Detailed Studies of the Impact of EEDI on VLCC Design and CO2 Emissions

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Version: 1.0
Date: 2010-11-06

This report contains detailed calculations supporting the CTX position paper The Impact of EEDI on VLCC Design and CO2 Emissions. The position paper is more succinct and much better organized. Most readers should probably refer to this report only as needed for detailed back-up.

Contents

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.[1] While the formula is complex, for VLCC's it basically boils down to the ratio of installed power to speed at that power. Readers unfamiliar with EEDI might want to check out EEDI: A Case Study in Indirect Regulation of CO2 Emissions for a much more complete description.

IMO has yet to finalize the mandated decrease in EEDI; but the discussion has focused on the reductions shown in Table 1.

Table 1: Proposed EEDI 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.[2] 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 power required at a given speed 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 vessel 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, ***the 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%.[3]

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[1] Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for new Ships, MEPC.1/Circ.681, 2009-08-17.

[2] Akiyama A, Tagg R, An Evaluation of the Energy Efficiency Design Index for Tankers, Containerships, and LNG Carriers, Tripartite Workshop on GHG Emission Reduction, Beijing, 2010-06-3/4.

[3] These numbers are based on comparing a no EEDI newbuilding 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 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 about 7% 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 proposed EEDI reductions create a difficult problem for the VLCC designer. Before we consider reducing installed power, let's take a brief look at other proposed measures. These might be called "true" efficiency improvements because they attempt to reduce fuel consumption without reducing speed. They fall into four categories:

1. economic and reasonably reliable,
2. ineffective, uneconomic, in the noise,
3. possibly economic but unreliable, unsafe.
4. maybe.

2.1 Economic

Thanks to the massive, post-2005 increase in bunker prices, a number of measures which were not economic or at best marginally economic at $200 per ton Bunker Fuel Oil (BFO) are now economic at $450 per ton BFO. These measures will be implemented on just about all VLCC newbuildings, whether or not additional regulation is enacted.

More efficient lighting Replacing fluorescent lights with LED's, halogen. A typical VLCC 440/220 volt transformer is 120 kW. If we assume incorrectly that all of that is lighting and we can cut that in half, we save 60 kW or about 0.2% of full power. Additional cost is negligible.

Shaft generators Average electric load of a VLCC is about 900 kW. By installing a shaft generator, we gain about 10% (190 to 170 g/kW-hr) in SFC, since the main engine is more efficient than a medium speed, 4 cycle generator engine. This savings is equivalent to reducing power required by about 80 kW or about 0.4%. However, this measure has been superseded by additional Waste Heat Recovery, see below.

Multi-speed pumps In the past, just about all VLCC engine room pumps and fans were single speed. The only way they could adjust to low loads was by throwing away energy in throttling losses and the like. It is probably now economic to invest in multi-speed control for the biggest engine room motors. However, this will have nil impact at or near full power, and therefore won't effect the ship's EEDI. Ditto inverters and DC motors.

Electronic controlled engine The tanker industry is switching from camshaft controlled to electronically controlled fuel injection and exhaust valves. This technology became available for VLCC's around 2005. At 75% MCR and above, this has little impact, at most 2%. However, if combined with some turbo-charger modifications, it allows the engine to operate at very low loads continuously via sequential cylinder cut-out, and results in a substantial reduction in fuel consumption at low loads. Once again low load improvements have no impact on the ship's EEDI.

Variable pitch turbo-chargers Low loads have always presented a difficult problem for turbo-chargers. The development of variable pitch vanes, first installed on tankers in late 2007, is an important step in increasing turbocharger flexibility and allowing the engine to operate efficiently at low loads. However, this important technology has nil impact at the engine design point and thus nil impact on the ship's EEDI.

Streamlining superstructure Current tanker superstructure is strikingly un-aerodynamic. Hirota has shown that superstructure wind resistance can be decreased by 10% by very simple measures.[4] More drastic measures such as true streamlining should be able to double or triple this figure. However, superstructure wind resistance represents only about 2% of a VLCC's total resistance, so the most we can expect here is about 0.5% overall.

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[4] Hirota, K., GHG Emission Reduction, GHG Workshop, Beijing, June, 2010.

Hull form changes The current VLCC hull form is the result of a massive amount of research. The Japanese and Korean yards have studied literally thousands of VLCC hull form variations, on the computer, in the model tank, and in some cases at sea. There is nothing big to be gained here. However, it is true that hull form is a compromise between initial/maintenance costs and fuel efficiency. As fuel costs rise, this compromise shifts toward fuel efficiency. When BFO prices skyrocketed in 2005-2008, the yards rethought their hull forms and were able to wring another 2 to 4% improvement in either resistance or propulsive coefficient, mostly by refining the aft body. This will show up in ships delivered from about 2009 on. Repeating this improvement will be extremely difficult.

Additional waste heat recovery (WHR) At least at or near full power, it is possible to extract enough energy from a VLCC's 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 pay-back 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.[5]

Just about all the measures in this category will be implemented without any regulation. In the jargon, they have *negative abatement cost*, meaning that the owner's bottom line will be improved by investing in them in his newbuildings. Most of them are already being implemented.

The single most important recent development is the ability of VLCC main engines to operate well below 50% load continuously and do it quite efficiently. However, this major change is ignored by EEDI.

The problem for our VLCC designer is that, if you add up all the economic measures from the point of EEDI, you are talking at most a 10% improvement in fuel consumption at 75% installed power, the EEDI design point.

2.2 Inefficient, uneconomic, in the noise

Fixed Hydrodynamic devices There have been any number of fixed hydrodynamic devices proposed, including swirl fins, propeller boss fins, fancy rudders, propeller winglets, etc, etc. These ideas have been around for decades. Most of them add very little to the cost of the ship. If they did work as claimed, they would have been implemented a long time ago. Unfortunately, the evidence that they actually work is uncompelling in the extreme. Many are proven busts. There is little reason to believe this is going to change.

Solar Solar panels are still an extremely expensive means of generating electricity, as both the DNV and SNAME MACC reports admit.[6] But the most fundamental problem with solar is that it is not always available. Therefore, unless accompanied by massive amount of batteries, owners can't reduce installed generating power. So even if an owner installed solar panels, it would have no effect on the ship's EEDI.

Fuel cells This moves the CO2 emissions off the ship to where ever the hydrogen is generated. So while this looks good to EEDI, it really does nothing for overall CO2 emissions. Fortunately, the cost of making and transporting the hydrogen render this inefficient technology totally infeasible for VLCC's.

Bigger, slower propeller An obvious target for decreasing fuel consumption is propeller efficiency. VLCC's use highly loaded propellers. Only about 70% of the energy transmitted to a VLCC's propeller is converted into thrust. The rule of thumb for VLCC's is that propeller efficiency goes at diameter to the 0.25 power. Doubling the diameter

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[5] Antonopoulos, D, Ship Power Merchant, August, 2010.

