Chapter 9
Green Maritime Transportation: Speed and Route Optimization

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Abstract Among the spectrum of logistics-based measures for green maritime transportation, this chapter focuses on speed optimization. This involves the selection of an appropriate speed by the vessel, so as to optimize a certain objective. As ship speed is not fixed, depressed shipping markets and/or high fuel prices induce slow steaming which is being practised in many sectors of the shipping industry. In recent years the environmental dimension of slow steaming has also become important, as ship emissions are directly proportional to fuel burned. Win-win solutions are sought, but they will not necessarily be possible. The chapter presents some basics, discusses the main trade-offs and also examines combined speed and route optimization problems. Some examples are finally presented so as to highlight the main issues that are at play.

Abbreviations

AIS	Automatic Identification System
CEO	Chief Executive Officer
CIF	Cost Insurance Freight
CO_2	Carbon dioxide
COA	Contract Of Affreightment
DWT	Deadweight Ton
GHG	Green House Gas
GPCI	Global Ports Congestion Index
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MBM	Market Based Measure
MCR	Maximum Continuous Rating

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H.N. Psaraftis (ed.), *Green Transportation Logistics*, International Series in Operations Research & Management Science 226,
DOI 10.1007/978-3-319-17175-3_9

MEPC	Marine Environment Protection Committee
MSC	Mediterranean Shipping Company
NTUA	National Technical University of Athens
OPEX	Operating Expenses
OR/MS	Operations Research/Management Science
Ro/Pax	Ro/Ro Passenger
Ro/Ro	Roll On Roll Off
SECA	Sulphur Emissions Control Area
SO_x	Sulphur oxides
TEU	Twenty ft Equivalent Unit
VLCC	Very Large Crude Carrier
WS	World Scale (index)

9.1 Introduction

As mentioned in Chap. 8, the classical breakdown of measures to reduce maritime emissions divides such measures into the following three major classes:

- *Technological* measures include more efficient engines, ship hulls and propellers, cleaner fuels, alternative fuels, devices to trap exhaust emissions, energy recuperation devices, "cold ironing" in ports, various kites, and others. Chapter 5 gave a flavor of such technologies for all surface transportation modes, including maritime.
- *Logistics-based* (tactical or operational) measures include speed optimization, optimized weather routing, optimal fleet management and deployment, efficient supply chain management, and others that impact the logistical operation.
- *Market-based measures* (MBMs). These were examined in Chap. 8, but we will see them again in this chapter from another angle.

We note again the remark made in Chap. 8: the above taxonomy is, in many respects, artificial. Indeed, MBMs can induce logistics-based measures in the short run and technological measures in the long run. With this proviso, the purpose of this chapter is to deal with logistics-based, or tactical/operational measures. In particular, we shall focus on the important tool of *speed optimization*, including its interface with *ship routing*.

Before we focus on speed optimization, we note that the spectrum of logistics-based problems in maritime transportation is very broad and can be broken down in the categories broadly shown in Table 9.1 below. Some related references are also shown in the table (neither list is encyclopedic).

It is important to note that, in much of the OR/MS maritime literature, environmental criteria such as emissions reduction are scarce, traditional economic criteria such as cost reduction being the norm. Sometimes such economic criteria map directly into environmental criteria: if for instance *fuel cost* is the criterion, as it is

Table 9.1 Sample of logistics-based problems in maritime transportation and sample of related references

