Journal of the Operational Research Society (2011) 62, 211–216

www.palgrave-journals.com/jors/

The effect of oil price on containership speed and fleet size

D Ronen*

College of Business Administration, University of Missouri– St Louis, St Louis, USA

The changing prices of bunker fuel open the door for substantial cost savings by adjusting the sailing speed of ships. A large ship may be burning up to 100 000 USD of bunker fuel per day, which may constitute more than 75% of its operating costs. Reducing the cruising speed by 20% reduces daily bunker consumption by 50%. However, in order to maintain liner service frequency and capacity, reducing the cruising speed may require additional ships to operate a route. We construct a cost model that we use to analyse the trade-off between speed reduction and adding vessels to a container line route, and devise a simple procedure to identify the sailing speed and number of vessels that minimize the annual operating cost of the route. Using published data, we demonstrate the potential for large-cost savings when one operates close to the minimal-cost speed. The presented methodology and procedure are applicable for any bunker fuel price.

Journal of the Operational Research Society (2011) **62,** 211–216. doi:10.1057/jors.2009.169
Published online 13 January 2010

Keywords: sea transport; liner shipping; oil price; optimal speed; containership fleet size

Introduction

The steep increase in oil prices during the last several years has caused containership operators to consider reduction in the sailing speed of their vessels in order to reduce bunker fuel consumption and the associated financial hemorrhage (Leach, 2008). At the historic price of 135 USD per ton bunker fuel costs were about half the operating cost of larger containerships (Notteboom, 2006). When oil price approached 150 USD per barrel bunker fuel price exceeded 750 USD per ton. When bunker fuel price hovers around 500 USD per ton it constitutes about three quarters of the operating cost of a large containership. Moreover, the contemplated move to using cleaner (less polluting) bunker fuel will further exacerbate the situation (Stanley, 2007). However, significantly reducing the sailing speed of containerships requires an increase in the number of ships deployed on a route in order to maintain service frequency (Vernimmen *et al*, 2007). Thus, there is a trade-off between reducing the sailing speed that results in lower annual bunker fuel costs on the one hand, and adding ships to maintain the service frequency and capacity (that increases the annual operating cost) on the other hand. The exploration of this trade-off is the focus of this paper. The paper presents a procedure for determining the sailing speed and the associated fleet size that minimizes the annual ship operating and bunker fuel costs of a containership route while maintaining the desired service frequency (for a given demand).

Containerships are usually operated on closed *routes* (also known as *cycles* or *strings* or *loops*) and follow a published schedule of sailings. A route is a specified sequence of calling ports that each containership assigned to that route repeats on each voyage. Generally there are two types of routes: *main-line* (or *trunk*) routes and *feeder* routes. The main-line routes are longer (often intercontinental) and they connect *hub* ports. The feeder routes are usually regional ones that feed and distribute containers to/from the hub ports, at which containers are transshipped between the two types of routes. Due to customer service and competitive considerations most routes provide at least weekly service to each calling port, where a ship calls a specific port on a given day of the week. Most containership routes take from a few weeks up to a few months to complete and in order to provide weekly service they require multiple vessels to operate on the route with weekly phasing between them. Thus, a route that takes 6 weeks and provides a weekly service will require six vessels to operate it.

A recent review chapter on OR in maritime transportation (Christiansen *et al*, 2007) reveals that relatively little research has been published regarding optimizing the speed of vessels. Following the former oil crisis in the 1970s Ronen (1982) presented three models for determining the optimal speed of vessels with a single engine operating under different commercial circumstances. However, each of these models analysed a single vessel at a time and do not take into account service frequency. More recently, Brown *et al* (2007) showed how to optimize the fuel consumption of a vessel with multiple

**Correspondence: D Ronen, College of Business Administration, University of Missouri– St. Louis, 8001 Natural Bridge Road, St. Louis, MO 63121, USA.*
E-mail: David.Ronen@UMSL.edu

engines, but again, it applies only to a single vessel at a time. Notteboom and Vernimmen (2009) provide some background information about container lines and bunker fuel types and costs, and a more detailed (but descriptive) cost model that calculates the cost of a specific route at various specified speeds for different vessel sizes. Their descriptive cost model complements our prescriptive model that is presented in this paper.

The remainder of this paper is organized as follows: the next section presents a cost model that relates the average annual cost of operating containerships on a route to the vessels' speed. Insights from the structure of that model allow us to formulate a procedure that facilitates identification of the speed at which the costs are minimized. Next we provide numerical examples that demonstrate the application of that procedure to real routes data. Then we discuss practical considerations and we close with a summary.