[6] DNV, Pathways to Low Carbon Shipping, June 2010. SNAME, Marginal Abatement Cost and Cost Effectiveness of Energy Efficiency Measures, MEPC 61/INF.18, 2010-07-13

would increase propeller efficiency by about 20%. Unfortunately to turn a bigger propeller at lower RPM, we need an engine with a lot more torque or a reduction gear. But EEDI will reduce total installed power, so developing a bigger bore VLCC engine is out of the question. And even at the same power, we are looking at a 5 cylinder engine which means horrendous vibration problems. A reduction gear would suck up at least 2% of the engine's output in friction, so we would need a a 10% larger prop just to break even. At which point, the prop is already nearly as large as current casting technology allows.

Twin screw Another way of reducing propeller loading is twin screw. Twin screw properly implemented would result in a thousand-fold increase in machinery reliability, and a dramatically improved low speed maneuverability. And a twin screw VLCC shows promise of being economic.[7] But it would be a high powered, high speed VLCC which means that, while it might well have better than single screw, fuel efficiency at any given speed, its EEDI would be high. ***EEDI effectively outlaws twin screw.***

One problem with EEDI is that a number of efficiency measures that might make sense in a high fuel cost environment become less attractive economically if EEDI forces the owner to reduce installed power.

2.3 Economic but unreliable, unsafe

Contra-rotating propellers Another way of increasing propeller efficiency is contra-rotating propellers. At VLCC design conditions, contra-rotating propellers in which the aft propeller captures some of the energy lost in the wake of the forward propeller could theoretically result in about a 10% increase in propeller efficiency after netting out the energy lost to the gearing. Unfortunately, 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. The worst thing we could do is further reduce steel weight. Nonetheless, EEDI will put additional pressure on the VLCC designer to take chances in this area.

2.4 Possible but too much uncertainty for EEDI

Kites Kites are intriguing. This 5000 year old technology still needs considerable development for VLCC's, but may actually end up being implemented on tankers, and save some fuel. But like solar they will do nothing for the ship's EEDI because the owner knows that the kite will only help him in a limited number of wind speed and direction situations. A kite will not allow him to reduce installed power. Same thing is true for sails, Flettner rotors, etc except they all look more expensive, less feasible than a kite.

Air cavities Another intriguing idea. The concept is to pump air over the flat bottom so that if flows aft at the same rate as the water, replacing water/hull friction with air/hull friction. The promoters claim a calculated 15% reduction in required power for their system for a VLCC. But so far there has been only one at sea test on a very small freighter which resulted in claims of a 10% reduction. Big issues remains with respect to cavity stability and the effect of the air on propeller efficiency. In the meantime, no prudent VLCC owner can spec reduced installed power on the basis of current claims. And even if the technology turns out to be as successful as the promoters say it will, it will be at least five years before he can do so. Once again if the technology proves successful, it will be adopted with or without EEDI.

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[7] See for example The Case for Twin Screw.

In summary, with the possible exception of air cavity which is at least five years away, a reasonable upper bound on the reduction of EEDI by means other than reducing installed power is about 8%. 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.[8] Just about all these measures will be implemented whether or not EEDI is enacted.

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[8] Schack, C, Green Ship of the Future, Asia-Pacific Maritime, Singapore, March, 1010.

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.[9]

As Figure 2 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 handful of voyages. In order to estimate VLCC CO2 emissions, we must first figure out what the owners will do as a function of the spot rate. 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.

3.2 Standard Route and Ship

The particulars of the route we will use for all our calculations are shown in Table 2. 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 due to failure to acknowledge NOX requirements, and 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.[10] The ***relative*** differences between the non-EEDI and EEDI ships were almost unchanged. Within reason, whatever you assume about inventory carrying costs will not change our bottom line conclusions about the effectiveness of EEDI.

Fortunately, for our purposes, almost all VLCC's are very similar. The single most important characteristic of the ship 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.

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[9] 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 The Impact of Bunker Prices on VLCC Rates, Appendix 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.

[10] The main effect of including inventory carrying costs is to speed the ships up at the bottom of the market.

Table 2: 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	1.4	Cylinder LO $/T	3000
Brokers Commis %	1.25	Hotel TPD	10
Consumables(tons)	500	BFO Capacity tons	12,577
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

3. The engine Specific Fuel Consumption (SFC) curve which determines the amount of fuel the engine needs to produce a given amount of power.

3.2.1 Hull form

In all our calculations, we kept the hull form constant. The hull we used is that studied by Min et al.[11] In this 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 1. 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.

3.2.2 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. This an 8.0 meter propeller will have a Propulsive Efficiency of 0.69.

3.2.3 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/kW-hr. 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.

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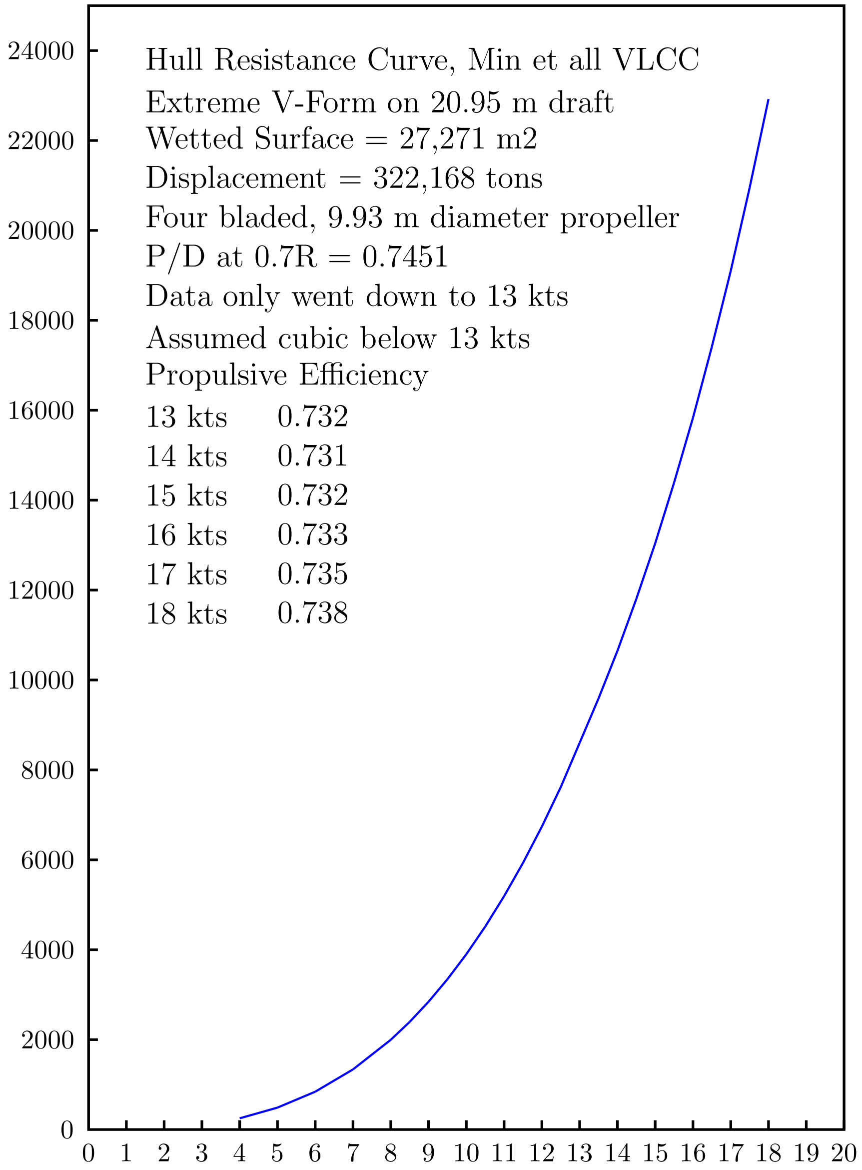
[11] Min, K. S., Choi, J. E., et al, Study on the CFD Application for VLCC Hull Form Design, 24th Symposium on Naval Hydrodynamics (2003), p 98-106