Problem category	Related references
Ship routing and scheduling (general)	Christiansen, Fagerholt, Nygreen, and Ronen (2007), Christiansen, Fagerholt, and Ronen (2004, 2013), Ronen (2011)
Ship routing and scheduling (tramp)	Andersson, Duesund, and Fagerholt (2011), Fagerholt et al. (2010), Jetlund and Karimi (2004), Lin and Liu (2011)
Ship routing and scheduling (offshore supply)	Aas, Gribkovskaia, Halskau, and Shlopak (2007), Halvorsen-Weare and Fagerholt (2011, 2013)
Fleet deployment (liner)	Andersson et al. (2014), Meng and Wang (2011), Powell and Perakis (1997)
Fleet size and mix (liner)	Alvarez, Tsilingiris, Engebrethsen, and Kakalis (2011), Zeng and Yang (2007)
Speed optimization (general)	Devanney (2007), Fagerholt and Ronen (2013), Gkonis and Psaraftis (2012), Hvattum et al. (2013), Norstad et al. (2011), Psaraftis and Kontovas (2013, 2014, 2015).
Network design (liner)	Agarwal and Ergun (2008), Brouer, Alvarez, Plum, Pisinger, and Sigurd (2013), Imai et al. (2009), Meng, Wang, Andersson, and Thun (2013), Reinhardt and Pisinger (2012).
Weather routing (general)	Lo and McCord (1998), Perakis and Papadakis (1989).
Transshipment (liner)	Hsu and Hsieh (2005), Wang and Meng (2012a, 2012b)
Terminal management	Du et al. (2011), Goodchild and Daganzo (2007), Moccia, Cordeau, Gaudioso, and Laporte (2006), Stahlbock and Voß (2008).

directly proportional to *emissions*, if fuel cost is to be minimized as an objective, so will emissions, and the solution is win-win.

However, for other objective functions this direct relationship may cease to exist and one would need to look at environmental criteria in their own right. Even though such criteria were not very common in the past, the body of knowledge that includes such criteria is growing in recent years. Among the set of maritime logistics problems which are important as regards both economic and environmental criteria, perhaps *speed optimization* is the most important.

The importance of ship speed on ship emissions can be seen in Fig. 9.1, which breaks down CO_2 emissions from the world commercial fleet by ship type-size combination (Psaraftis and Kontovas, 2009a). The data of Fig. 9.1 is from the IHS Fairplay database and the base year is 2007 (45,620 commercial ships accounted for).

According to this analysis, containerships are the top CO_2 emitters in the world fleet. This is perhaps something to be expected, given the relatively high design speeds of these vessels (20–26 knots) as opposed to those carrying bulk cargoes (13–15 knots) and given the nonlinear relationship between speed and fuel consumption and hence emissions. This is also in line with later results. See for instance Fig. 8.7 of this book, taken from the Third IMO GHG study (2014), in which the

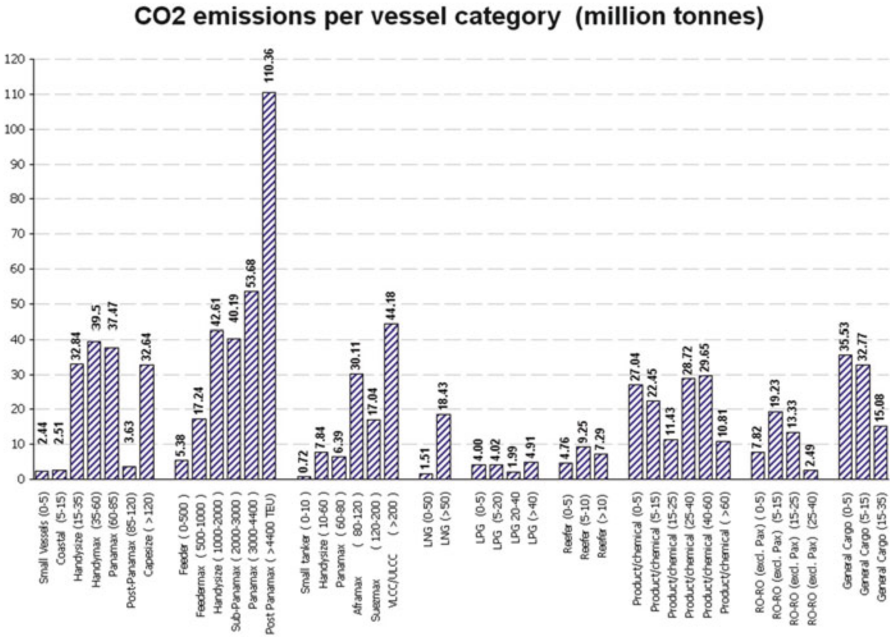

Fig. 9.1 CO_2 emissions, world fleet, 2007. *Source*: Psaraftis and Kontovas (2009a)

baseline year was 2012, and where this class of vessels was identified as the top CO_2 emitter of the world fleet.

