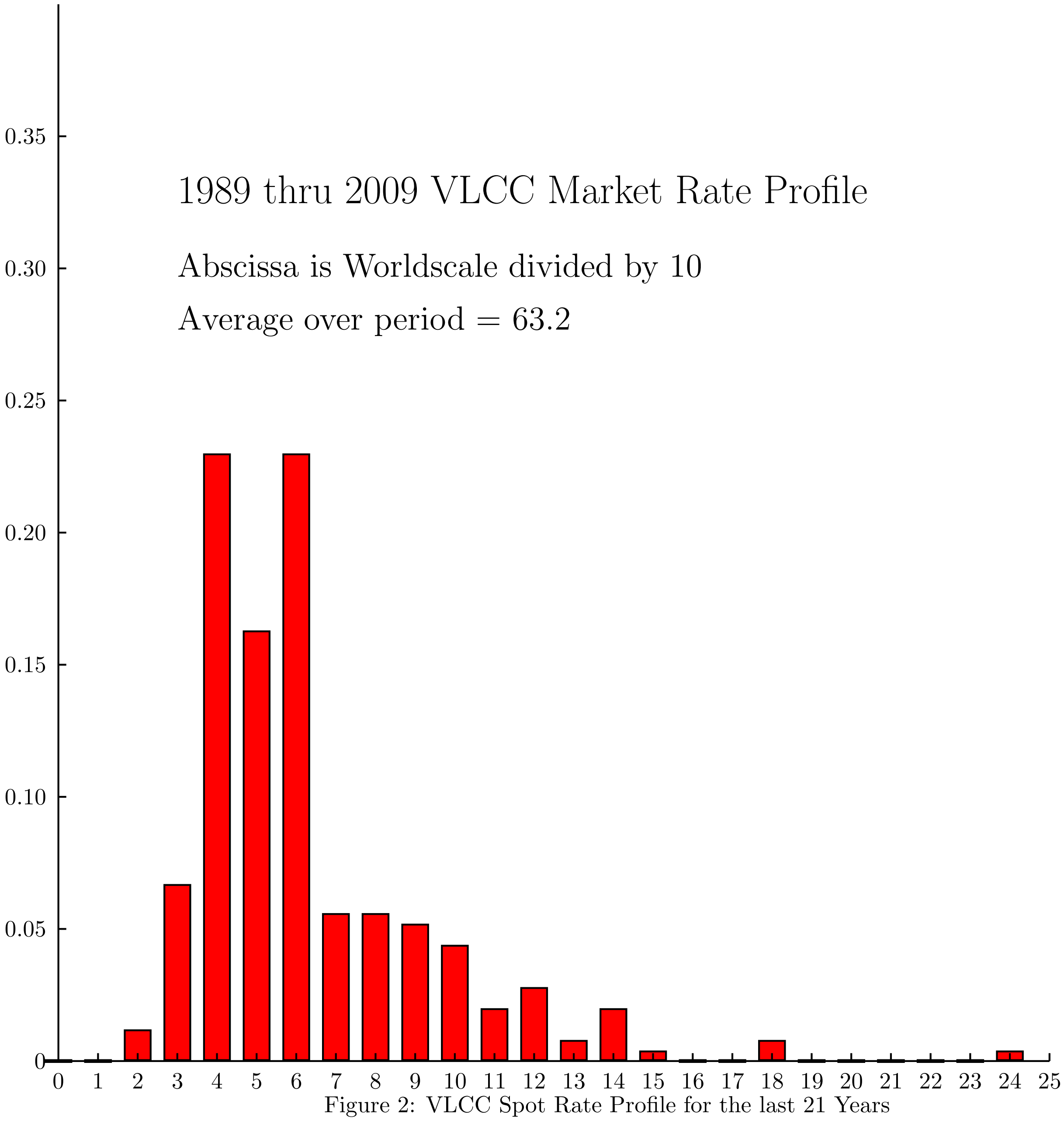

Figure 2: VLCC Spot Rate Profile for the last 21 Years

Figure 3: Standard hull resistance curve

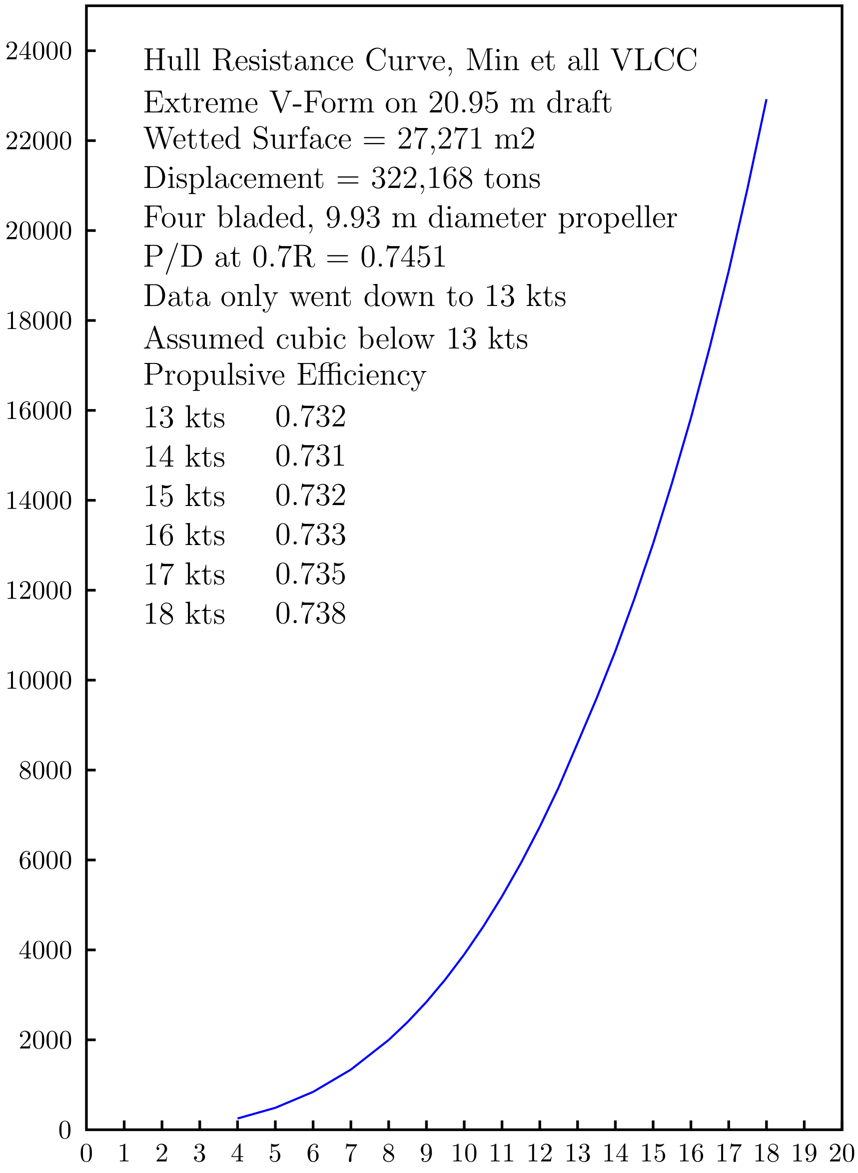

Table 3: Speed/Fuel Consumption Curves for Newbuilding VLCC's

```
   LOADED   |   7RTA84T-D    |    6RTA84T-D   |Imaginary 5 cyl|Imaginary 4 cyl|7RTA84T-Flex   |
SPEED|POWER |eedi=2.31       |eedi=2.09       |eedi=1.85      |eedi=1.60      |Slowstming Mods|
 Kts |  KW  |  SFC  |  TPD   |  SFC  |  TPD   |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
10.50|  7507|       |        |       |        |       |       | 165.7|   27.2| 165.7|   27.2|
11.00|  8632|       |        |       |        |       |       | 164.0|   31.0| 164.0|   31.0|
11.50|  9863|       |        |       |        | 165.0|   35.6| 162.9|   35.2| 162.9|   35.2|
12.00| 11207|       |        | 165.7|   40.7| 163.6|   40.1| 162.6|   39.9| 162.6|   39.9|
12.50| 12667| 166.2|   46.1| 164.3|   45.5| 162.8|   45.1| 163.4|   45.3| 162.8|   45.1|
13.00| 14303| 164.6|   51.5| 163.0|   51.0| 162.7|   50.9| 165.1|   51.7| 162.7|   50.9|
13.50| 15946| 163.4|   57.0| 162.6|   56.8| 163.5|   57.1|       |       | 162.6|   56.8|
14.00| 17706| 162.8|   63.1| 162.8|   63.1| 165.0|   63.9|       |       | 162.8|   63.1|
14.50| 19626| 162.6|   69.8| 163.9|   70.4| 168.0|   72.2|       |       | 162.6|   69.8|
15.00| 21683| 163.2|   77.4| 165.3|   78.4|       |       |       |       | 163.2|   77.4|
15.50| 23928| 164.6|   86.2|       |       |       |       |       |       | 164.6|   86.2|