Figure 1: Standard hull resistance curve



4 VLCC Speed/Fuel Curves

4.1 Speed/Fuel Curves for Existing VLCC's

Putting all our assumptions together, we arrive at the speed/fuel curves shown in Table 3 for existing VLCC's.

Table 3: 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|
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  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|
```

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/kW-hr.[12]

According to Table 3, 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 3. 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

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[12] 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.

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. So this appears to be a reasonable number for existing VLCC's.

4.2 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 3.

Table 4: 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|
```

The ship on the right will be our BASE newbuilding VLCC, the ship that would be built with no new regulation. It has an EEDI of 2.31 well above the Phase 1 requirement of 2.09.

5 Phase 1 EEDI

5.1 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 4 reveals that our BASE 7 cylinder ship is illegal, but the six cylinder ship just meets the proposed Phase 1 requirement.

Tables 5 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.

Table 5: 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

Comparing Tables 5 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 uses as WS200. At WS200 and above, the difference is about 6%. Table 7 summarizes this comparison

The VLCC market spends most of its time at or below WS80. Over the last twenty years, the number is 81%.[13] The Required Freight Rate (RFR), which is also the long-run average of the spot rate, for this route and BFO cost is about WS60.[14] Historically, the

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[13] Based on Clarksons numbers. See Appendix A.

[14] 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. Over the very long run, the market must average the RFR. 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

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

Table 7: Percent Reduction in CO2, BASE vs 6 cylinder ship. BFO=$465

WS	TCE	TCE	Ratio	%
	BASE	6 cyl	CO2	Down
30	9913	9913	1.0000	-0.0
40	18133	18133	1.0000	-0.0
50	26723	26723	1.0000	-0.0
60	36556	36556	1.0000	-0.0
70	46744	46744	1.0000	-0.0
80	58424	58496	0.9820	-1.8
90	70465	70415	0.9846	-1.5
100	83064	82621	0.9948	-0.5
110	95689	95157	0.9732	-2.7
120	108438	107688	0.9903	-1.0
130	121712	120448	0.9747	-2.5
140	135055	133465	0.9762	-2.4
150	148313	146386	0.9632	-3.7
160	161703	159308	0.9632	-3.7
170	175093	172229	0.9632	-3.7
180	188483	185150	0.9632	-3.7
190	201873	198071	0.9632	-3.7
200	215355	210992	0.9427	-5.7

market is in full boom less that 10% of the time; but, 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. Conversely, the spot market cannot go below the *Layup Rate* for any length of time. The Layup Rate is the rate below which the owner would be better off laying up his ship rather than trading it. Currently, this is about $8000 per day TCE or about WS28 in the Table 7 situation. The VLCC market spends most of its time fluctuating between the Layup Rate and RFR with occasional spikes much higher during booms.

In order to reduce Table 7 to a single number for each ship, we need a *spot rate profile*, that is, the percentage of time we can expect the market to spend at each spot rate. Such a profile is developed in Appendix A using market data for the 1989 to 2009 period inclusive; but intentionally biased toward the lower powered ship. We call this our *Standard* spot rate profile, although *EEDI biased* might be a better name. See Appendix A for the details.

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 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. Any reasonable market profile will produce similar or lower differences. Due to the tenuous connection between installed power and power actually used, a 10% reduction in EEDI results in nil reduction in operational CO2 emissions.

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.

5.2 Slow-steaming curves for $620 BFO cost

Tables 8 and 9 repeat the slow-steaming analyzes for a BFO cost of $620 per ton. If the market price of HFO is $465 as assumed in Tables 5 and 6, this could be accomplished by a $50 per ton CO2 bunker tax or an equivalent ETS permit price.[15]

The reader can check for himself that the difference in CO2 emissions from the two ships over a market cycle is even smaller than for $465 BFO cost. 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%.[16]

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

A far more interesting comparison is to match Table 5 against Table 8 as Table 10 does. If this $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.

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

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would move out of the VLCC market raising the rate.

[15] Assuming incorrectly that there is no difference in uncertainty between taxes and permit prices.

[16] Be aware that 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.

Table 8: 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

of $620 BFO cost than he does for $465 BFO.[17] Between WS50 and WS150, 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 6.6%.

So far throughout this analysis we have been acting as if society's goal were to minimize CO2 emissions. In fact, the goal is to minimize the sum of the societal cost of CO2 plus all the other costs associated with movingthe 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.

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[17] 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 10 shows, it wouldn't make that much difference.