Cost model

In this section, we develop a model relating the annual operating cost of containerships on a route to their sailing speed and develop a procedure to identify the optimal sailing speed. We make the following assumptions:

1. The route (sequence of calling ports) is already specified,
2. A weekly service frequency is required, and
3. The vessels that operate on the route have similar physical and economic characteristics and for practical purposes can be considered identical (usually sister ships operate on a route).

The bunker fuel consumption of a motor ship is proportional to the third power of its sailing speed (see, for example, Alvarez, 2009). This relationship is well established and confirmed by empirical observations (see, for example, Vernimmen *et al*, 2007).

Notation

We use the index i to indicate the vessel speed. Specifically, $i=0$ for the vessel *service speed* (also known as *design* or *cruising* speed), and $i=m$ for the minimal steerage speed.

D Cycle (route) distance [nautical miles]
P Port time during the cycle (including pilotage, mooring, time buffers etc.) [hours]
V Vessel speed ($V_m \leqslant V_i \leqslant V_0$) [knots]
S Sailing time of the cycle [hours]
T Cycle time [hours]
W Cycle time [weeks]
N Number of vessels operating in the cycle
F Vessel bunker fuel consumption [tons/day]
C_v Daily cost of a vessel [USD/day]
C_b Bunker fuel price [USD/ton]
CB_d Average daily cost of bunker fuel for the cycle [USD/day]
CV_d Daily cost of the vessels for the cycle [USD/day]
TC_d Average total daily operating cost for the cycle [USD/day]

For an owned ship the daily cost of the vessel (C_v) includes: crew, repair and maintenance, insurance, stores and lubes, fuel for auxiliary power, administration, and (possibly) capital costs; namely, all the costs incurred when the ship is not sailing. For a time-chartered vessel it is the daily charter hire. Whether to include the capital costs (or the opportunity cost) of a vessel in its daily cost depends on the economic circumstances. When there is an alternate employment for the vessel those costs should be included.

We observe the following relations:

$$S = D/V \tag{1}$$

$$T = S + P \tag{2}$$

$$W = (S + P)/168 \quad \text{(rounded up to the next integer value)} \tag{3}$$

In order to provide weekly service on the cycle the number of vessels operating on it, N, must be equal to the length of the cycle in weeks, W. Thus:

$$N = W \tag{4}$$

We try to find the speed that minimizes the cost of operating the cycle. In order to do that we have to minimize the cost per time unit. Therefore we shall translate all cycle costs into cost per cycle day. We separate the total operating cost into two components: (1) the cost of bunker fuel, and (2) all the other operating costs of the vessels (conveyed in [USD/day]). Port entry charges and canal fees are not included in these costs because the weekly frequency means that the number of these activities per time unit is constant.

Bunker fuel consumption *per vessel cycle* is: $(S/24)F$. The average *daily* bunker fuel consumption *per vessel* is the vessel cycle fuel consumption divided by the cycle time: $[(S/24)F]/[(S+P)/24]$ or $(SF)/(S+P)$. However, in order to provide weekly service the cycle time must be an integer number of weeks. Therefore the average *daily* bunker fuel consumption *per vessel* on the cycle will be: $(S/24)F/(7W)$ or $(S/24)F/(7N)$ in [tons/day]. We multiply it by the price of bunker fuel (C_b) and get the *average daily cost of bunker fuel per vessel*: $C_b(S/24)F/(7W)$ or $C_b(S/24)F/(7N)$ in [USD/day]. Then the *average daily cost of bunker fuel for all the vessels operating on the cycle* is arrived at by multiplying the average daily cost of bunker fuel per vessel by the number of vessels: $[C_b(S/24)F/(7N)]N$ or

$$CB_d = C_b SF/168 \tag{5}$$

The daily cost of the vessels operating on the cycle is:

