Report No. 228
September 1980

SOME ASPECTS OF FUEL ECONOMY IN BULK CARRIER DESIGN AND OPERATION

Robert M. Scher
Harry Benford

Department of Naval Architecture
and Marine Engineering
College of Engineering
The University of Michigan
Ann Arbor, Michigan 48109

SOME ASPECTS OF FUEL ECONOMY IN BULK CARRIER DESIGN AND OPERATION

Robert M. Scher (Associate Member), Research Associate,
Department of Naval Architecture and Marine Engineering,
The University of Michigan.

Harry Benford (Fellow), Professor of
Naval Architecture and Marine Engineering,
The University of Michigan.

Abstract

In this paper we look at near-term solutions to the impact of higher fuel costs on the design of bulk carriers and strategies for fleet operation. We propose analytical techniques that recognize the inventory cost of the goods in transit as well as the economics of the ship itself. As an illustration of our proposals, we show the results of a study to determine the best combination of design speed and block coefficient for a bulk carrier of Panamax size under various levels of fuel price. A section on fleet management proposes a method for selecting the most fuel-efficient plan for operating a fleet of ships during conditions of fuel shortage or unforeseen rises in price.

Introduction

For the maritime community, faced with continuing uncertainty about fuel sources and availability, together with drastic escalation of fuel prices, the years ahead will be a most challenging period. The prudent shipowner, naval architect, and marine engineer will have to recognize the changing energy situation as one of the essential facts of economic life when making decisions in the design and operation of their vessels. It is scant comfort that marine transport interests are not alone in the grip of the energy malaise; there is hardly a part of the world's economy that does not feel the chill in some way. We are all unfortunate enough, as the old Chinese proverb goes, to live in interesting times.

Yet, within our own industry there are several promising signs, indications that we can successfully adapt to the new age of precious petroleum. Certainly, the problems that we will have to master in the coming years are already under attack on many fronts: the development of more efficient machinery, modified hull forms and improved coating systems for reduced resistance, the potential use of alternative fuels (most notably coal and its derivatives), and even the possible revival of commercial wind-powered vessels. Further improvements in over-all fuel efficiency may be realized through the widespread use of weather routing and traffic control procedures, or by the rational reduction of speed and horsepower. Finally, the avoidance of trips in ballast, where feasible, represents an important advantage in the efficient use of fuel in marine transport; thus, the increasing popularity of multi-purpose cargo vessels should be recognized as a potential energy saver.

The actual extent to which each of these factors will influence the future development of maritime commerce is clearly beyond our scope. Indeed, if we could predict the future with such breadth and exactitude we might have avoided the energy crisis entirely. Be that as it may, the purpose of this paper is to examine some specific design and operating decisions that are strongly influenced by changes in fuel price While our attention will be confined, for convenience, to a particular type and size of vessel--ocean going dry bulk carriers of approximately Panamax dimensions--many of our conclusions will be applicable to other classes of bulk carriers and tankers as well.

In the first section of this paper, we shall consider the influence of fuel price on the optimum design speed and block coefficient, decisions that must be made relatively early in the design process. We have eased our computational burden somewhat by choosing as an example a vessel whose over-all dimensions are more or less preordained. In doing so, we set out to solve the typical design problem of a bulk carrier of constrained dimensions under conditions of unlimited cargo availability. It should be recognized that in the equally valid alternative problem of fixed annual cargo throughput, with freedom of dimensions, the choice of vessel speed and size becomes the paramount issue, with hull form as a secondary question. There are undoubtedly some valuable lessons to be learned in considering the impact of fuel price on the optimum ship size problem, but we'll put that aside for a later date.

The second part of this paper considers the plight of the fleet manager who finds himself saddled with ships designed in an era of cheap fuel. What strategy should he adopt in order to produce minimum costs or maximum profits? Should he rely on his most energy efficient ships and leave the others in lay-up, or should he slow steam the entire fleet? What changes in strategy should be incorporated if fuel oil supplies were to be severely curtailed again? Such are the questions that must be dealt with in fleet management for improved energy efficiency, and we shall offer some relatively simple methods for answering them.

Two potential complications of the following economic analyses are best mentioned here, since we have neither the courage nor the wisdom to pursue them much further in the body of the paper. First, and most obviously, we are considering the impact of fuel price on design and operating decisions only in the strict and limited sense of a partial derivative. We are perfectly free, in terms of our economic model, to raise the price of fuel arbitrarily, while reflecting no corresponding increases in other cost components: steel, shipyard labor, outfit and machinery acquisition, insurance, stores, the value of the cargo, or anything else. The real economic world, of course, doesn't behave this way at all. Theoretically, at least, it should be possible to use econometric methods to model the influence of fuel prices on all the elements of transport cost, and thus to predict the future progression of freight rates that would be entailed by a given progression of fuel price increases. That job we shall leave to the econometricians; the aim of this paper is more modest. We shall attempt to show the effects of large increases in fuel price alone, realizing that there may be economic forces in the world (for good or ill) that will prevent a ton of fuel from reaching the same price as a ton of steel, or an American seaman's weekly wage, at least for a while.

The second complication that we have chosen to ignore is the problem of balancing the energy saved by adopting lower service speeds against the energy expended to build the additional ships required to replace the lost transport capacity. It appears that fuel requirements in ship operation are many times greater than the energy consumed in shipbuilding. However, if all energy expenditures were to be included in our analysis, we should still have a merry debate on whether present and future energy expenditures should be weighed using standard discounting relationships. We welcome suggestions as to what interest rate we should use in discounting future BTU's.

Fuel Price and Design Speed

In this section we consider the role of fuel price in determining optimum design speed and block coefficient. Our basic measure of merit will be the required freight rate (RFR), defined as the amount that must be charged, per ton of cargo, in order to obtain a specified rate of return on the investment:

$$\mathrm{RFR} = \frac{P(CR)+AOC}{ATC} \qquad (1)$$

where P is the ship price, CR the capital recovery factor (a function of the specified interest rate, tax rate, economic life, and method of depreciation), AOC the annual operating cost, and ATC the vessel's annual transport capacity in tons.

While the required freight rate is a convenient and useful measure of merit in ship design, it excludes the inventory costs that should be charged on the cargo in transit. In order to reflect this inventory cost, we propose another measure of merit, which we call the economic cost of transport (ECT) which is in units of dollars per ton of cargo. We define it as follows:

$$\mathrm{ECT} = \mathrm{RFR} + \frac{iDV}{365(1-t)} \qquad (2)$$

where V is the cargo value per ton, i is the time value of money, D the transit time in days per voyage and t the tax rate. In practice, the definitions of V and D are often somewhat nebulous, and there are other ways of assessing inventory costs. However, it is logical (and simple) to identify V with the price of the cargo at the loading port, and to relate D to the time the cargo is actually on board. It should be recognized that there are additional inventory costs accrued by cargo in the stock-piles at either end of the voyage, and that some of these costs may be logically charged to the ship, depending on the detailed timing of the purchase and sale of the cargo.

For any particular route and service, the optimization of ship design characteristics consists of finding a combination of principal dimensions, form coefficients, speed and power that gives the most satisfactory value of the appropriate measure of merit. Given a suitable mathematical model of ship resistance and propulsion, weights, and costs, any of a number of computer-aided optimization techniques can be applied, and an optimum solution found. In the following example, as in many practical situations in bulk carrier design, the optimization process is confined to speed and block coefficient, the over-all dimensions being constrained. As we shall see, however, our interest may not be limited to finding minimum RFR's for various fuel prices; we should be just as concerned with the economic effects of slight departures from optimum design characteristics.