Table 9: Slow-steaming curve for 6 cylinder new ship. BFO=$620, EEDI=2.09

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	14.25	2703	83552	42.95	276486	46331	1.3445
120	14.99	2957	95619	41.03	276347	48478	1.4055
130	15.25	3067	107684	40.39	276347	49236	1.4352
140	15.49	3155	120222	39.83	276265	49920	1.4562
150	15.49	3155	132663	39.83	276265	49920	1.4562
160	15.72	3254	145418	39.30	276173	50578	1.4825
170	15.94	3373	158039	38.82	276173	51197	1.5182
180	16.17	3488	171063	38.32	276067	51845	1.5502
190	16.17	3488	183984	38.32	276067	51845	1.5502
200	16.17	3488	196906	38.32	276067	51845	1.5502
210	16.17	3488	209827	38.32	276067	51845	1.5502
220	16.17	3488	222748	38.32	276067	51845	1.5502
230	16.17	3488	235669	38.32	276067	51845	1.5502
240	16.17	3488	248590	38.32	276067	51845	1.5502
250	16.17	3488	261512	38.32	276067	51845	1.5502
260	16.17	3488	274433	38.32	276067	51845	1.5502
270	16.17	3488	274433	38.32	276067	51845	1.5502

A $50 per ton carbon price will result in at least six times more VLCC CO2 emissions reductions than EEDI Phase I, for the ships actually affected by Phase 1; and

1. it will apply to all VLCC's not just those built under Phase 1 after they are delivered, and
2. it will not force owners to artificially reduce installed power with the attendant unnecessary increases in market costs and loss in reserve power, and
3. it will not force owners to operate at a higher percentage of MCR, resulting in a substantial increase in main engine failures.

5.4 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 and increasing his fuel consumption slightly at lower speeds. 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 costs 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 the expensive and pernicious side-effects. And it we want a bigger reduction, we simply increase the tax.[18]

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[18] For worldwide efficiency, the carbon price to ship owners must be the same as the carbon price to any other source of CO2.

Table 10: Percent Reduction, BASE ship $465 versus $620 BFO cost

WS	TCE BASE	TCE 6 cyl	Ratio CO2	% Down
30	9913	6236	0.9854	-1.5
40	18133	14570	0.9472	-5.3
50	26723	22631	0.9307	-6.9
60	36556	31248	0.9197	-8.0
70	46744	40434	0.8965	-10.4
80	58424	50252	0.8865	-11.3
90	70465	60576	0.9094	-9.1
100	83064	71888	0.9224	-7.8
110	95689	83549	0.9141	-8.6
120	108438	95718	0.9301	-7.0
130	121712	108243	0.9262	-7.4
140	135055	120611	0.9290	-7.1
150	148313	133549	0.9297	-7.0
160	161703	146506	0.9678	-3.2
170	175093	159658	0.9678	-3.2
180	188483	172986	0.9867	-1.3
190	201873	186299	0.9867	-1.3
200	215355	199553	0.9787	-2.1
210	228839	212943	0.9787	-2.1
220	242323	226333	0.9787	-2.1
230	255806	239723	0.9787	-2.1
240	269290	253113	0.9787	-2.1
250	282773	266503	0.9787	-2.1
260	296257	279893	0.9787	-2.1
270	309740	293458	1.0000	-0.0

6 Phase 2 EEDI

6.1 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 4 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 9.93m to about 7.1 m. This will result in about a 5 percent loss in propulsive efficiency. On top of this, the smaller bore engine has a 3 g/KW-hr (2%) disadvantage in SFC.

Table 11 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.

Table 11: 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|
```

This engine still does not quite meet the Phase 2 EEDI requirement. Therefore we will have to derate the engine slightly to an MCR of 16,500, resulting in the fuel consumption curve at the far right.[19] When he does this, he obtains the speed-fuel curve on the far right.

Table 12 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 5, we obtain Table 13

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[19] 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 8.

Table 12: 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

Table 13: Percent CO2 Reduction, BASE ship vs 6S65ME at $465 BFO cost

WS	TCE BASE	TCE 6S65	Ratio CO2	% Down
30	9913	9743	1.0269	+2.7
40	18133	17325	1.0392	+3.9
50	26723	25305	1.0461	+4.6
60	36556	34623	1.0480	+4.8
70	46744	44876	1.0136	+1.4
80	58424	55579	1.0340	+3.4
90	70465	66601	1.0083	+0.8
100	83064	77797	1.0029	+0.3
110	95689	88938	0.9939	-0.6
120	108438	100248	0.9701	-3.0
130	121712	111768	0.9758	-2.4
140	135055	123210	0.9571	-4.3
150	148313	134652	0.9444	-5.6
160	161703	146094	0.9444	-5.6
170	175093	157536	0.9444	-5.6
180	188483	168978	0.9444	-5.6
190	201873	180420	0.9444	-5.6
200	215355	191862	0.9242	-7.6

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 suffered a larger speed reduction due to prop cavitation and limited 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%.

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, in 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 will 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 Base 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%.

6.2 Slow-steaming curves for $620 BFO cost

Table 14 show the slow-steaming table for this ship for a bunker cost of $620 per ton. With this bunker cost, the owner of the Phase 2 ship speeds up a bit more slowly and will require WS170 or better to go full speed.

Table 14: Slow-steaming curve for 6S65ME ship. BFO=$620, EEDI=1.74

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	8.98	1370	6932	65.82	276998	30289	1.0425
40	9.25	1432	14290	64.02	276998	31138	1.0594
50	9.74	1574	21696	60.97	276998	32697	1.1093
60	9.97	1651	29698	59.66	276998	33414	1.1383
70	10.97	1926	38396	54.58	276898	36514	1.2154
80	11.74	2139	47944	51.26	276783	38860	1.2682
90	12.24	2304	57770	49.33	276719	40371	1.3150
100	12.99	2519	68647	46.74	276520	42582	1.3631
110	13.25	2637	79109	45.89	276520	43367	1.4012
120	13.49	2719	90229	45.15	276445	44067	1.4216
130	13.72	2809	101467	44.46	276361	44737	1.4469
140	13.93	2929	112525	43.83	276361	45381	1.4872
150	13.93	2929	123836	43.83	276361	45381	1.4872
160	13.93	2929	135146	43.83	276361	45381	1.4872
170	14.12	3028	146714	43.31	276269	45910	1.5199
180	14.12	3028	158156	43.31	276269	45910	1.5199
190	14.12	3028	169598	43.31	276269	45910	1.5199
200	14.12	3028	181040	43.31	276269	45910	1.5199
210	14.12	3028	192482	43.31	276269	45910	1.5199
220	14.12	3028	203924	43.31	276269	45910	1.5199
230	14.12	3028	215366	43.31	276269	45910	1.5199
240	14.12	3028	226808	43.31	276269	45910	1.5199
250	14.12	3028	238250	43.31	276269	45910	1.5199
260	14.12	3028	249692	43.31	276269	45910	1.5199
270	14.12	3028	261134	43.31	276269	45910	1.5199

If we compare this table with the BASE ship's results at $620 bunkers, we obtain Table 15. Once again we see that higher bunker prices shift the numbers in favor of the non-EEDI BASE ship. Both ships speed up more slowly at higher BFO costs, extending the WS 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 BASE ship averages 1.161 tons CO2/TPD; the EEDI compliant ship 1.180.

6.3 Summary

- The Phase 2 EEDI regulations will not result in any noticeable decrease in VLCC operational CO2 emissions over a market cycle. In fact, it is likely that the net effect will be to increase VLCC CO2 emissions slightly. The fuel savings due to forcing the owner to go slower in booms are balanced by the inefficiencies associated with a far 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, and a like increase in non-operational CO2 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.

Table 15: Percent CO2 Reduction, BASE ship vs 6S65 at $620 BFO cost

WS	TCE BASE	TCE 6S65	Ratio CO2	% Down
30	6236	6932	1.0047	+0.5
40	14570	14290	1.0210	+2.1
50	22631	21696	1.0343	+3.4
60	31248	29698	1.0392	+3.9
70	40434	38396	1.0450	+4.5
80	50252	47944	1.0557	+5.6
90	60576	57770	1.0256	+2.6
100	71888	68647	1.0243	+2.4
110	83549	79109	1.0245	+2.4
120	95718	90229	0.9969	-0.3
130	108243	101467	1.0029	+0.3
140	120611	112525	1.0081	+0.8
150	133549	123836	0.9939	-0.6
160	146506	135146	0.9548	-4.5
170	159658	146714	0.9758	-2.4
180	172986	158156	0.9571	-4.3
190	186299	169598	0.9571	-4.3
200	199553	181040	0.9444	-5.6
210	212943	192482	0.9444	-5.6
220	226333	203924	0.9444	-5.6
230	239723	215366	0.9444	-5.6
240	253113	226808	0.9444	-5.6
250	266503	238250	0.9444	-5.6
260	279893	249692	0.9444	-5.6
270	293458	261134	0.9242	-7.6

7 Phase 3 EEDI

7.1 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 will use 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.

Table 16 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.

Table 16: Speed/Fuel Consumption Curves for 6S60ME with cylinder cutout