What is perhaps not so obvious to expect and can be seen in Fig. 9.1 is that just the top tier category of container vessels (712 vessels of 4,400 TEU and above) are seen to produce 110.36 million tonnes of CO_2 emissions, which is higher than the 106 million tonnes produced by the entire crude oil tanker fleet (2,028 vessels). This means that if ship speed were to be reduced, perhaps uniformly across the board, or even selectively for some categories of vessels, emissions would be reduced too, perhaps drastically. Reducing speed could also have important side benefits: cost reduction is one, and helping a depressed market in which shipping overcapacity is the norm these days is another. In that sense, reducing ship speed may conceivably be a 'win-win' proposition.

Even though ships travel slower than the other transportation modes, a basic premise has always been that there is value in ship speed. The FAST series of conferences, held every 2 years, have been the world's leading technical conferences addressing fast sea transportation issues. As long-distance trips may typically last 1–2 months, the benefits of a higher speed may be significant: they mainly entail the economic added value of faster delivery of goods, lower inventory costs and increased trade throughput per unit time.

The need for higher speeds in shipping was mainly spurred by strong growth in world trade and development, and in turn was made possible by significant technological advances in maritime transportation in a broad spectrum of areas, including hull design, hydrodynamic performance of vessels, engine and propulsion efficiency, to name just a few. By extension, developments in cargo handling systems and supply chain management and operation have also contributed significantly to fast door-to-door transportation.

However, the above basic premise is being challenged whenever shipping markets are depressed and whenever fuel prices are on the increase. In such situations, ships tend to slow down.

Perhaps the most significant factor that is making a difference in recent years is fact that a ship has to be environmentally friendly as regards air emissions. Previous chapters have examined this issue from various angles (for instance, the technology angle in Chap. 5 and the market-based angle in Chap. 8). Because of the non-linear relationship between speed and fuel consumption, it is obvious that a ship that goes slower will emit much less than the same ship going faster.

If one starts with the simple way to reduce fuel costs (and by extension emissions) by reducing speed, this can be done at two levels. One level is the technological one, that is, build future ships with reduced installed horsepower so that they cannot sail faster than a prescribed speed. The first cellular containerships of the late 1960s and early 1970s that went up to 33 knots in the late 1960s when fuel was cheap are gone forever. Maersk's new flagship 'Triple-E' fleet of 18,000-TEU containerships (see Fig. 9.2 next page) have a design speed of 17.8 knots, down from the 20–26 knots range that has been the industry's norm, and will emit 20 % less CO_2 per container moved as compared to the *Emma Maersk*, previously the world's largest container vessel, and 50 % less than the industry average on the Asia-Europe trade lane (Maersk, 2013).[1] Triple-E stands for Economy of scale, Energy efficiency and Environmentally improved performance. Perhaps as an extreme example of how far speed reduction can go, EU-funded research project "Ulysses," whose logo is, conveniently enough, a snail, aims at designing tankers and bulk carriers that can sail as slow as 5 knots (Ulysses, 2012).

The other level of speed reduction is the logistics-based (tactical/operational) one. At that level, an existing ship can sail slower than its design speed. In shipping parlance this is known as "slow steaming" and may involve just slowing down or even 'derating' a ship's engine, that is, reconfiguring the engine so that a lower power output is achieved, so that even slower speeds can be attained. Such a reconfiguration may involve dropping a cylinder from the main engine or other measures. Depending on engine technology, 'slow steaming kits' are provided by engine manufacturers so that ships can smoothly reduce speed at any desired level. In case speed is drastically reduced, the practice is known as "super slow steaming".