16.00| 26326| 166.8|   96.1|       |       |       |       |       |       | 166.8|   96.1|
MCR  SPD/TPD| 16.20|  101.2| 15.40|   86.7| 14.50|   72.3| 13.40|   57.8| 16.20|  101.2|

  BALLAST   |   7RTA84T-D    |    6RTA84T-D   |Imaginary 5 cyl|Imaginary 4 cyl|7RTA84T-Flex   |
SPEED|POWER |eedi=2.31       |eedi=2.09       |eedi=1.85      |eedi=1.60      |Slowstming Mods|
 Kts |  KW  |  SFC  |  TPD   |  SFC  |  TPD   |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
11.50|  7268|       |        |       |        |       |       | 166.1|   26.4| 166.1|   26.4|
12.00|  8258|       |        |       |        |       |       | 164.5|   29.7| 164.5|   29.7|
12.50|  9333|       |        |       |        | 165.8|   33.9| 163.1|   33.3| 163.1|   33.3|
13.00| 10539|       |        |       |        | 164.3|   37.9| 162.6|   37.5| 162.6|   37.5|
13.50| 11750|       |        | 165.1|   42.4| 163.0|   41.9| 162.8|   41.9| 162.8|   41.9|
14.00| 13046| 165.8|   47.3| 163.9|   46.8| 162.7|   46.5| 163.8|   46.8| 162.7|   46.5|
14.50| 14462| 164.5|   52.1| 162.9|   51.6| 162.7|   51.5| 165.3|   52.3| 162.7|   51.5|
15.00| 15977| 163.4|   57.1| 162.6|   56.9| 163.5|   57.2|       |       | 162.6|   56.9|
15.50| 17631| 162.8|   62.8| 162.8|   62.8| 164.9|   63.6|       |       | 162.8|   62.8|
16.00| 19398| 162.5|   69.0| 163.7|   69.5| 167.6|   71.2|       |       | 162.5|   69.0|
16.50| 21334| 163.1|   76.1| 165.0|   77.1|       |       |       |       | 163.1|   76.1|
17.00| 23402| 164.2|   84.1| 167.8|   85.9|       |       |       |       | 164.2|   84.1|
17.50| 25667| 165.8|   93.2|       |       |       |       |       |       | 165.8|   93.2|