$$CV_d = C_v N \tag{6}$$

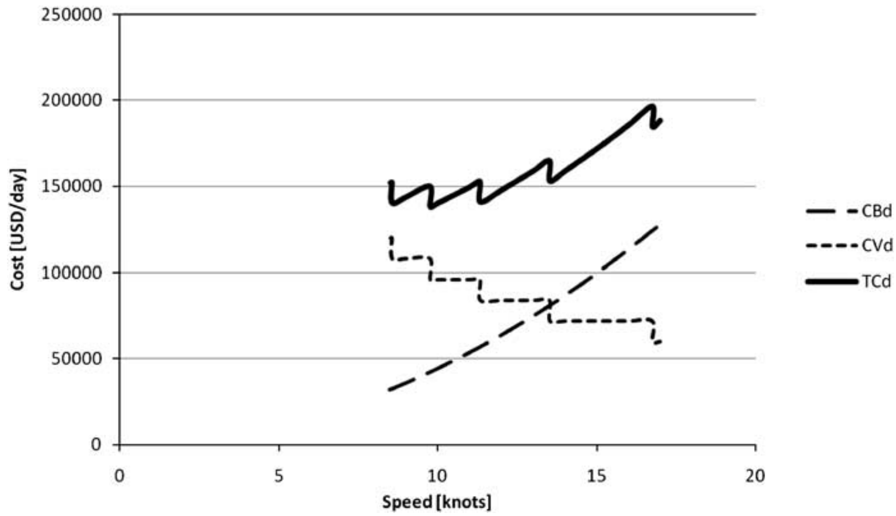

Figure 1 Average total daily cost.

Thus the total average daily operating cost of the cycle (which we are trying to minimize) is $CB_d + CV_d$ or:

$$TC_d = C_b SF/168 + C_v N \tag{7}$$

We observe that *S*, *F* and *N* are functions of the sailing speed V_i. The next step is to convey TC_d as a function of V_i.

From (1) $S = D/V$. As noted earlier, the daily fuel consumption, *F*, is proportional to the third power of the speed (see also Ronen, 1982). At speed V_i:

$$F_i = F_0(V_i/V_0)^3 \tag{8}$$

The number of vessels operating in the cycle, *N*, must be an integer. Therefore (7) is not a continuous function of *V*. We shall denote *N* by $N(V)$. Inserting (1) and (8) into (7) provides the average total daily cost (TC_d) as a function of the speed *V* at speed V_i (where $V_m \leqslant V_i \leqslant V_0$):

$$TC_d = [C_b DF_0/(168V_i)](V_i/V_0)^3 + C_v N(V_i) \tag{9}$$

or

$$TC_d = [C_b DF_0/(168V_0^3)]V_i^2 + C_v N(V_i) \tag{10}$$

Since $N(V_i)$ is a discontinuous function of V_i calculus tools will not help us in finding the optimal speed V_i, and we have to resort to some logical analysis. The average total daily costs of operating the cycle as a function of the sailing speed (10) are qualitatively depicted in Figure 1.

The first component in the average total daily cost (CB_d) is proportional to the square of the operating speed (V_i) and is represented by the dashed upward sloping curve. The second component (CV_d, which is not continuous) is represented by the step function. Above them is their sum, the average total daily cost function (TC_d). The exact shape of these curves depends on the data for the specific route under consideration and the bunker fuel price. Or, to put it differently, the relative height of the dips in the total cost curve (the top one) depend on the specific data instance (the data for Figure 1 comes from Table 2 that follows, with bunker fuel price of 400 USD/ton). However, the shape of the total cost curve allows us to draw the following conclusions:

1. For a given number of vessels (N) the minimal cost will be attained at the lowest vessel speed for which weekly frequency can still be provided,
2. In order to find the speed for which the total cost is minimized, we have to identify the speed that corresponds to the lowest dip in the total cost curve.

These observations lead us to formulate the following procedure to identify the optimal operating speed:

1. Using the vessel service speed (V_0) find the minimal cycle time in weeks, *W* (use Equation (3))
2. Round the cycle time up to the next integer (also set $N = W,\ i = 1$) and calculate the associated sailing speed, $V_1 = D/(168N - P)$, and the total daily cost, TC_d (use Equation (10))
3. Increase the cycle time by 1 week (namely, increase *N* by 1, and *i* by 1). Calculate the associated sailing speed, $V_i = D/(168N - P)$. If $V_i < V_m$ go to step 4. Else calculate the associated total cost, TC_d (use Equation (10)). Go to step 3.
4. Calculate the total cost TC_d (use Equation (10)) for the minimal speed V_m.
5. Select the speed V_i that resulted in the lowest total cost, TC_d.