Vessel Design

The ship under consideration here is a single-screw diesel-powered bulk carrier of approximately Panamax dimensions, with 10 percent additional design draft over normal canal operating draft. Vessel particulars and range of variations are given in Table I. (For the purposes of the calculations in this paper, all hull form coefficients and deadweights will be referred to the maximum design draft.) The vessel is flush-decked, with all-aft superstructure, and limited deck gear for lightering operations. Details of the synthesis model are included in the appendix, and the basic economic assumptions are given in Table II.

Alternative speeds and block coefficients were evaluated over a considerable range: speeds from 8.6 to 20 knots ($V_k/L^{1/2}$=0.3 to 0.7), and block coefficients from 0.75 to 0.90. This extensive range of speeds was intended to permit a series of optimizations over a wide range of hypothetical fuel prices.

TABLE I. Ship Particulars and Variations

Length over-all	835.0 ft	(254.5m)
waterline	820.3	(250.0)
between perps	810.0	(246.9)
Beam	105.8	(32.2)
Depth	60.7	(18.5)
Draft maximum	47.6	(14.5)
canal operating	43.0	(13.1)
Block coefficient	0.75 - 0.90	
Displacement, long tons	88,500 - 106,200	
Deadweight, long tons	72,800 - 90,200	
Service speed	8.6 - 20 kt	
Machinery type: Single screw, geared diesel		
Brake horsepower (MCR)	3,520 - 39,600	
Propeller rpm (design speed)	30 - 72	
Auxiliary generator load	750 kW sea, 600 kW port	
Fuel (main engine)	3500 sec Redwood	
Complement	26 - 30	

TABLE II. Basic economic assumptions. All values in January 1980 U.S. dollars. For details of synthesis model, see appendix.

Average steel material	$460/ton
Average shipyard wage/benefits	$ 10/man•hr
Shipyard overhead	100%
Average annual salary and benefits per crew member	$29,600
Fuel price 3500 sec	$150/ton
#2 MDO	$240/ton
Interest rate (constant value $)	10%
Tax rate	46%
Economic life	20 yr
Depreciation scheme	Tax deferred
Investment tax credit	None
Subsidy	None

RFR vs Block Coefficient and Speed-Length Ratio

Subject to the basic assumptions listed in Table II, the required freight rate can be represented as a function of $V_k/L^{1/2}$ and C_B, as shown in Figure 1. For this specific case, a 6000 mile round trip distance is assumed, with cargo carried on one leg only. The minimum RFR is found in the neighborhood of $V_k/L^{1/2}$=0.46, or 13-1/4 knots, with a block coefficient of about 0.85. This speed is well below the traditional service speed for bulk carriers of this size, typically 14-1/2 to 16 knots. It is noteworthy, however, that a design speed of 16 knots ($V_k/L^{1/2}$=0.55) results in less than 1 percent increase in RFR, provided that the block coefficient is suitably reduced to about 0.80. Consideration of inventory costs or competitive factors may well lead to a preference for the higher speed, and we shall return to these factors subsequently.

In terms of RFR, however, the influence of fuel price on optimum speed and block coefficient is shown in Figure 2, for fuel prices varying from zero (i.e., free fuel) to triple the base price. The shift of optimum speed and block coefficient is apparent, although the trend is distorted by the discrete data points presented in Figure 2. The actual variation of the optima, plotted as functions of fuel price, is shown in Figure 3. It is apparent from these results that large fuel price increases, as represented by a tripling of the base price, will lower the optimum speed by as much as 2-3 knots, neglecting inventory costs. The idea of an 800-ft bulk carrier engined for a 10-knot design speed is somewhat disconcerting, perhaps; but it should be remembered that this design corresponds to a world in which a ton of fuel and a ton of steel are roughly equivalent in price, which is disconcerting enough in itself.

RFR vs Fuel Price

It may be surprising to note that the required freight rate of optimum designs increases only 77 percent in going from free fuel to a price of $450 per ton. This apparent insensitivity merely reflects the fact that fuel price has been varied within the model without any corresponding impacts on other costs. In the real world, by contrast, it may be assumed that if fuel prices were to increase by a factor of three, the accompanying increases in other material and labor costs would reduce the over-all impact on optimum design, while greatly increasing the required freight rate. Thus, the 10-knot Panamax bulker may be further off than a simple extrapolation of recent fuel prices might suggest. Shall we weep or rejoice?

Alexander Revisited

The empirical relationship between design speed and optimum block coefficient is a beloved subject of discussion among naval architects, particularly British ones. In spite of its simplicity, the Alexander formula's linear relation $C_B = a - bV_k/L^{1/2}$ gives a surprisingly good fit if confined to particular vessel types and reasonable speed ranges. However, as might be expected, the coefficients in the formula show some variation with fuel price. The results of such an analysis are plotted in Figure 4. In general, increased fuel price levels appear to favor somewhat finer ships for a given ship speed, and the slopes are slightly different, but perhaps the most striking feature of Figure 4 is the limited extent of the difference imposed by such a wide range in assumed fuel prices.

Inventory Costs and Design Speed

As already stated, the effect of inventory cost on design speed is to place a penalty on slow-speed designs. Using the definition of inventory cost given in Eq. (2), optimum design speeds are plotted in Figure 5 for cargo values from zero to $500/ton. The difference between the optimum design speeds with and without the effect of inventory cost may have some interesting implications for both ship design and operation, particularly when dealing with relatively high-priced bulk cargoes. For example, in the case of oil tankers it is clear that any major increase in fuel price must be accompanied by a comparable increase in cargo value and inventory cost. Thus, provided that the transfer of cargo ownership takes place at loading and unloading, it might be logical to operate at two distinct speeds: a relatively high speed based on minimum ECT when loaded, and a reduced speed based on minimum RFR while in ballast. We know