In practice, super slow steaming has been pioneered by Maersk Line after it initiated trials involving 110 vessels beginning in 2007. Maersk Line North Asia

[1] The 18,000 TEU yardstick as the world's largest containership size was fated to be surpassed. As this chapter was being completed, the baton was being held by the 19,224 TEU *MSC Oscar*, of the Mediterranean Shipping Company (MSC).

Fig. 9.2 The *Majestic Maersk*, one of Maersk's Triple-E container ships, at dock in Copenhagen harbor. Photo courtesy H. N. Psaraftis

Region CEO Tim Smith said that the trials showed it was safe to reduce the engine load to as low as 10 %, compared with the traditional policy of reducing the load to no less than 40–60 % (TradeWinds, 2009). Given the non-linear relationship between speed and power, for a containership a 10 % engine load means sailing at about half of the design speed. Furthermore, China Ocean Shipping (Group) and its partners in the CKYH alliance (K Line, Yang Ming Marine and Hanjin Shipping) were also reported to introduce super-slow steaming on certain routes (Lloyds List, 2009).

Slow steaming is not only practiced in the container market, although it may seem to make more sense there due to the higher speeds of containerships. Slow steaming is reported in every market. In December 2010, Maersk Tankers was reported to have their Very Large Crude Carriers (VLCCs) sailing at half their speed. The speed of 16 knots (design speed) was reduced to less than 10 knots on almost one third of its ballast legs and between 11 and 13 knots on over one third of its operating days. For example, a typical voyage from the Persian Gulf to Asia normally takes 42 days (at 15 knots laden and 16 knots in ballast). Maersk Tankers decreased speed to 8.5 knots on the ballast leg, thus increasing roundtrip time to 55 days and saving nearly $400,000 off the voyage's bunker bill (TradeWinds, 2010).

Slow steaming has also an important role on absorbing fleet overcapacity. Since early 2009, the total containership capacity absorbed due to the longer duration of total roundtrip time for long haul services has reached 1.27 million TEU in October 2013 (taking early 2009 as a starting point), based on Alphaliner's latest estimates (Alphaliner, 2013). The average duration of Far East-North Europe strings had increased from 8 weeks in 2006 to 9 weeks in 2009 when slow steaming was first adopted. The application of even lower speeds has pushed the figure to 11 weeks currently as carriers continue to seek further cost reductions by adopting slower sailing speeds. The same phenomenon has been observed on Far East-Med strings, where the average duration has risen to 10 weeks, compared to only 7 weeks in 2006. As a record number of deliveries of new vessels is continuing to hamper the supply and demand momentum, analysts expect that slow steaming is here to stay. As a record number of vessels were scrapped in 2013; the idle fleet averaged 595,000 TEUs in 2013 compared to 651,000 TEUs in 2012. The lay-up of surplus box ships has been the worst and has lasted for the longest period since early 2009. The twin impact of extra slow steaming and longer port stays has helped to absorb much of capacity but it seems that sailing at even slower speeds is not an option. A similar situation pertains to bulk carriers and tankers. Thus, slow steaming is here to stay for the foreseeable future.

At the same time, and even though win-win solutions may look as natural consequences of speed reduction, the practice may have other ramifications which may not be beneficial. For instance, in the long run more ships will be needed to produce the same transport throughput, and this will entail some costs, some of them financial and some environmental, such as lifecycle emissions due to shipbuilding and recycling (see Chap. 11 of this book for a discussion on this topic).

Also, in-transit inventory costs will generally increase, due to the increased transit time of the cargo. These inventory costs are proportional to the value of the cargo, so if a ship hauls high-value goods, sailing at a lower speed may entail significant costs to the shipper (we shall come back to this point later in the chapter).