```
  LOADED   |    6S60ME     |Down 1 cylinder|Down 2 cylinder|Down 3 cylinder|6260ME     with|
SPEED|POWER |eedi=1.59      |eedi=1.41      |eedi=1.21      |eedi=1.00      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
 8.00|  3749|       |       |       |       |       |       |  167.5|   13.7|  167.5|   13.7|
 8.50|  4496|       |       |       |       |  168.8|   16.6|  165.9|   16.3|  165.9|   16.3|
 9.00|  5337|       |       |       |       |  166.8|   19.5|  165.8|   19.4|  165.8|   19.4|
 9.50|  6278|       |       |  167.4|   23.0|  165.7|   22.8|  167.8|   23.1|  165.7|   22.8|
10.00|  7321|  167.7|   26.9|  165.9|   26.6|  166.0|   26.6|       |       |  165.9|   26.6|
10.50|  8474|  166.1|   30.8|  165.6|   30.7|  168.1|   31.2|       |       |  165.6|   30.7|
11.00|  9745|  165.6|   35.3|  166.6|   35.5|       |       |       |       |  165.6|   35.3|
11.50| 11134|  166.1|   40.5|  169.2|   41.2|       |       |       |       |  166.1|   40.5|
12.00| 12651|  168.0|   46.5|       |       |       |       |       |       |  168.0|   46.5|
MCR  SPD/TPD|  12.40|   53.4|  11.70|   44.5|  10.90|   35.6|   9.90|   26.7|  12.20|   49.1|