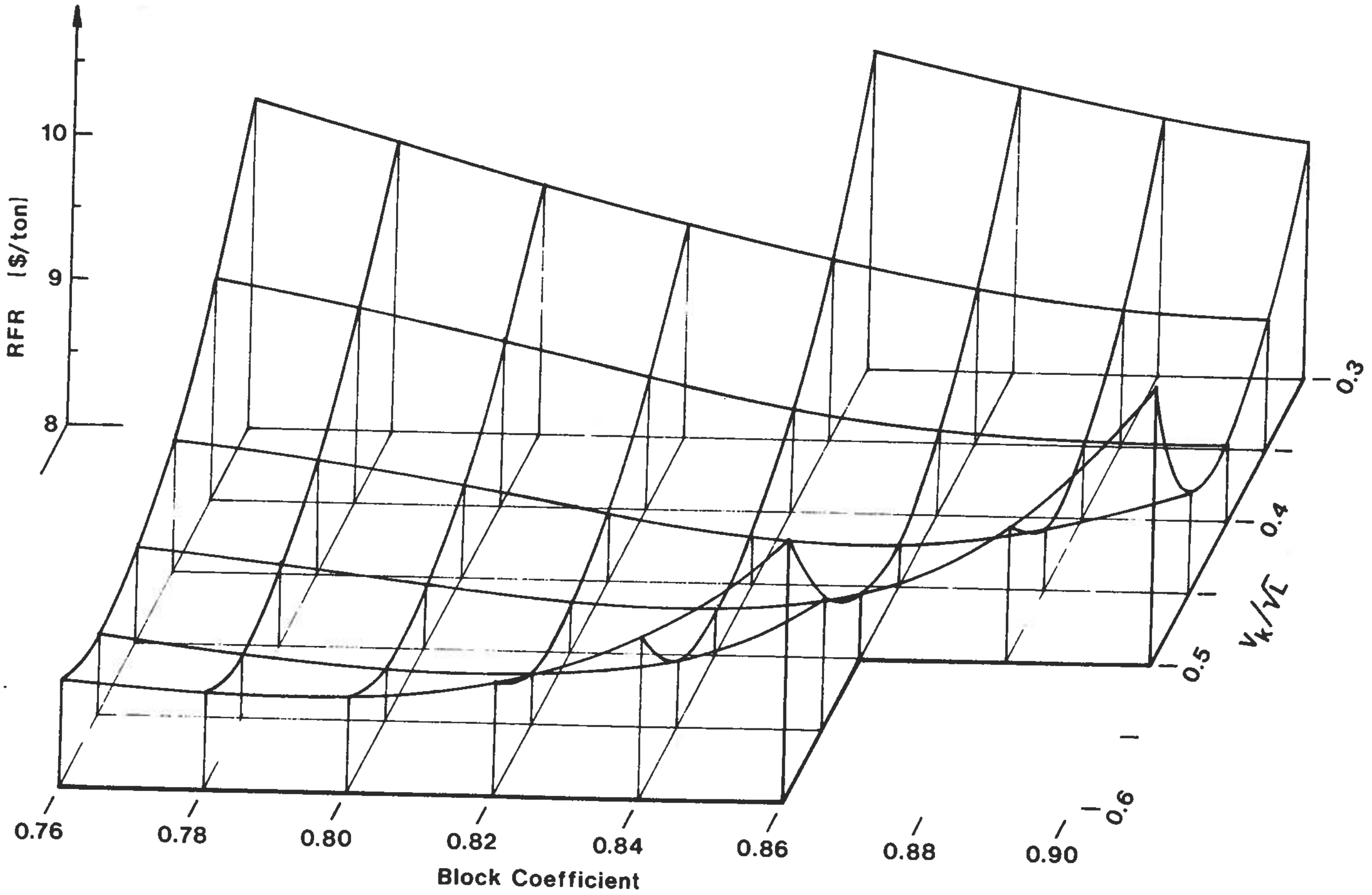

Fig. 1. Required freight rate (RFR) as a function of block coefficient and design speed-length ratio; base fuel cost. Results are plotted for 6000 nautical mile round trip. Note on the vertical scale that the "floor" of this drawing is $8 per ton, not zero.

$V_k/L^{1/2}$	Block Coefficient: 0.76	0.78	0.80	0.82	0.84	0.86	0.88	0.90
Base Fuel Price								
0.30					10.20	9.98	9.79	9.64
0.35	10.28	10.00	9.74	9.48	9.26	9.07	8.96	8.91
0.40	9.53	9.36	9.15	8.92	8.71	8.59	8.54	8.54
0.45	8.91	8.79	8.64	8.47	8.34	8.29	8.43	8.70
0.50	8.66	8.57	8.45	8.35	8.33	8.45	8.94	9.92
0.55	8.56	8.44	8.37	8.36	8.47	8.92		
0.60	8.76	8.68	8.68	8.79	9.14	9.81		
50% Fuel Price Increase								
0.30					10.67	10.44	10.25	10.10
0.35	10.85	10.56	10.29	10.02	9.79	9.59	9.48	9.44
0.40	10.17	10.00	9.78	9.42	9.32	9.21	9.17	9.20
0.45	9.63	9.51	9.36	9.07	9.05	9.05	9.28	9.69
0.50	9.48	9.39	9.29	9.21	9.23	9.43	10.13	11.65
0.55	9.53	9.41	9.36	9.38	9.58	10.21		
0.60	9.93	9.86	9.90	10.10	10.60	11.58		
100% Fuel Price Increase								
0.30					11.14	10.91	10.71	10.56
0.35	11.42	11.11	10.83	10.55	10.31	10.11	10.00	9.96
0.40	10.82	10.63	10.41	10.16	9.94	9.83	9.80	9.86
0.45	10.34	10.22	10.07	9.91	9.81	9.82	10.13	10.67
0.50	10.30	10.21	10.12	10.06	10.13	10.42	11.33	13.37
0.55	10.49	10.38	10.35	10.39	10.69	11.51		
0.60	11.10	11.03	11.11	11.40	12.06	13.34		
200% Fuel Price Increase								
0.30					12.08	11.84	11.63	11.47
0.35	12.56	12.00	11.92	11.62	11.37	11.16	11.04	11.01
0.40	12.10	11.91	11.68	11.40	11.17	11.06	11.07	11.19
0.45	11.78	11.66	11.51	11.35	11.28	11.34	11.84	12.65
0.50	11.93	11.86	11.66	11.77	11.93	12.39	13.71	16.82
0.55	12.43	12.32	12.32	12.42	12.91	14.09		
0.60	13.44	13.38	13.54	14.01	14.99	16.87		
50% Fuel Price Decrease								
0.30					9.73	9.51	9.33	9.18
0.35	9.71	9.45	9.19	8.94	8.73	8.55	8.44	8.38
0.40	8.89	8.72	8.52	8.30	8.10	7.97	7.91	7.88
0.45	8.19	8.07	7.92	7.75	7.61	7.53	7.58	7.71
0.50	7.84	7.75	7.61	7.49	7.43	7.47	7.75	8.19
0.55	7.59	7.47	7.38	7.34	7.36	7.63		
0.60	7.59	7.50	7.46	7.48	7.68	8.04		
100% Fuel Price Decrease (Free Fuel)								
0.30					9.26	9.05	8.87	8.72
0.35	[illegible].14	8.89	8.65	8.41	8.20	8.03	7.92	7.86
0.40	8.24	8.09	7.89	7.68	7.48	7.35	7.28	7.22
0.45	7.48	7.36	7.21	7.03	6.87	6.76	6.73	6.73
0.50	7.02	6.92	6.78	6.64	6.53	6.48	6.47	6.47
0.55	6.63	6.50	6.39	6.33	6.25	6.33		
0.60	6.42	6.33	6.25	6.18	6.22	6.28		

Fig. 2. Effect of relative fuel price on RFR as a function of block coefficient and speed-length ratio. Round trip distance: 6000 miles. Dotted lines show approximate loci of optimum block coefficient for given speed. Contours represent RFR values 1 percent higher than optima, which are shown by crosses.

of at least one oil company that recognizes both high fuel price and high cargo value by doing exactly that. Similar operating philosophies will probably be found in certain dry bulk trades, although the parallel between fuel price and cargo value is less neatly drawn.

Fuel Efficiency

Apart from the usual economic measures of merit, such as RFR, design decisions will be increasingly guided by a consideration of fuel efficiency per se. This has been represented in a number of ways, whether as a measure of transport produced per unit of fuel consumed, as ton•miles/barrel, or as an energy consumption per unit of transport, as BTU/ton•mile. Results for our hypothetical Panamax bulk carrier are shown in Figure 6, with the previously stated assumptions of a 6000-mile round trip, one way cargo, and operation at normal continuous power (90% of maximum continuous rating) on both the loaded and ballast legs. The advantage of lower design speeds in fuel conservation is striking. In fact, there must be a limit on the energy saving that can be obtained by lower design speeds, but it seems to be imposed mainly by the fuel consumption of the ship's service generator. This "optimum" value of ton•miles/barrel will occur at a speed well below the range of this investigation, and presumably below the range of practicality.

To Save Fuel, Cut Taxes

An examination of the equations for either required freight rate or economic cost of transport shows what should be intuitively obvious, namely that corporate income taxes increase the freight rates that must be paid by the customer. Increased freight rates just as obviously justify higher ship speeds. High speeds, in turn, lead to lower energy efficiencies. Thus, it becomes clear that the federal government can do its part to encourage energy conservation by the happy expedient of abolishing income taxes at the corporate level and contenting itself with wringing them out of the stockholders. (If this conclusion doesn't win us an award from some shipowners' association, we shall be bitterly disappointed.)