MCR  SPD/TPD| 17.80|  101.2| 17.00|   86.7| 16.00|   72.3| 14.90|   57.8| 17.80|  101.2|
```

Table 4: Slow-steaming curve for 7 cylinder BASE ship. BFO=$465, EEDI=2.32

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	10.25	1566	9913	58.16	276943	34270	1.0530
40	10.74	1702	18133	55.66	276943	35807	1.0954
50	11.19	1860	26723	53.58	276943	37198	1.1523
60	11.97	2046	36556	50.35	276848	39576	1.1911
70	13.20	2436	46744	46.04	276734	43258	1.2974
80	14.24	2724	58424	42.96	276550	46327	1.3551
90	15.00	2969	70465	41.00	276419	48525	1.4099
100	15.49	3126	83064	39.83	276274	49922	1.4427
110	15.99	3335	95689	38.71	276190	51353	1.4963
120	16.25	3466	108438	38.15	276190	52098	1.5331
130	16.49	3567	121712	37.65	276097	52771	1.5576
140	16.72	3681	135055	37.18	275991	53419	1.5880
150	16.83	3752	148313	36.97	275991	53726	1.6094
160	16.83	3752	161703	36.97	275991	53726	1.6094
170	16.83	3752	175093	36.97	275991	53726	1.6094
180	16.83	3752	188483	36.97	275991	53726	1.6094
190	16.83	3752	201873	36.97	275991	53726	1.6094
200	16.97	3861	215355	36.70	275891	54101	1.6445
210	16.97	3861	228839	36.70	275891	54101	1.6445
220	16.97	3861	242323	36.70	275891	54101	1.6445
230	16.97	3861	255806	36.70	275891	54101	1.6445
240	16.97	3861	269290	36.70	275891	54101	1.6445
250	16.97	3861	282773	36.70	275891	54101	1.6445
260	16.97	3861	296257	36.70	275891	54101	1.6445
270	16.97	3861	309740	36.70	275891	54101	1.6445
280	16.97	3861	323224	36.70	275891	54101	1.6445
290	16.97	3861	336707	36.70	275891	54101	1.6445
300	16.97	3861	350191	36.70	275891	54101	1.6445