This procedure can be easily implemented in a spreadsheet. The following section provides numerical examples

Table 1 Examples data

Data Item	*Ting and Tzeng (2003)*	*Notteboom (2006) PANAMAX*	*Notteboom (2006) Post PANAMAX*
Vessel size (TEU)	2000	4000	10 000
Design speed (Knots)	17	22.5	22.5
Cycle Distance (NM)	11 730	16 200*	16 200*
Port time in cycle (HRS)	140	280	280
Bunker fuel consumption (Tons/Day)	78	120	180
Daily cost of vessel (USD/Day)	12 000	8264**	11 736**
Bunker fuel price (USD/Ton)	104*	135	135

*Calculated from the provided data.
**Doesn't include capital costs.

Table 2 Average total daily cost (in USD/Day) as a function of bunker fuel price [Ting and Tzeng (2003) data]

No. Vessels	*Speed*	*Bunker fuel price [USD/Ton]*				
	.	104	200	300	400	500
5	16.8	**92 372**	122 254	153 381	184 508	215 635
6	13.5	93 054	112 488	132 732	152 975	173 219
7	11.3	98 779	**112 421**	**126 632**	140 842	155 053
8	9.7	106 942	117 043	127 565	**138 086**	148 608
9	8.5	116 427	124 205	132 308	140 410	**148 513**
10	8.5*	128 329	136 018	144 026	152 036	160 045

*Minimal speed.

Table 3 Average total daily cost (in USD/Day) as a function of bunker fuel price [Notteboom (2006) PANAMAX data]

No. Vessels	*Speed*	*Bunker fuel price [USD/Ton]*				
	.	135	200	300	400	500
6	22.3	117 495	150 193	200 497	250 802	301 106
7	18.1	102 680	124 266	157 474	190 683	223 892
8	15.2	**97 904**	113 211	136 761	160 311	183 860
9	13.1	98 089	**109 506**	127 071	144 636	162 201
10	11.6	101 003	109 845	**123 447**	**137 049**	**150 652**
11	11.2*	108 261	116 618	129 475	142 333	155 190

*Minimal speed.

of applying this procedure using published data, as well as some discussion of the sensitivity of the results.

Numerical examples

We demonstrate the above procedure using three examples derived from published data. The first example comes from Ting and Tzeng (2003), and the other two from Notteboom (2006). The data for these examples is presented in Table 1.

The results of each example are provided in a separate table, Tables 2 through 4.

Each one of Tables 2 through 4 provides the number of vessels (same as the length of the cycle in weeks), the associated sailing speed, and the resulting average total daily cost for several bunker fuel prices. For each bunker fuel price the lowest average total daily cost is highlighted. Since the minimal steerage speed (V_m) is seldom lower than half of the design speed (V_0) the sailing speed in these tables is confined to the range $(0.5V_0;\, V_0)$. One can see that as the bunker fuel price increases the lowest-cost speed decreases. In the data for Tables 3 and 4 the daily cost of a vessel does not include the capital cost (because the source of the data did not include it). Including the capital cost would have increased the minimal-cost speed.

In each of these tables for a given number of vessels (or speed, namely a row in the table) the average total daily cost is a linear function of the bunker fuel price [see Equation (10)]. However, for a given bunker fuel price (a column in the table) the average total daily cost is relatively flat around its minimal value but increases steeply as the sailing speed is increased. The implication is that one should know what the minimal-cost speed is, but increasing the speed to the next

Table 4 Average total daily cost (in USD/Day) as a function of bunker fuel price [Notteboom (2006) PostPANAMAX data]

No. Vessels	*Speed*	*Bunker fuel price [USD/Ton]*				
	.	135	200	300	400	500
6	22.3	172 283	231 330	296 786	372 243	447 700
7	18.1	149 400	181 778	231 592	281 405	331 218
8	15.2	141 576	164 537	199 862	235 187	270 511
9	13.1	**141 193**	158 319	184 667	211 014	237 362
10	11.6	144 905	**158 167**	**178 571**	**198 974**	**219 378**
11	11.2*	155 132	167 667	186 953	206 239	225 525

*Minimal speed.

level has usually a relatively small impact on the average total daily cost. However, large increases in the speed (from the minimal-cost one) have major cost implications.