We have to date made only a small beginning in our attempt to quantify the abovementioned effect of the tax on energy efficiency. We can, however, cite

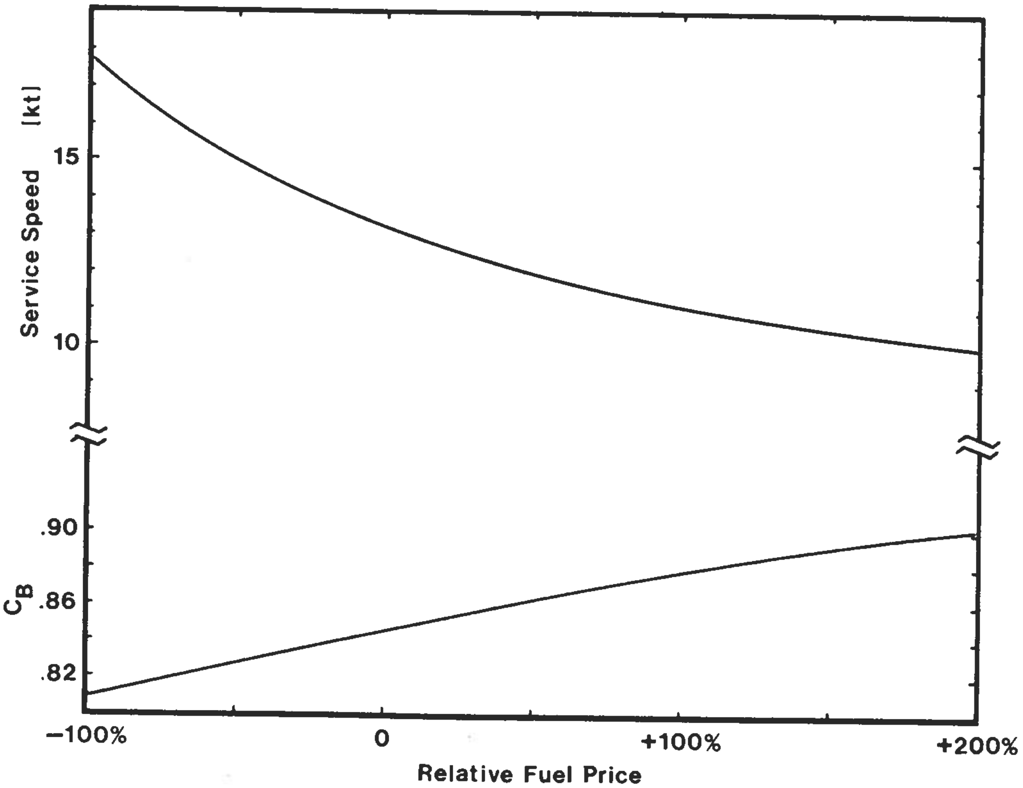

Fig. 3. Optimum service speed and block coefficient versus relative fuel price, based on minimum RFR. The zero relative fuel price refers to the base assumption of Table II. Results are plotted for a 6000 mile round trip; 12,000 and 24,000 mile round trips differ only slightly.

one figure derived from a recent bulk transport study. Assuming a cargo valued at $1000 per ton, and using an after-tax rate of return of 10 percent, we found that eliminating an assumed 45 percent tax would drop the optimum shaft horsepower (for a proposed ship) from 20,500 to 17,900. This would then increase the energy efficiency from 9600 ton-miles per barrel to 10,800 ton-miles per barrel--a gain of 12.5 percent. We can conceive of no energy-saving measure that the government could impose that would be more enthusiastically embraced by all segments of the industry.

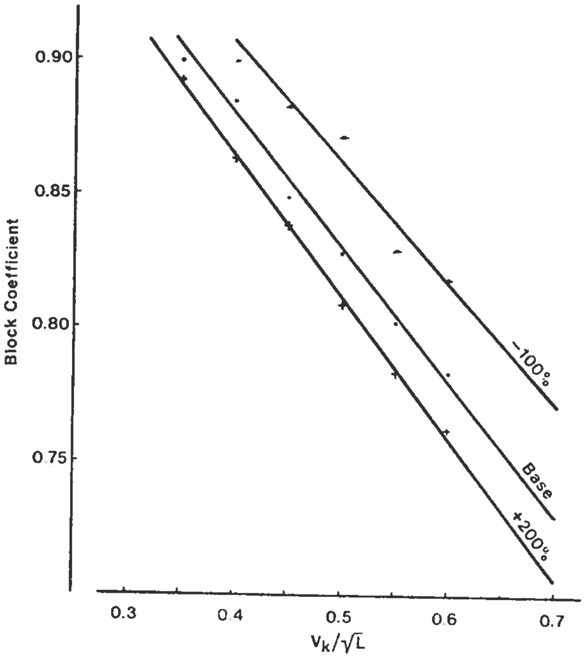

Fig. 4. Optimum block coefficient versus service speed, based on minimum RFR, for various relative fuel prices.

Fleet Management

The previous section deals with ships that are still in the design stage. Let us next consider existing ships. A fleet manager will normally make his operating decisions on a basis of maximizing annual profits--or, if income is fixed, minimizing operating costs. During periods of acute shortages of fuel, however, he may find it desirable to base those decisions on the criterion of minimizing energy requirements. Our purpose here is to propose a technique that will allow him to achieve that goal. We shall illustrate our proposal by means of the following simple numerical example. More complex situations can be readily analyzed by applying logical modifications to the basic approach shown here.

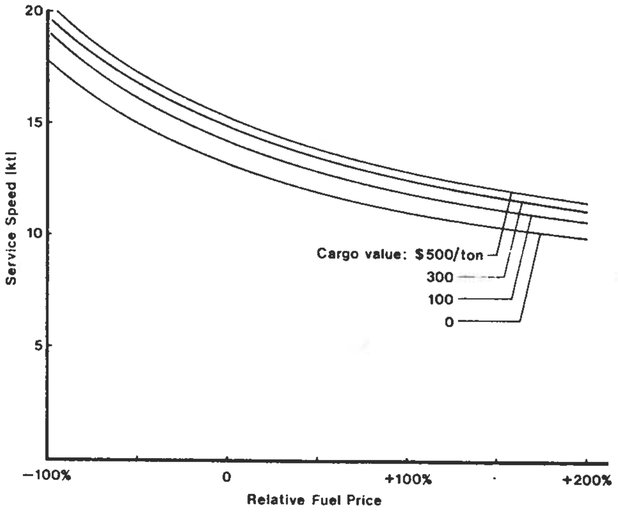

Fig. 5. Optimum service speed versus relative fuel price, based on economic cost of transport (ECT), for various cargo values.

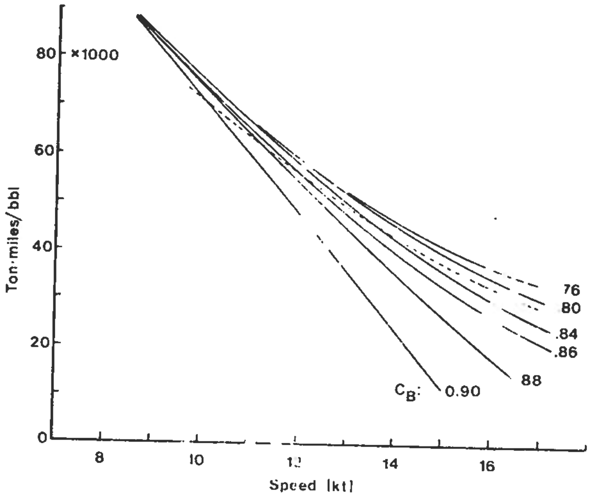

Fig. 6. Ton•miles per barrel of fuel versus design speed for various block coefficients. Dotted line represents approximate locus of optima for minimum RFR at given speed.

<u>Example</u>

A fleet manager has agreed to carry 1,150,000 tons of coal each year between two ports 12,000 miles apart. He has no other commitments and no immediate prospects for any others. He has available to him a fleet of ten suitable bulk carriers, some more energy efficient than others. These ships are identified as Ships A to J. Table III shows each ship's design speed and the number of tons of coal it could deliver each year if operated at its design speed. The energy efficiency, in ton-miles of cargo per barrel of fuel, is also shown.