  BALLAST  |   6s60ME      |Down 1 clyinder|Down 2 clyinder|Down 3 clyinder|6S60ME     with|
SPEED|POWER |eedi=1.59      |eedi=1.41      |eedi=1.21      |eedi=1.00      |slow-steam mods|
 Kts |  KW  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |  SFC  |  TPD  |
 8.50|  3313|       |       |       |       |       |       |  169.1|   12.3|  169.1|   12.3|
 9.00|  3933|       |       |       |       |       |       |  167.0|   14.4|  167.0|   14.4|
 9.50|  4626|       |       |       |       |  168.4|   17.1|  165.8|   16.8|  165.8|   16.8|
10.00|  5395|       |       |  169.4|   20.0|  166.7|   19.7|  165.9|   19.6|  165.9|   19.6|
10.50|  6244|       |       |  167.5|   22.9|  165.7|   22.6|  167.7|   22.9|  165.7|   22.6|
11.00|  7180|  167.9|   26.4|  166.0|   26.1|  165.8|   26.1|       |       |  165.8|   26.1|
11.50|  8204|  166.5|   29.9|  165.6|   29.7|  167.5|   30.1|       |       |  165.6|   29.7|
12.00|  9322|  165.7|   33.8|  166.1|   33.9|  170.4|   34.8|       |       |  165.7|   33.8|
12.50| 10536|  165.7|   38.2|  168.0|   38.7|       |       |       |       |  165.7|   38.2|
13.00| 11897|  166.9|   43.5|  171.0|   44.5|       |       |       |       |  166.9|   43.5|
13.50| 13264|  169.1|   49.1|       |       |       |       |       |       |  169.1|   49.1|
MCR  SPD/TPD|  13.80|   53.4|  13.00|   44.5|  12.00|   35.6|  10.90|   26.7|  13.50|   49.1|
```

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. The resulting speed-fuel curve is shown on the far right.

Table 17 shows the slow-steaming table for this ship for a bunker cost of $465 per ton. The ship is so under-powered that at WS90, it is already going as fast as it 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 terrible heavy weather performance.

If we compare this ship with the non-EEDI BASE ship from Table 5, we obtain Table 18. 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 17: Slow-steaming curve for 6S60ME ship. BFO=$465, EEDI=1.51

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	8.97	1446	9610	65.89	277073	30265	1.1007
40	9.38	1601	16749	63.13	277073	31586	1.1677
50	9.89	1731	24834	60.11	277030	33168	1.2026
60	10.97	1990	34200	54.58	276876	36511	1.2560
70	11.84	2268	43839	50.89	276756	39142	1.3354
80	12.35	2411	54320	48.94	276624	40682	1.3657
90	12.82	2586	64924	47.28	276462	42087	1.4161
100	12.82	2586	75414	47.28	276462	42087	1.4161
110	12.82	2586	85903	47.28	276462	42087	1.4161
120	12.82	2586	96392	47.28	276462	42087	1.4161
130	12.82	2586	106881	47.28	276462	42087	1.4161
140	12.82	2586	117371	47.28	276462	42087	1.4161
150	12.82	2586	127860	47.28	276462	42087	1.4161
160	12.82	2586	138349	47.28	276462	42087	1.4161
170	12.82	2586	148838	47.28	276462	42087	1.4161
180	12.82	2586	159328	47.28	276462	42087	1.4161
190	12.82	2586	169817	47.28	276462	42087	1.4161
200	12.82	2586	180306	47.28	276462	42087	1.4161

Table 18: Percent CO2 Reduction, BASE ship vs 6S60ME at $465 BFO cost

WS	TCE BASE	TCE 6S60	Ratio CO2	% Down
30	9913	9610	1.0453	+4.5
40	18133	16749	1.0660	+6.6
50	26723	24834	1.0437	+4.4
60	36556	34200	1.0545	+5.4
70	46744	43839	1.0293	+2.9
80	58424	54320	1.0078	+0.8
90	70465	64924	1.0044	+0.4
100	83064	75414	0.9816	-1.8
110	95689	85903	0.9464	-5.4
120	108438	96392	0.9237	-7.6
130	121712	106881	0.9092	-9.1
140	135055	117371	0.8918	-10.8
150	148313	127860	0.8799	-12.0
160	161703	138349	0.8799	-12.0
170	175093	148838	0.8799	-12.0
180	188483	159328	0.8799	-12.0
190	201873	169817	0.8799	-12.0
200	215355	180306	0.8611	-13.9

7.2 Slow-steaming curves for $620 BFO cost

Table 19 shows the slow-steaming table for this ship for a bunker cost of $620 per ton. With this bunker cost, the owner of the Phase 3 ship speeds up a bit more slowly and will require WS120 or better to go full speed. If we compare this table with the BASE ship's results at $620 bunkers, we obtain Table 20.

The indicated advantage of the EEDI-compliant ship at the very low end of the market is phony. The MFIX program is limited to 16 steaming speeds. As a result, as far as MFIX is concerned, the BASE ship cannot go below 9.5 knots, while the EEDI compliant ship can. In reality, the BASE ship can go just as slow as the EEDI-compliant ship if it wants to. Despite this artifical bias in favor of the EEDI-compliant ship, when you apply our Standard spot rate profile to these numbers, the non-EEDI BASE ship averages 1.161 tons of CO2 per ton per day delivered; the EEDI-compliant vessel averages 1.181.

7.3 Summary

The Phase 3 results follow a now familiar pattern.

Table 19: Slow-steaming curve for 6S60ME ship. BFO=$620, EEDI=1.51

WS	AVESPD	BFO	TCE	DAYS	CARGO	BPD	C02/TPD