Practical considerations

There are several issues that may have to be considered before implementing the recommendations of the model presented above. First, reducing the sailing speed of a container line increases the transit time of the containers (and the cargo inside them) and may put the line operator in a competitive disadvantage. On the other hand, the increased transit time provides the operator more flexibility to improve schedule reliability. Almost 50% of liner vessels arrive late (Notteboom and Rodrigue, 2008), and steaming at reduced speed provides them the option to catch-up. The increased transit time increases the inventory carrying cost for the owner of the shipped goods, and these additional costs (as well as the cost of the containers) can be added to the daily cost of the vessels. Further discussion of this issue is provided in Notteboom (2006). However, all containership operators pay the same bunker prices and have strong financial incentives to adjust the sailing speed of their ships accordingly.

Not always identical vessels operate on the same cycle. But usually the vessels are of similar size and, in order to maintain the service frequency, must sail at the same speed. In case the vessels are not identical the average total daily cost of each vessel can be calculated separately using the equations above, and the average total daily cost for the cycle will be the sum of the average total daily cost of the vessels operating in the cycle. The sailing speed is dictated by the number of vessels in the cycle, thus the minimal-cost speed can be identified using the procedure provided above.

Even if one claims that the relationship (8) is only an approximation, the above observations regarding the shape of the average total daily cost function are still valid, and only minor modifications are necessary in the suggested procedure in order to calculate the average total daily cost at each speed. In such a case one has to know the daily bunker fuel consumption of the vessels at the various sailing speeds that are derived from the different cycle times (fleet sizes).

Loss of time due to canal passage (Suez, Panama) can be accommodated by increasing the port time (P) by the time that such a passage takes. Vessel out-of-service periods (say a vessel operates only 350 days a year) can be accommodated by increasing the cycle time to cover the non-operating days for the purpose of calculating the average daily cost of the vessel (this is a minor adjustment).

Summary

We have analysed the relationship among bunker fuel price, sailing speed, service frequency and the number of vessels operating on a container line route, and devised a procedure that facilitates the determination of the sailing speed, cycle time, and number of vessels that minimize the annual operating cost of the route. With the increasing bunker fuel prices lower sailing speeds and a larger number of vessels are called for. Lowering the sailing speed has the potential of large reductions in the annual operating costs but increases transit times. However, reducing the number of vessels on a cycle by one (relative to the number that provides the minimal annual operating cost) and increasing the sailing speed accordingly usually increases the annual operating cost only marginally.

The need for increasing the number of vessels on a cycle that is associated with the increasing bunker fuel prices may increase demand for containerships as well as for containers and seafarers. In the short term this may also increase the cost of containerships, both second hand and new buildings.

Some ship operators have reduced the speed of their vessels, but the question is to what extent? Comparative analysis of published container line sailing schedules may shed more light on this phenomenon.

The cost model and the associated procedure for finding the minimal-cost speed that we have developed in this work are applicable to any liner with constant service frequency and hopefully will assist liner operators in managing their operations more economically.

References

Alvarez JF (2009). Joint routing and deployment of a fleet of container vessels. *Maritime Econ Logist* **11**: 186–208.

Brown GG, Kline JE, Rosenthal RE and Washburn AR (2007). Steaming on convex hulls. *Interfaces* **37**(4): 342–352.

Christiansen M, Fagerholt K, Nygreen B and Ronen D (2007). Maritime transportation. In: Barnhart C and Laporte G (eds). *Handbooks in Operations Research and Management Science: Transportation*. North-Holland: Amsterdam, pp 189–284.

Leach PT (2008). Galloping gulf line. *The Journal of Commerce* 7 July, p 22.

Notteboom TE (2006). The time factor in liner shipping services. *Maritime Econ Logist* **8**: 19–39.

Notteboom T and Rodrigue J-P (2008). Containerisation, box logistics and global supply chains: The integration of ports and liner shipping networks. *Maritime Econ Logist* **10**: 152–174.

Notteboom TE and Vernimmen B (2009). The effect of high fuel costs on liner service configuration in container shipping. *J Transport Geogr* **17**: 325–337.

Ronen D (1982). The effect of oil price on the optimal speed of ships. *J Opl Res Soc* **33**: 1035–1040.

Stanley B (2007). Ships draw fire for rising role in air pollution. *The Wall Street Journal* 27 November, p 1.

Ting S-C and Tzeng G-H (2003). Ship scheduling and cost analysis for route planning in liner shipping. *Maritime Econ Logist* **5**: 378–392.

Vernimmen B, Dullaert W and Engelen S (2007). Schedule unreliability in liner shipping: Origins and consequences for the hinterland supply chain. *Maritime Econ Logist* **9**: 193–213.

Received March 2009;
accepted November 2009 after one revision