Yet another side effect of speed reduction is that in the short run, freight rates will go up once the overall transport supply shrinks because of slower speeds. Reducing speed may help a depressed market, but it is the shippers who will suffer and in fact they will do so in two ways: they will pay more, and receive their cargo later. For a discussion how tanker spot rates may be impacted as a result of slow steaming see Devanney (2007).

Psaraftis and Kontovas (2009b) investigated, among other things, the option to slow down in Sulphur Emissions Control Areas (SECAs) to reduce the quantity of SO_x produced. It was shown however that if the ship speeds up outside the SECA to make up for lost time within the SECA, more emissions will be produced overall, including SO_x. Fagerholt et al. (2015) examine route-speed alternatives in the context of SECAs. More on SECAs can be found in Chap. 10 of this book.

Last but not least, another possible side effect concerns effects that speed reduction may have on other modes of transportation, to the extent these are alternatives to sea transportation. This is the situation mostly as regards short-sea trades, in Europe but also in North America. If ships are made to go slower, shippers may be induced to prefer land-based transportation alternatives, mostly road, and that may increase overall GHG emissions. Even in long-haul scenarios such as the Far East to Europe trade, some cargoes may tempted to use the rail alternative (via the Trans-Siberian railway) if the speed of vessels is low enough (see Psaraftis and Kontovas (2010) for a discussion).

An important point we would like to stress is connected to an issue also brought up in Chap. 8 in the context of the Marginal Abatement Cost curves. Even though speed reduction can be considered as *a measure* to reduce emissions, this measure is typically manifested as *a response* of whoever pays for the fuel, to exogenous market parameters such as the fuel price and the freight rate. Unless speed limits are mandated by legislators (and this has been the objective of various lobbying groups—thus far without success), speed reduction should be considered not as an independent measure but as a reaction of shipping operators to such external parameters. This is of course within the feasible space dictated by ship and engine technology, as well as by the contractual arrangements between the ship owner and the charterer.

This chapter will examine ship speed optimization from various angles. In that context, some basics will be outlined, the main trade-offs will be analysed, and some decision models will be presented, including combined speed and routing scenarios. The examples to be presented will highlight the main issues that are at play. Material of this chapter is mainly taken from various papers and other work by the authors and their colleagues. These include Gkonis and Psaraftis (2012), Kapetanis, Gkonis, and Psaraftis (2014) and Psaraftis and Kontovas (2013, 2014).

The rest of this chapter is organized as follows. Section 9.2 presents some basics of speed optimization. Section 9.3 discusses factors that may impact fuel consumption. Section 9.4 discusses the possible impact of inventory costs. Section 9.5 summarizes results for tankers and bulk carriers. Section 9.6 discusses speed vis-à-vis mixed chartering scenarios. Section 9.7 presents combined speed-route optimization model. Last but not least, Sect. 9.8 presents the chapter's conclusions and discusses some extensions.

9.2 Ship Speed Optimization Basics

Before we see how ship speed can be optimized, we present some basics. We do this so as to clear possible misconceptions and highlight some issues which we find important.

The first basic is that *ships do not trade at fixed or predetermined speeds*.

In the charter (tramp) market, those who pay for the fuel, that is, the ship owner whose ship trades on the spot market, or the charterer if the ship is on time or bareboat charter, will typically choose ship speed as a function of two main input parameters: (a) the fuel price and (b) the market freight rate. In periods of depressed market conditions, as is the typical situation in recent years, ships tend to slow steam. The same is the case if bunker prices are high. Conversely, in boom periods or in case fuel prices are low, ships tend to sail faster.

An exception to the above is in case the ship is *on spot charter* (rental of the ship for a single voyage) and its speed is prescribed in the charter party contract, either explicitly (speed is, say, 15 knots) or implicitly (cargo pickup and delivery dates are prescribed). In spot charters the fuel is paid for by the ship owner. Agreeing on a prescribed speed in the charter party involves in most cases only the laden part of the trip, with the owner free to choose his speed on the ballast return leg. The speed that is agreed upon for the laden leg may or may not be the speed that the ship owner would have freely chosen if no explicit agreement were in place. If it is higher, the ship owner may ask for a higher rate than the prevailing market spot rate, understanding of course that in this case he may lose the customer to a competitor ship, with whom the charterer can obtain more favorable terms. For a discussion of possible distortions and additional emissions that can be caused by charter party speed agreements, see Devanney (2011).