Table III shows that the fleet could, if operated at full power, deliver 1,317,000 tons of coal each year, some 14 percent above requirements. The manager is thus free to cut back on the

TABLE III. Fleet Characteristics

Ship	Design Speed (knots)	Annual Transport Capability (1000 long tons)*	Energy Effic. at Design Speed (ton-miles per barrel)*
A B C	17.6	3 x 190 = 570	9500
D E	17.5	2 x 148 = 296	8000
F G H	16.5	3 x 105 = 315	9200
I J	15.5	2 x 68 = 136	9700
	Total	1317	

*Assuming back trip in ballast

number of ships he keeps in operation, or cut back on speed, or some combination of those strategies. Examining the last column in the table (ton-miles per barrel) he would note that Ships I and J are the most fuel efficient and Ships D and E the least. He might then decide on some strategy that would make maximum use of Ships I and J, and minimum use of D and E. That would be unwise, however, because further examination would show him that, when slowed down to the same speed, Ships D and E would be more energy efficient than I and J. The upper family of contours in Fig. 7 illustrates this.

The strategy we propose is to guess at some maximum attainable value of ton-miles per barrel. Hold that the same for all ships and find the corresponding speed and annual transport capability for each. Then add transport capabilities. If the total is smaller than the requirement, we need to run the ships faster. This means that we must lower the guessed-at maximum attainable value of ton-miles per barrel. If it is larger, we can slow the ships and so raise the attainable ton-miles per barrel.

Let us start by guessing that the fleet can deliver the required 1,150,000 tons while attaining an energy efficiency of 20,000 ton-miles per barrel. Table IV shows for each ship the corresponding speed and annual transport capacity. Both numbers are derived from Fig. 7. The dashed lines illustrate this. The individual annual transport capacities add up to 1,205,000 tons. This exceeds the requirement, so we can raise our assumed energy efficiency (i.e., lower speeds). Let us then increase our assumed ton-miles per barrel from 20,000 to 25,000. If we return to Fig. 7 and follow the procedure outlined above, we will arrive at the figures shown in Table V. These show us that if we use 25,000 ton-miles per barrel as our standard we can expect to carry 1,110,000 tons of cargo, somewhat below the required value of 1,150,000.

TABLE IV. Operating Strategy Based on Attaining 20,000 Ton-Miles per Barrel

Ship	Operating Speed (knots)	Annual Transport Capacity (1000 tons)
A B C	15.2	3 x 177 = 531
D E	14.5	2 x 138 = 276
F G H	13.6	3 x 94 = 282
I J	12.5	2 x 58 = 116
	Total	1205

Our first guess (using 20,000 ton-miles per barrel) produced excess transport capacity. This second guess (using 25,000 ton-miles per barrel) produced a deficiency. Let us therefore try an intermediate value, say 22,500 ton-miles per barrel. Taking values of speed and individual transport capacity once more from Fig. 7, we arrive at the numbers shown in Table VI. This time we come to within less than half a percent of the required annual transport capacity and should feel satisfied that we have found

TABLE V. Operating Strategy Based on Attaining 25,000 Ton-Miles per Barrel

Ship	Operating Speed (knots)	Annual Transport Capacity (1000 tons)
A B C	14.1	3 x 166 = 498
D E	13.4	2 x 127 = 254
F G H	12.4	3 x 86 = 258
I J	11.0	2 x 50 = 100
	Total	1110

TABLE VI. Operating Strategy Based on Attaining 22,500 Ton-Miles per Barrel

Ship	Operating Speed (knots)	Annual Transport Capacity (1000 tons)
A B C	14.6	3 x 171 = 513
D E	14.0	2 x 132 = 264
F G H	13.0	3 x 90 = 270
I J	11.7	2 x 54 = 108
	Total	1155

$$\text{Total fuel required} = \frac{\text{tons per year x distance}}{\text{ton-miles per barrel}}$$

$$= \frac{1{,}150{,}000 \text{ x } 12{,}000}{22{,}500}$$

$$= 613{,}000 \text{ bbls per yr}$$

TABLE VII. Operating Strategy Based on Maximizing Use of Most Efficient Ships

Ship	Energy Effic. at Design Speed (ton-miles per bbl)	Speed (knots)	Annual Transport Capacity (1000 tons)	Cumulative Transport Capacity (1000 tons)	Fuel Required[(1)] (1000 bbl per yr)
I J	9700	15.5	2 x 68 = 136	136	168
A B C	9500	17.6	3 x 190 = 570	706	720
F G H	9200	16.5	3 x 105 = 315	1021	411
D	24,000[(2)]	13.6	129[(2)]	1150	575
E	(Leave idle)				
			Total Fuel Required		1.874 million bbl

Notes:

(1) Fuel required = $\dfrac{\text{tons per year x distance}}{\text{ton-miles per bbl}}$

(2) The speed of Ship D is reduced so as to round out the fleet's annual transport capacity to the exact requirement of 1,150,000 tons. Energy efficiency is adjusted accordingly. Ship E is left idle.

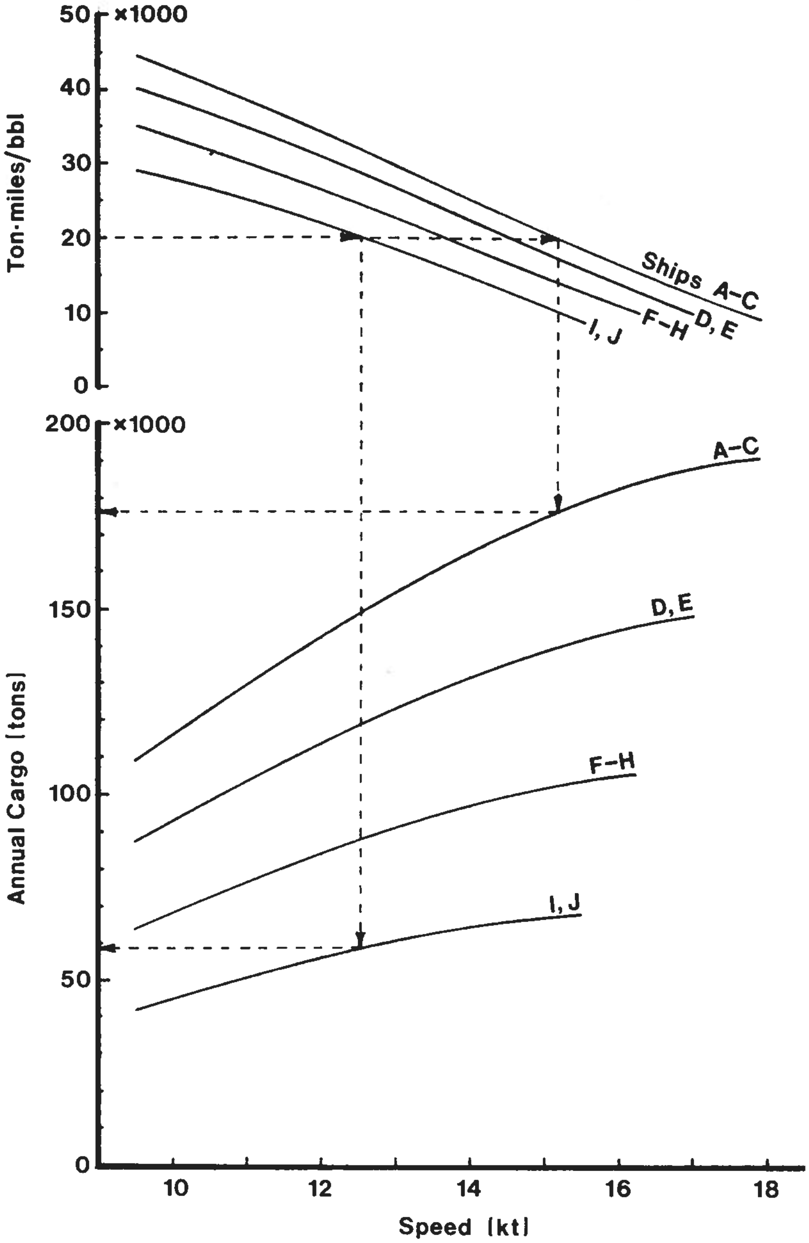

Fig. 7. Ton·miles per barrel and annual cargo versus operating speed for various units of a 10-ship fleet.

close to the best plan of action for carrying out our commitment with a minimum expenditure of fuel.