Table 5: Slow-steaming curve for 7 cylinder BASE ship. BFO=$620, EEDI=2.32

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	9.98	1506	6236	59.61	276943	33438	1.0376
40	9.98	1506	14570	59.61	276943	33438	1.0376
50	10.50	1632	22631	56.85	276943	35058	1.0725
60	10.74	1702	31248	55.66	276943	35807	1.0954
70	11.74	1962	40434	51.26	276848	38869	1.1631
80	12.24	2105	50252	49.33	276793	40382	1.2013
90	13.24	2414	60576	45.91	276672	43376	1.2822
100	14.00	2634	71888	43.64	276550	45608	1.3307
110	14.50	2794	83549	42.27	276486	47072	1.3677
120	15.25	3047	95718	40.39	276347	49236	1.4260
130	15.49	3126	108243	39.83	276274	49922	1.4427
140	15.75	3244	120611	39.24	276274	50673	1.4753
150	15.99	3335	133549	38.71	276190	51353	1.4963
160	16.49	3567	146506	37.65	276097	52771	1.5576
170	16.49	3567	159658	37.65	276097	52771	1.5576
180	16.72	3681	172986	37.18	275991	53419	1.5880
190	16.72	3681	186299	37.18	275991	53419	1.5880
200	16.83	3752	199553	36.97	275991	53726	1.6094
210	16.83	3752	212943	36.97	275991	53726	1.6094
220	16.83	3752	226333	36.97	275991	53726	1.6094
230	16.83	3752	239723	36.97	275991	53726	1.6094
240	16.83	3752	253113	36.97	275991	53726	1.6094
250	16.83	3752	266503	36.97	275991	53726	1.6094
260	16.83	3752	279893	36.97	275991	53726	1.6094
270	16.97	3861	293458	36.70	275891	54101	1.6445
280	16.97	3861	306941	36.70	275891	54101	1.6445
290	16.97	3861	320425	36.70	275891	54101	1.6445
300	16.97	3861	333908	36.70	275891	54101	1.6445

Table 6: Slow-steaming curve for 6 cylinder newbuild ship. BFO=$465 EEDI=2.09

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	10.25	1566	9913	58.16	276943	34270	1.0530
40	10.74	1702	18133	55.66	276943	35807	1.0954
50	11.19	1860	26723	53.58	276943	37198	1.1523
60	11.97	2046	36556	50.35	276848	39576	1.1911
70	13.20	2436	46744	46.04	276734	43258	1.2974
80	14.00	2634	58496	43.64	276550	45608	1.3307
90	14.75	2879	70415	41.63	276419	47789	1.3882
100	15.25	3067	82621	40.39	276347	49236	1.4352
110	15.49	3155	95157	39.83	276265	49920	1.4562
120	15.94	3373	107688	38.82	276173	51197	1.5182
130	15.94	3373	120448	38.82	276173	51197	1.5182
140	16.17	3488	133465	38.32	276067	51845	1.5502
150	16.17	3488	146386	38.32	276067	51845	1.5502
160	16.17	3488	159308	38.32	276067	51845	1.5502
170	16.17	3488	172229	38.32	276067	51845	1.5502
180	16.17	3488	185150	38.32	276067	51845	1.5502
190	16.17	3488	198071	38.32	276067	51845	1.5502
200	16.17	3488	210992	38.32	276067	51845	1.5502
210	16.17	3488	223914	38.32	276067	51845	1.5502
220	16.17	3488	236835	38.32	276067	51845	1.5502
230	16.17	3488	249756	38.32	276067	51845	1.5502
240	16.17	3488	262677	38.32	276067	51845	1.5502
250	16.17	3488	275598	38.32	276067	51845	1.5502
260	16.17	3488	288520	38.32	276067	51845	1.5502
270	16.17	3488	301441	38.32	276067	51845	1.5502
280	16.17	3488	314362	38.32	276067	51845	1.5502
290	16.17	3488	327283	38.32	276067	51845	1.5502
300	16.17	3488	340204	38.32	276067	51845	1.5502