30	8.24	1243	7518	71.31	277073	27964	1.0239
40	8.74	1374	14097	67.49	277073	29545	1.0712
50	9.18	1523	21033	64.44	277073	30944	1.1338
60	9.68	1647	28947	61.30	277030	32524	1.1667
70	10.47	1840	37717	57.00	276930	34967	1.2123
80	11.24	2056	47024	53.36	276815	37333	1.2693
90	12.00	2295	56821	50.25	276691	39632	1.3342
100	12.35	2411	66972	48.94	276624	40682	1.3657
110	12.59	2499	77323	48.07	276543	41400	1.3907
120	12.82	2586	87924	47.28	276462	42087	1.4161
130	12.82	2586	98414	47.28	276462	42087	1.4161
140	12.82	2586	108903	47.28	276462	42087	1.4161
150	12.82	2586	119392	47.28	276462	42087	1.4161
160	12.82	2586	129881	47.28	276462	42087	1.4161
170	12.82	2586	140371	47.28	276462	42087	1.4161
180	12.82	2586	150860	47.28	276462	42087	1.4161
190	12.82	2586	161349	47.28	276462	42087	1.4161
200	12.82	2586	171838	47.28	276462	42087	1.4161
210	12.82	2586	182328	47.28	276462	42087	1.4161
220	12.82	2586	192817	47.28	276462	42087	1.4161
230	12.82	2586	203306	47.28	276462	42087	1.4161
240	12.82	2586	213795	47.28	276462	42087	1.4161
250	12.82	2586	224285	47.28	276462	42087	1.4161
260	12.82	2586	234774	47.28	276462	42087	1.4161
270	12.82	2586	245263	47.28	276462	42087	1.4161

- 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%.
- The Phase 3 regulations will eventually result in a 29% larger fleet, and a like increase in non-operational CO2 emissions, even before we adjust for the differences in heavy weather performance.
- The Phase 3 regulations will require that at least 29% more of the world's resources be devoted to VLCC transportation. The shipyards are strong supporters of EEDI for good reason.
- The Phase 3 regulations will increase our exposure to VLCC casualties by 29% even before we account for the fact that the EEDI compliant ship will be far less maneuverable, and far less able to get out of trouble than the non-EEDI ship.

Table 20: Percent CO2 Reduction, BASE ship vs 6S60 at $620 BFO cost

WS	TCE BASE	TCE 6S60	Ratio CO2	% Down
30	6236	7518	0.9868	-1.3
40	14570	14097	1.0324	+3.2
50	22631	21033	1.0572	+5.7
60	31248	28947	1.0651	+6.5
70	40434	37717	1.0423	+4.2
80	50252	47024	1.0566	+5.7
90	60576	56821	1.0406	+4.1
100	71888	66972	1.0263	+2.6
110	83549	77323	1.0168	+1.7
120	95718	87924	0.9931	-0.7
130	108243	98414	0.9816	-1.8
140	120611	108903	0.9599	-4.0
150	133549	119392	0.9464	-5.4
160	146506	129881	0.9092	-9.1
170	159658	140371	0.9092	-9.1
180	172986	150860	0.8918	-10.8
190	186299	161349	0.8918	-10.8
200	199553	171838	0.8799	-12.0
210	212943	182328	0.8799	-12.0
220	226333	192817	0.8799	-12.0
230	239723	203306	0.8799	-12.0
240	253113	213795	0.8799	-12.0
250	266503	224285	0.8799	-12.0
260	279893	234774	0.8799	-12.0
270	293458	245263	0.8611	-13.9

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

8.1 Saintly Slow-steaming curves for $465 BFO cost

We have seen that 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 6, 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 6 and 7. Either way we will end up with the Table 4 speed/fuel curve except that the max loaded/ballast speed will be 14.0/15.5 knots.

Table 21 shows the slow-steaming table for this ship for $465 bunkers.

Table 21: Slow-steaming curve for 7RAT84, derated 35%. BFO=$465, EEDI=1.74

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	14.49	2776	70434	42.31	276419	47025	1.3603
100	14.72	2854	82431	41.70	276347	47692	1.3789
110	14.72	2854	94317	41.70	276347	47692	1.3789
120	14.72	2854	106203	41.70	276347	47692	1.3789
130	14.72	2854	118089	41.70	276347	47692	1.3789
140	14.72	2854	129976	41.70	276347	47692	1.3789
150	14.72	2854	141862	41.70	276347	47692	1.3789
160	14.72	2854	153748	41.70	276347	47692	1.3789
170	14.72	2854	165634	41.70	276347	47692	1.3789
180	14.72	2854	177520	41.70	276347	47692	1.3789
190	14.72	2854	189407	41.70	276347	47692	1.3789
200	14.72	2854	201293	41.70	276347	47692	1.3789

Comparing this ship with the BASE un-derated ship, we obtain Table 22. Below WS 80 both ships are at the same speed and there is no difference. But at WS80, the derated ships 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.

8.2 Saintly Slow-steaming curves for $620 BFO cost

Table 23 shows the slow-steaming table for the derated ship and $620 bunkers. At this bunker cost, both ships go the same speed up to WS100, after which the un-derated ship starts using her superior speed. 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.

Table 22: Percent Reduction in CO2, BASE vs BASE derated 35%. BFO=$465

WS	TCE BASE	TCE 6 cyl	Ratio CO2	% Down
30	9913	9913	1.0000	-0.0
40	18133	18133	1.0000	-0.0
50	26723	26723	1.0000	-0.0
60	36556	36556	1.0000	-0.0
70	46744	46744	1.0000	-0.0
80	58424	58496	0.9820	-1.8