A Better Alternative?

What other strategy might we try? Table III shows the energy efficiencies at design speed. Suppose we rank our ships according to that criterion, then make maximum use of the most efficient ships (at design speed) and perhaps leave one or more of the least efficient ships idle. Table VII shows the results of that strategy. The total fuel required comes to 1.874 million barrels -- over three times that required under our proposed method. Other plans you may conceive will, we guarantee, suffer the same fate, although not necessarily to the same degree.

The method that we advocate here is not mathematically rigorous. A theoretically exact treatment would involve finding the set of speeds at which all the ships operate with the same marginal fuel expenditure per ton of cargo. Since practical fleet operating data usually consist of only a few isolated points, derivatives are extremely difficult to measure. Thus, the mathematically correct method is far more difficult to apply and, as we have found, yields no significant improvement in the result. In any case, the guesswork that inevitably surrounds fleet management makes such precision a chimera.

Maximizing Profits

The procedure we have shown for minimizing fuel use can also be used to minimize annual operating costs or to maximize annual profits. Turning back to Fig. 7, if we substitute contours of operating costs per ton-mile in place of the energy efficiency contours, we can apply exactly parallel procedures to find the most economic fleet strategy.

Summary

To emphasize what we said earlier, we have illustrated our principle with an over-simplified example. More complex, real life cases can be handled by elaborating on the same principle. In this, we need hardly add, one must remain flexible and ready to modify one's plan of action to meet the ever-changing demands of world commerce.

Summary and Implications for the Future

For reasons that have been made painfully obvious over the last six or seven years, the efficient use of fuel in merchant ships has become the cardinal issue in many design and operating decisions. Barring some unforeseen (and possibly unforeseeable) event, whether political or technological, the increasing price of energy, and its uncertain supply, will continue to be among our heaviest burdens.

In the field of ship design, progress has always been measured by improvements in machinery, hull forms, and propellers. Technical progress of this sort should be accelerated by the present energy situation, since fuel-saving developments will become more attractive investments as fuel costs rise. By contrast, the idea of reduced speed seems unenlightened, almost retrograde. Nevertheless, the adoption of rationally lowered design speeds represents an important factor in fuel conservation.

For the Panamax bulk carrier studied in this paper, analysis shows that even at current fuel prices the optimum service speed based on the required freight rate is in the neighborhood of 13 knots, versus the once fashionable 14-1/2 - 15-1/2 knots. A further fuel price increase of 50 percent, relative to other cost items, will produce an optimum of about 12 knots. In fact, if the relative price increases of the past decade were matched in the next, a design speed of 10-11 knots would be appropriate for a large bulk carrier, based on required freight rate. The inclusion of inventory costs moderates this trend, of course, but even with an assumed cargo value of $500 per ton the optimum service speed would barely reach 15-1/2 knots at present fuel price levels, and would be under 13 knots if relative fuel prices doubled. The potential impact of lower design speeds on fuel efficiency in transport, as measured in ton-miles per barrel, may be quite large. Even a relatively modest drop in design speed from 14-1/2 to 13 knots would produce an energy saving of about 16 percent, while a corresponding figure for 12 knots would be over 28 percent, assuming that minimum RFR hull forms are chosen for each speed.

In the field of fleet management, the impact of higher fuel prices on the operation of existing vessels has already been felt in the trend toward reduced operating speeds, particularly in ballast. We have proposed a methodical way to select operating speeds for an existing fleet so as to minimize the amount of fuel required to provide a given transport service. The same general procedure can be used to minimize costs or maximize returns.

The primary purpose of this paper has been to examine the issue of ship speed and its influence on design and fleet management decisions for bulk carriers in the era of expensive fuel. The results of this effort are summarized above. There are, however, many important issues left unresolved by this work, and some of these should be mentioned here, if only to serve as suggestions for further discussion.

Implications of Lower Speed

Within the scope of vessel and machinery design, the implications of lower speed and horsepower are quite varied. One consequence of lower design speed will be the apparent economic trend toward fuller hull forms. While such a trend is well documented for block coefficients up to 0.90, adequate resistance and especially propulsive data for fuller forms are limited to a few specialized types of vessel. The largest Great Lakes bulk carriers, for example, have successfully adopted block coefficients of 0.93 and higher. However, the unusual proportions of length, beam, and draft of these vessels, imposed by the restrictions of the Soo locks, must be credited with making this extreme fullness hydrodynamically and economically valid. (These ships, incidentally, are typically powered for speed-length ratios between 0.40 and 0.45).

By contrast, bulk carriers of normal ocean-going proportions, such as the vessel described in this paper, would require somewhat unconventional thinking in order to use block coefficients of 0.90 or higher. While an extremely short, bluff entrance might be tolerable on resistance grounds at very low speeds, questions of propulsive efficiency and propeller-induced vibration make the design of the stern a more subtle business. In view of the greatly reduced horsepower and lower propeller rpm associated with low speed ships, vibration might be regarded as of secondary importance. However, with the highly non-uniform wake typical of very full-formed hulls, combined with the natural temptation to increase propeller diameter, reduce tip clearance, and cut blade area in the search for higher efficiency, designers may encounter a new range of problems. The suggestion of unconventional hull forms, extremely high block coefficients, and perhaps even new types of propulsors for low-speed applications should send us scurrying to the test tank.

Safety

A somewhat more disturbing implication of lower design speed and small installed horsepower is the consequent reduction of maximum thrust to weight ratio. If the acceleration, stopping, and maneuvering characteristics of large ships are already troublesome at times, the possible effects of reduced available thrust should certainly not be neglected. In addition, performance under adverse weather and sea conditions may suffer, while the vessel's ability to avoid unfavorable weather is diminished by the lower speed. The slamming behavior of an unusually full bow will also be unpleasant. A relationship between ship safety and installed horsepower certainly exists, although it may be complex; with an economic trend toward slower ships this relationship may well deserve further study.

Dual Speed Operation

As mentioned above in connection with inventory costs, the combination of high fuel price and high cargo value has already led some operators to run at significantly reduced power only when in ballast. The two-speed concept may be carried into the design area as well, by incorporating machinery arrangements that are specifically adapted for maximum efficiency at two widely separated horsepowers. A twin-bank or multiple-unit diesel plant should be particularly well suited for this application.

Effects on Propulsion Plant Design

With decreased service speed and propeller rpm for large vessels, possibly with shaft speeds as low as 30 rpm, the available types of slow-speed diesel engine may no longer be suitable for direct-drive applications. While several alternatives exist, it seems likely that the efficient choice will be to resort to gearing, either with a slow-speed engine and single reduction, or a medium-speed engine with double reduction. The gears will be expensive, perhaps, but the fuel savings associated with reduced propeller rpm will be balanced against this initial cost.