Table 7: Speed/Fuel Consumption Curves for 6S65ME with cylinder cutout

```
  LOADED   |   6S65ME      |1 cylinder down|2 cylinder down|3 cylinder down|6S65ME     with|
SPEED|POWER |eedi=1.78      |eedi=1.57      |eedi=1.36      |eedi=1.12      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
 8.50|  4330|       |       |       |       |       |       |  167.9|   15.9|  167.9|   15.9|
 9.00|  5140|       |       |       |       |       |       |  166.1|   18.7|  166.1|   18.7|
 9.50|  6046|       |       |       |       |  167.5|   22.2|  165.5|   21.9|  165.5|   21.9|
10.00|  7052|       |       |  168.3|   26.0|  165.9|   25.6|  166.6|   25.7|  165.9|   25.6|
10.50|  8162|  168.8|   30.2|  166.6|   29.8|  165.6|   29.6|  169.5|   30.3|  165.6|   29.6|
11.00|  9386|  167.1|   34.3|  165.7|   34.0|  166.6|   34.2|       |       |  165.7|   34.0|
11.50| 10724|  165.9|   38.9|  165.8|   38.9|  169.2|   39.7|       |       |  165.8|   38.9|
12.00| 12185|  165.5|   44.2|  167.2|   44.6|       |       |       |       |  165.5|   44.2|
12.50| 13772|  166.3|   50.1|  169.9|   51.2|       |       |       |       |  166.3|   50.1|
13.00| 15552|  168.4|   57.3|       |       |       |       |       |       |  168.4|   57.3|
MCR  SPD/TPD|  13.40|   64.5|  12.60|   53.7|  11.70|   43.0|  10.60|   32.2|  13.20|   61.9|

 BALLAST   |   6S65ME      |1 cylinder down|2 cylinder down|3 cylinder down|6S65ME     with|
SPEED|POWER |eedi=1.78      |eedi=1.57      |eedi=1.36      |eedi=1.12      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
 9.50|  4455|       |       |       |       |       |       |  167.7|   16.3|  167.7|   16.3|
10.00|  5196|       |       |       |       |  169.4|   19.3|  166.0|   18.9|  166.0|   18.9|
10.50|  6014|       |       |       |       |  167.5|   22.1|  165.5|   21.8|  165.5|   21.8|
11.00|  6916|       |       |  168.5|   25.5|  166.0|   25.1|  166.4|   25.2|  166.0|   25.1|
11.50|  7902|  169.2|   29.3|  167.0|   28.9|  165.6|   28.6|  168.8|   29.2|  165.6|   28.6|
12.00|  8978|  167.6|   32.9|  165.9|   32.6|  166.1|   32.6|       |       |  165.9|   32.6|
12.50| 10148|  166.2|   36.9|  165.5|   36.8|  167.9|   37.3|       |       |  165.5|   36.8|
13.00| 11459|  165.7|   41.6|  166.3|   41.7|  170.9|   42.9|       |       |  165.7|   41.6|
13.50| 12775|  165.8|   46.3|  168.1|   47.0|       |       |       |       |  165.8|   46.3|
14.00| 14185|  166.7|   51.8|  170.7|   53.0|       |       |       |       |  166.7|   51.8|
14.50| 15724|  168.6|   58.0|       |       |       |       |       |       |  168.6|   58.0|
MCR  SPD/TPD|  14.90|   64.5|  14.00|   53.7|  13.00|   43.0|  11.80|   32.2|  14.70|   61.9|
```

Table 8: Slow-steaming curve for 6S65ME ship. BFO=$465, EEDI=1.74

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	9.50	1499	9743	62.42	276998	31940	1.0813
40	9.97	1651	17325	59.66	276998	33414	1.1383
50	10.39	1817	25305	57.39	276998	34739	1.2054
60	11.19	2015	34623	53.58	276898	37192	1.2483
70	12.24	2304	44876	49.33	276719	40371	1.3150
80	13.25	2637	55579	45.89	276520	43367	1.4012
90	13.49	2719	66601	45.15	276445	44067	1.4216
100	13.72	2809	77797	44.46	276361	44737	1.4469
110	13.93	2929	88938	43.83	276361	45381	1.4872
120	13.93	2929	100248	43.83	276361	45381	1.4872
130	14.12	3028	111768	43.31	276269	45910	1.5199
140	14.12	3028	123210	43.31	276269	45910	1.5199
150	14.12	3028	134652	43.31	276269	45910	1.5199
160	14.12	3028	146094	43.31	276269	45910	1.5199
170	14.12	3028	157536	43.31	276269	45910	1.5199
180	14.12	3028	168978	43.31	276269	45910	1.5199
190	14.12	3028	180420	43.31	276269	45910	1.5199
200	14.12	3028	191862	43.31	276269	45910	1.5199
210	14.12	3028	203304	43.31	276269	45910	1.5199
220	14.12	3028	214746	43.31	276269	45910	1.5199
230	14.12	3028	226188	43.31	276269	45910	1.5199
240	14.12	3028	237630	43.31	276269	45910	1.5199
250	14.12	3028	249072	43.31	276269	45910	1.5199
260	14.12	3028	260514	43.31	276269	45910	1.5199
270	14.12	3028	271956	43.31	276269	45910	1.5199
280	14.12	3028	283398	43.31	276269	45910	1.5199
290	14.12	3028	294840	43.31	276269	45910	1.5199
300	14.12	3028	306282	43.31	276269	45910	1.5199