90	70465	70434	0.9648	-3.5
100	83064	82431	0.9558	-4.4
110	95689	94317	0.9215	-7.8
120	108438	106203	0.8994	-10.1
130	121712	118089	0.8853	-11.5
140	135055	129976	0.8683	-13.2
150	148313	141862	0.8568	-14.3
160	161703	153748	0.8568	-14.3
170	175093	165634	0.8568	-14.3
180	188483	177520	0.8568	-14.3
190	201873	189407	0.8568	-14.3
200	215355	201293	0.8385	-16.2

8.3 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 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 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 really uses its 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.

Even if we somehow could make factor (2) disappear, the reduction in actual VLCC CO2 emissions would still be about a tenth of the reduction in EEDI. Even under impossibly optimistic set of assumptions, EEDI is an indirect and remarkably ineffective means of reducing 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, grasping, but EEDI-legal competitors. Hopefully, he finds comfort in this.

Table 23: Slow-steaming curve for 7RAT84T-D, derated 35%. BFO=\$620, EEDI=1.74

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	14.25	2703	83552	42.95	276486	46331	1.3445
120	14.72	2854	95610	41.70	276347	47692	1.3789
130	14.72	2854	107497	41.70	276347	47692	1.3789
140	14.72	2854	119383	41.70	276347	47692	1.3789
150	14.72	2854	131269	41.70	276347	47692	1.3789
160	14.72	2854	143155	41.70	276347	47692	1.3789
170	14.72	2854	155041	41.70	276347	47692	1.3789
180	14.72	2854	166927	41.70	276347	47692	1.3789
190	14.72	2854	178814	41.70	276347	47692	1.3789
200	14.72	2854	190700	41.70	276347	47692	1.3789
210	14.72	2854	202586	41.70	276347	47692	1.3789
220	14.72	2854	214472	41.70	276347	47692	1.3789
230	14.72	2854	226358	41.70	276347	47692	1.3789
240	14.72	2854	238245	41.70	276347	47692	1.3789
250	14.72	2854	250131	41.70	276347	47692	1.3789
260	14.72	2854	262017	41.70	276347	47692	1.3789
270	14.72	2854	273903	41.70	276347	47692	1.3789

Table 24: Percent Reduction, BASE ship versus derated, \$620 BFO cost

WS	TCE BASE	TCE 6 cyl	Ratio CO2	% Down
30	6236	6236	1.0000	-0.0
40	14570	14570	1.0000	-0.0
50	22631	22631	1.0000	-0.0
60	31248	31248	1.0000	-0.0
70	40434	40434	1.0000	-0.0
80	50252	50252	1.0000	-0.0
90	60576	60576	1.0000	-0.0
100	71888	71888	1.0000	-0.0
110	83549	83552	0.9830	-1.7
120	95718	95610	0.9670	-3.3
130	108243	107497	0.9558	-4.4
140	120611	119383	0.9347	-6.5
150	133549	131269	0.9215	-7.8
160	146506	143155	0.8853	-11.5
170	159658	155041	0.8853	-11.5
180	172986	166927	0.8683	-13.2
190	186299	178814	0.8683	-13.2
200	199553	190700	0.8568	-14.3
210	212943	202586	0.8568	-14.3
220	226333	214472	0.8568	-14.3
230	239723	226358	0.8568	-14.3
240	253113	238245	0.8568	-14.3
250	266503	250131	0.8568	-14.3
260	279893	262017	0.8568	-14.3
270	293458	273903	0.8385	-16.2

A The VLCC Spot Rate Profile

Figure 2 displays the VLCC spot rate from 1989 to 2009 inclusive. The numbers shown are monthly averages according to Clarksons. The average spot rate over that 21 year period was WS63.2. The VLCC Required Freight Rate over that period is a bit of a moving target for several reasons, but mainly because the newbuilding price of a VLCC is constantly changing. This is due principally to strength or weakness in the very competitive newbuilding market. When the shipbuilding market is very strong, the price of a VLCC can easily 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. In short, the actual average spot rate is about where we would expect it to be.

Figure 3 is a histogram showing the fraction of the time the market spent at each rate. For the purposes of this diagram, we broke the rates down into 10 WS point intervals.

The market spents 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, obviously a highly skewed distribution. Table 25 shows the actual numbers.

Table 25: 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	

The column labeled "Standard" is the market rate profile that was used in collapsing the CO2 per TPD delivered numbers at each rate to an average number over a market cycle. In using this profile, all rates above WS100 are considered to be full boom, and mapped to WS200. It is a reasonable approximation to the observed rates below WS100; but is intentionally biased upward, that is, in favor of the 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 artifically speeds up the 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 CO2 per ton per day delivered.

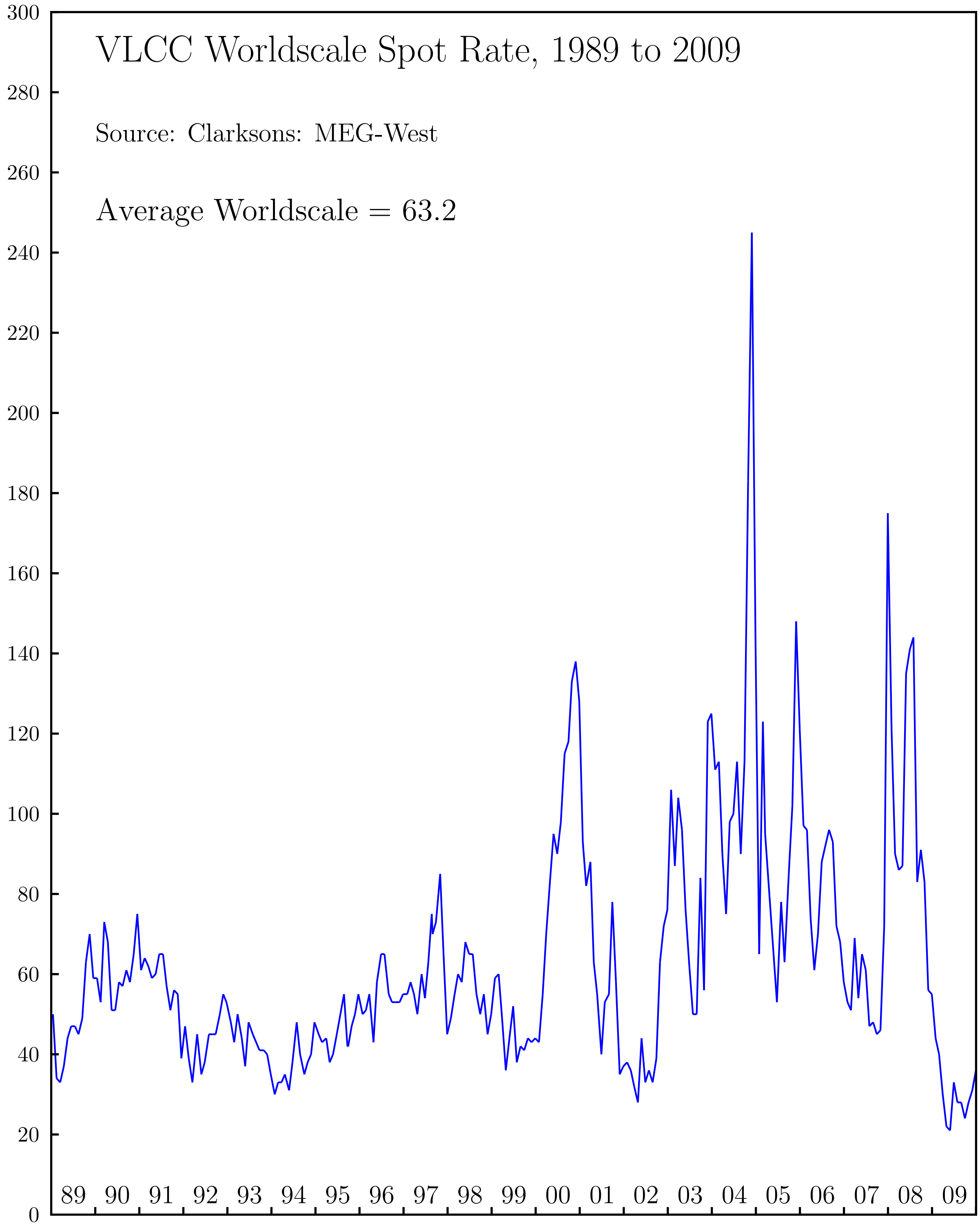

Figure 2: VLCC Spot Rate for the last 21 Years

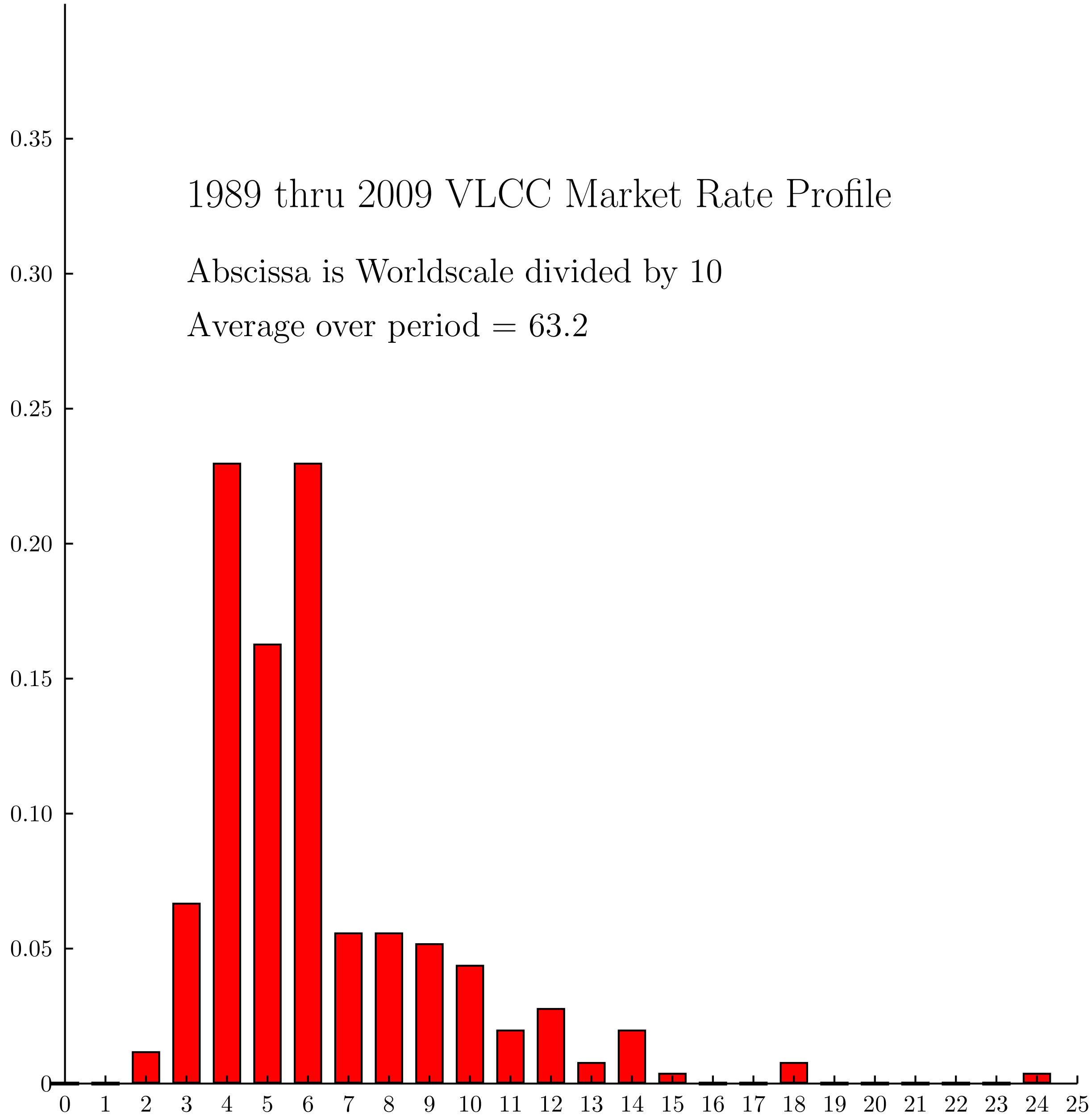

Figure 3: VLCC Spot Rate Profile for the last 21 Years