The influence of fuel costs on auxiliary machinery is already evident in the increasing use of waste heat boilers and steam turbogenerators in diesel-power vessels. Clearly, this is a trend that will continue in the future, and it can be expected that more sophisticated combined cycles will become cost effective as fuel prices continue to rise. For extremely low horsepower installations, however, the exhaust heat alone will not be sufficient to support the full service auxiliary load. For this reason, main-engine-driven generators may become the standard for low-speed vessels, with the waste-heat turbine (if fitted) geared back into the propulsion shafting. Part load operations will still present some difficulties, as they do now, but presumably the lower-powered vessels will spend less time operating at reduced power. Each of these design decisions probably deserves a study of its own.

The preceding remarks have been confined to diesel machinery, principally because the intent of this paper has been to explore the economic possibilities of lower speed and correspondingly lower installed horsepower. At such low ratings it seemed less speculative to rely on diesel powerplants. Renewed interest in coal promises to keep the steam alternative alive, however. Clearly, the relative merits of steam and diesel machinery will be debated as long as there are vendors of each. There seems to be plenty of development potential left in both types of machinery, and the future undoubtedly holds surprises for everyone, especially if new fuels become technically and economically feasible. Apart from this we have nothing to add to the steam versus diesel debate, other than to wish that we could somehow convert the heat that has been expended on this subject into its mechanical equivalent.

Shipbuilding Energy

As already mentioned, slowing ships to save fuel should perhaps be balanced against the resulting demand for more ships, since shipbuilding itself requires energy. Initial investigations (References 1-3) show, however, that shipbuilding energy requirements are relatively unimpressive when compared to operating energy requirements. Table VIII, for example, indicates that shipbuilding energy per ton-mile of cargo carried amounts to only 4 to 10 percent of the total. The initial conclusion has to be that recognition of construction energy requirements will usually have but little effect on the choice of design speed. If a decision is nonetheless made to recognize its influence, one would still have to balance future energy savings in operation against present additional consumption for shipbuilding. The proper discounting rate to use in such a calculation is problematic, however. In fact, a strong argument can be advanced for using a negative interest rate on energy, reflecting the intrinsically higher future value of in-

TABLE VIII. Relative Energy Required
per Ton-Mile of Transport

Ship	Construction	Maintenance	Fuel
15-knot Panamax bulk carrier	6%	4%	90%
15-knot 200,000 DWT bulk carrier	8%	4%	88%
20-knot break-bulk cargo liner	10%	negligible	90%
20-knot container ship	4%	negligible	96%

Notes: Figures are derived from Reference 1.

Construction energy requirements include energy going into producing materials as well as shipyard assembly.

creasingly scarce energy. Even if it could be shown that it is philosophically proper to apply cash-flow methods to energy-flow problems, it must be remembered that money is a renewable resource while fossil fuels are not.

Other Kinds of Ships

This paper has been confined to bulk carriers; other kinds of ships merit similar studies. A start was made in this direction in Reference 4. Part of that work was devoted to a consideration of the influence of fuel costs on optimum design characteristics for container ships. Among other conclusions, the author noted the wasteful results of speed competition induced by conference rate-setting practices. Since then those influences have become ever more apparent. Liner ships have been slowed dramatically, and conferences are exhibiting some tendencies suggesting either imminent dissolution or the adoption of long overdue reforms.

Taxes

Our brief exposition on the subject of taxes suggests a course of action. First, someone should look more carefully into the question of how much energy might be saved if corporate income taxes were reduced or eliminated. This analysis should be carried from engineering economics to the national macro-economic level. The results, in terms of both energy and transport cost savings, should then be laid before the appropriate powers that be, including of course the key mobilizers of public opinion. We recognize that this sounds naive, but if engineers don't point out common-sense courses of action, who will?

Epilogue

We are the first to admit that this paper provides more questions than answers. We also admit to some untidiness in organization. But, such shortcomings are inevitable consequences of the scope and complexity of the issues involved. Our hope is that our findings may prove as useful as our suggestions prove provocative.

References

1. Mortimer, "Gross Energy Requirements of Marine Transport," Open University, Buckinghamshire, England, 1974.
2. IBI Group for Strategic Studies Branch, "Indirect Energy in Transportation," Transport Canada, Ottawa, 1978.
3. Buxton, Personal communications, 1980.
4. Benford, "Of Dollar Signs and Ship Designs," SNAME STAR Alpha Meeting, 1975.
5. Gertler, "Reanalysis of the Original Test Data for the Taylor Standard Series," DTMB Rept. 806, Mar 1954.
6. Swift, Nowacki, and Fischer, "Estimation of Great Lakes Bulk Carrier Resistance Based on Model Test Data Regression," Marine Technology, Oct 1973.
7. Hadler, Wilson, and Beal, "Ship Standardization Trial Performance and Correlation with Model Prediction," SNAME Trans., 1962.
8. Elste, Swigart, and Swift, "Transport Analyses: Great Lakes and Seaway. Vol III: Seaway Transport and Overseas Trade," Department of Naval Architecture and Marine Engineering, University of Michigan, Dec 1974.
9. Watson and Gilfillan, "Some Ship Design Methods," TRINA 1976.

Appendix:

Bulk Carrier Synthesis Model

The following sections describe the resistance, propulsion, weight, and cost relationships for oceangoing dry bulk carriers that have been used in this paper. All dimensions are in feet, weights in long tons, and costs in U.S. dollars (January 1980).

Resistance Estimation

Residuary resistance coefficients C_r were based on Taylor Standard Series, Ref. 5, for prismatic coefficients up to 0.86. For fuller forms, up to a block coefficient of 0.90, extrapolation of C_r was required. The slopes for this extrapolation were suggested by comparison with results from Ref. 6. An estimated correction factor for the effect of bulbous bow was applied to the Taylor residuary coefficient, as:

$$C_r = C_r(\text{Taylor})\ (1 - 0.12\ V_k/\sqrt{L}\ )\ ,$$

where L is the length on the design waterline.

Friction formulation was based on the Schoenherr line, as approximated by the substitute relationship

$$C_f = 0.4631(\log_{10} R_n)^{-2.6}\ .$$

Correlation allowance was adopted from Ref. 7, as

$$C_a = (0.523 - 0.000566L) \times 10^{-3}\ .$$

Wetted surface was estimated from Taylor standard coefficients, Ref. 5.

Total resistance coefficients were increased 2%, for appendages, to estimate trial condition resistance R, and effective horsepower P_e.

Propulsive Coefficients (Single Screw)

Hull efficiency was estimated following Ref. 8, as

$$\eta_h = (1-t)/(1-w),$$

$$w = 0.727 - 1.86C_B + 1.749C_B^2,$$

$$t = 0.60w.$$

Open-water efficiency was based on a selection of 16 preliminary propeller selections using Wageningen B-Series 4-bladed propellers. The following predictive equation is proposed:

$$\eta_o = 0.767 - 0.245\ \frac{T}{\rho d^2\ V_a^2}$$

where T = thrust (lb) = $R/(1-t)$
d = propeller diameter (ft)
V_a = speed of advance (ft/sec)
= $1.69\ V_k\ (1-w)$

For the purposes of this model, maximum propeller diameter was set at 0.6 of full load draft, and propeller rpm was optimized.

Relative rotative efficiency η_r was taken as 1.01.

Sterntube and reduction gear losses were assumed to be 1% and 1.5%, respectively, resulting in a transmission efficiency $\eta_t = 0.975$.

Trial brake horsepower was then estimated as

$$P_b = P_e/\eta_o\eta_h\eta_r\eta_t\ .$$

Service margin for roughness and weather was estimated as suggested by R.M. Cameron in his discussion of Ref 9:

$$\text{service margin} = 1.075 + 0.1667\ V_k/\sqrt{L}\ .$$

Service brake horsepower used for fuel consumption estimates was calculated as

$$\text{NCR} = P_b\ (\text{service margin}).$$

Diesel-engine service derating of 10% was assumed. Therefore, the installed maximum continuous rating (MCR) used for weight, acquisition, and maintenance costs was estimated as

$$\text{MCR} = 1.11\ \text{NCR}.$$

Ballast speed was estimated as 8.5% higher than full load, operating at service shaft horsepower.