A similar situation plays out in the liner market. Container and Ro/Ro operators typically operate a mixed fleet of vessels, some of which are owned vessels and some are chartered from independent owners who are not engaged in liner logistics. In either case, fuel is paid for by the liner operator. The operator receives income from the multitude of shippers whose cargoes are carried on the ship and the rates charged to these shippers can be high or low depending on the state of the market. As in the charter market, high fuel prices and/or depressed market conditions imply lower speeds for the fleet.

In spite of the above, many of the models found in the OR/MS maritime literature assume fixed and known ship speeds. See for instance Agarwal and Ergun (2008), Hwang, Visoldilokpun, and Rosenberger (2008), Grønhaug, Christiansen, Desaulniers, and Desrosiers (2010), Rana and Vickson (1991) and Song and Xu (2012), among others. In these models, ship speed is typically considered not as a decision variable but as a *fixed input* to the problem. Most of the time this input is *implicit*, in the sense that it is used to compute various other *explicit inputs* that depend on speed, such as sailing times, due dates for cargo pickup and delivery, and ship operating costs, of which fuel cost is an important component.

Assuming fixed ship speeds is typically also the case for models that compute shipping emissions worldwide, even though these do not belong to the OR/MS literature. See for instance the 2009 IMO GHG study (IMO, 2009) and Psaraftis and Kontovas (2009a), among others. In their calculations, these models typically take as input *design speeds* extracted from commercially available ship databases, such as those maintained by IHS Fairplay, among others. Such information may be inaccurate and does not necessarily represent actual ship speeds. The 2014 IMO GHG study (IMO, 2014) is more advanced in that it uses actual ship speeds in its calculations. Actual ship speeds were taken from ship Automatic Identification System (AIS) data.

Coming back to maritime transportation OR/MS models, it is clear that *not* considering speed as a decision variable may render solutions suboptimal. This is because doing so ignores the economic trade-off between (a) the lower voyage and cargo inventory costs associated with a higher speed and (b) the higher fuel costs associated with such higher speed. Assuming a fixed speed precludes the balancing of such trade-offs.

A speed that is assumed fixed may also in some cases remove flexibility in the overall decision making process. For problems that include port capacity constraints, berth occupancy constraints, time window constraints or other constraints that preclude the simultaneous service of more than a given number of vessels (see, for instance, Cordeau, Laporte, Legato, and Moccia (2005) and Halvorsen-Weare and Fagerholt (2013), among others), satisfying such constraints would conceivably be easier to meet were it not for the assumed constancy in ship speed. The same is the case for problems that analyze disruptions of service due to weather or other unpredictable events. It is clear that removing the flexibility to adjust ship speed in such scenarios would render any response to the disruption suboptimal.

Still, dealing with speed is not new in the maritime transportation literature and this body of knowledge is rapidly growing. In Psaraftis and Kontovas (2013) some 42 relevant papers were reviewed and a taxonomy of these papers according to various criteria was developed. Several additional papers dealing with ship speed appeared after the above paper was published. Its Google Scholar citations in April 2015 stood at 48, of which there was even a related paper in *Meat Science* (Mills, Donnison, & Brightwell, 2014). This indicates a growing interest of researchers in this topic.

We have amended the Psaraftis and Kontovas (2013) taxonomy and enlarged it to include 51 papers, including some of the most recent ones. The full table is available in the Appendix at the end of this chapter.