Light Ship Weights

Hull steel weight was based on the numeral

$$E = L(B+T) + 0.85L(D-T) + 0.75 \sum L_e H_e\ ,$$

where L is the length between perpendiculars, B the beam, D the depth, T the draft, and L_e and H_e the length and height of raised decks or houses. Following Ref. 9, steel weight was estimated as

$$W_s = 1.185 \times 10^{-3}\ E^{1.36}[0.65 + 0.5C_B + (1-C_B)\ \frac{0.8D-T}{6T}\ ]\ ,$$

Outfit weight, again adopted from Ref. 5:

$$W_o = 0.0290LB - 1.59 \times 10^{-5}L^2B\ .$$

This outfit weight excludes specialized cargo access gear, cranes, etc.

Machinery weight was based on low-speed and medium-speed prime mover weights, with a remainder weight cited in Ref. 9. The proposed relation is

$$W_m = 0.124(\mathrm{MCR})^f(\mathrm{RPM})^{-0.167} + 0.555\ \mathrm{MCR}^{0.7}$$

$$f = 1.299(\log_{10}\mathrm{RPM})^{-0.44};\ f \leq 1\ .$$

Note: RPM is engine speed, not propeller shaft.

Crew and effects were estimated at 0.35 tons per crew member.

Light ship margin of 3% was applied to total of light ship weight items listed above.

Shipbuilding Costs

Steel costs were estimated on the basis of ship steel weight plus a scrap allowance adopted from Ref. 9. The total steel weight used for material and labor cost estimates was

$$W_{si} = W_s(1.167 - 0.117\ C_B)$$

Average steel material cost, January 1980, was placed at $460/ton.

Structural steel labor requirements were estimated according to Ref. 8, as

$$MH_s = 157\ W_{si}^{0.9}\ \text{(man-hr)}$$

Average shipyard labor rate was placed at $10/man-hr, and overhead at 100%. The total hourly rate was used for both steelwork and outfit labor costs.

Average outfit material cost was estimated at $4,350/ton; including normal items of outfit and hull engineering. A labor requirement of 270 man-hr per ton was assumed in addition to this acquisition cost.

Machinery cost, including acquisition and installation, was estimated for medium-speed diesel plants from Ref. 8:

$$\text{Machy cost} = \$8{,}090(\mathrm{MCR})^{0.70} + \$450{,}000$$

For low-speed diesels, a cost increase of 18%-30% is considered appropriate, depending on engine speed.

Electronics and automatic logging were estimated at $350,000.

Profit was placed at 7-1/2% of total materials and labor.

Operating Profile

Round trip time was estimated as

$$\mathrm{RTT(hr)} = \frac{1.926\ \mathrm{DIST}}{V_k} + \mathrm{CDWT}\left(\frac{\mathrm{LR+UR}}{\mathrm{LR\times UR}}\right) + \mathrm{DEL},$$

where DIST is the port to port distance (1 way) CDWT is the cargo deadweight, LR and UR are the loading and unloading rates (ton/hr), and DEL is the assumed average port and maneuvering delay time. In this study, loading and unloading rates were set at 8,000 and 2,400 ton/hr, respectively, and port delays were assumed as 24 hr per round trip.

An operating year of 350 days was assumed.

Operating Deadweight

Fuel and lubricating oil weights (and costs) were based on a main engine service specific fuel consumption of 0.358 lb/bhp·hr and cylinder lube consumption of 0.0019 lb/bhp·hr. These rates are consistent with fuel of 9,400 kcal/kg lower heating value, assumed to be Redwood 3,500 sec.

Generator fuel consumption was estimated as 0.55 lb/kW·hr, on #2 marine diesel oil.

Accordingly, the average fuel consumption per round trip (tons) is made up as follows:

Main engine:

$$M = \frac{0.358}{2240}\left[\frac{1.926\mathrm{DIST}}{V_k}\mathrm{NCR} + 0.25\mathrm{DEL}(0.2\mathrm{NCR})\right]$$

Auxiliary generator:

$$G = \frac{0.55}{2240}\left[\left(\frac{1.926\mathrm{DIST}}{V_k} + 0.25\mathrm{DEL}\right)\ \mathrm{GEN_s}\right.$$

$$\left.+\left\{\mathrm{CDWT}\left(\frac{\mathrm{LR+UR}}{\mathrm{LR\times UR}}\right) + 0.75\mathrm{DEL}\right\}\ \mathrm{GEN_p}\right]$$

where $\mathrm{GEN_s}$ and $\mathrm{GEN_p}$ are at-sea and in-port auxiliary generator outputs, respectively.

Total fuel consumption per round trip is then

$$\mathrm{FCPRT} = M + G\ .$$

Fuel weight for operating deadweight is calculated as

$W_f = 1.25$ FCPRT for bunkering at one port

and

$W_f = 0.65$ FCPRT for bunkering at both ports.

Lube oil weight was estimated as

$$W_{lo} = 0.015W_f\ .$$

Fresh water, stores, and provisions were approximated by

$$W_{wsp} = 0.003(\mathrm{LBD})^{0.7} + 5\ N_c$$

where N_c is the complement. This figure is considered typical for relatively short voyages, up to approximately 3,000 miles one way. Above this, a 20% increase was adopted for each doubling of voyage length.

Annual Operating Costs

Manning requirements were estimated using the following relationships:

Deck department: $N_d = 4 + 0.9\ LBD^{0.16}$

Engineering department: $N_e = 1+0.45MCR^{0.3}$

Stewards department: $N_s = 0.22(N_d+N_c)$

Total complement: $N_c = N_d+N_e+N_s$

Crew costs, including salaries and benefits, overtime, travel and replacement costs, subsistence, and personal insurance, are estimated as

$$Crew\$ = 75{,}000\ N_c^{0.8} + 4{,}100\ N_c\ .$$

Hull maintenance and repair is estimated from Ref. 8, as:

$$HMR\$ = 10.20(LBD)^{0.685}\ .$$

Machinery maintenance and repair is estimated from recent data on low- and medium-speed diesel plants, as

$$MMR\$ = 6.0\ MCR + 95\ MCR^{0.6} + 20{,}000\ .$$

Fuel costs are calculated as follows:

$$FUEL\$ = \frac{350\times 24}{RTT}(M\times PRICE_m+G\times PRICE_g)\ ,$$

where $PRICE_m$ and $PRICE_g$ are the costs of main engine and generator fuel per ton.

Lubricating oil was correspondingly estimated as

$$LUBE\$ = \frac{350\times 24}{RTT}\ 0.0053\ M\ PRICE_{lo}$$

Current values used in this study were:

$PRICE_m = \$150/ton$, $PRICE_g = \$240/ton$,

$PRICE_{lo} = \$1{,}450/ton$

Port charges were approximated by $0.06 per deadweight ton per call. Per diem charges were assumed to be paid under cargo handling, hence, were not assigned to the vessel.

Overhead cost is estimated as $175,000.

Hull and machinery insurance is estimated as 1.4% of total ship price.

Annual Capital Costs

The annual cost of capital recovery has been calculated under the assumption of an all equity investment, using tax deferral, with no investment tax credit. The capital recovery factor (CR) may be calculated from the transcendental equation

$$\frac{i}{CR} + t\left(\frac{1}{1+i}\right)^{1/CR} = 1 - (1-t)\left(\frac{1}{1+i}\right)^{N}\ ,$$

where i is the desired return on investment, t is the tax rate, and N the economic life (years). The annual cost of capital is then given by

$$CAP\$ = CR(\text{ship price})\ .$$