Another basic property of optimal speeds is not immediately obvious. It applies mainly to the charter (tramp) market and compares, for a specific ship and a specific route, the speed optimization problem of its ship owner and that of a time charterer who may charter the same ship. The ship owner wants to maximize average profit per day and the charterer wants to minimize average cost per day. Even though these two optimization problems appear at first glance different, the optimal ship speed for both problems turns out to be the same. For a proof in a rudimentary tramp scenario see Devanney (2010).

In Psaraftis and Kontovas (2013) it was further shown that both the above problems reduce to the following formulation:

$$\min_v \{\rho f(v) - Qv/L\}$$

where

v = sailing speed (nautical miles per day[2])

$\rho = P_{FUEL}/s$

P_{FUEL} = fuel price (\$/tonne) and

s = spot rate received by the owner (\$/tonne)

$f(v)$ = ship's daily fuel consumption (tonnes/day)

Q = ship's cargo capacity (tonnes)

L = roundtrip distance (nautical miles)

[2] This is 24 times the ship speed in knots. We use this unit to avoid carrying the number 24 through the calculations. One knot is one nautical mile per hour (1.852 km per hour) and is the typical unit of ship speed.

In fact from the above it can be seen that a key determinant parameter of the speed optimization problem is ρ, *the non-dimensional ratio of the fuel price divided by the market spot rate* (both expressed in \$/tonne). Higher ρ ratios will generally induce lower speeds than lower ratios. This corresponds to the typical behavior of shipping lines, which tend to slow steam in periods of depressed market conditions and/or high fuel prices and go faster if the opposite is the case.

For the simple case of a cubic fuel consumption function, $f(v) = kv^3$ and no constraints on speed, the optimal solution to the above problem is $v^* = (Q/3k\rho L)^{1/2}$, confirming the basic dependency of the optimal speed to the ρ ratio. Later we will see more realistic fuel consumption functions.

All OR/MS models that include speed that we have reviewed incorporate fuel prices as part of their input. However, in many models such inclusion is only *implicit*, whereas in others it is *explicit*. An implicit formulation is a fuel cost function $FC(v)$ instead of the product $P_{FUEL}f(v)$ and means that P_{FUEL} is not explicitly a part of the problem's input. An implicit formulation has the drawback of not allowing someone to directly analyze the functional dependency between P_{FUEL} and the optimal value of v, which can be very important.

Together with fuel price, another important input parameter is the state of the shipping market and in particular the freight rate (spot rate or other). Yet, a typical modeling assumption that is reflected in many OR/MS models that deal with ship speed is to *not* include the state of the market as part of their formulation. In most of these models it is assumed (at least implicitly) that fuel costs are being borne by the ship owner. In the tramp shipping market (served by tankers, dry bulk carriers, product carriers, and gas carriers) this is the case if the ship is on spot charter. It is known that the predominance of charter party contracts are time charters, in which fuel costs are borne by the charterer. Even though most models assume the ship owner as the party that bears the costs, including fuel, the related optimization problem is typically cost minimization rather than profit maximization. This is tantamount to assuming that revenue for the service is fixed. This is not the case however if the ship speeds up to make more profit-earning trips per unit time. Thus, some of the OR/MS models that optimize speed do not capture the trade-off between a higher speed to make more trips per unit time and the impact of such higher speed on costs (mainly on fuel).

Figure 9.3 is adapted from Gkonis and Psaraftis (2012) and captures the impact of both freight rate and bunker price on optimal speed for a specific Very Large Crude Carrier (VLCC) trading from the Persian Gulf to Japan. Optimal here means maximize average per day profit for the ship owner, and speeds are optimized in both laden and ballast conditions. Two market conditions are shown for the spot rate, one at Worldscale (WS) 60 and one at WS120.[3] Bunker prices (HFO, Heavy Fuel Oil) range from \$400 to \$1,000 per tonne. It can be observed that the impact of

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[3] WS is a nondimensional index measuring the spot rate and is exclusively used in the tanker market. For a specific route, WS is proportional to the spot rate on that route (in \$/tonne) and is normalized by the 'base rate' on that route. See Stopford (2009) for a detailed definition.

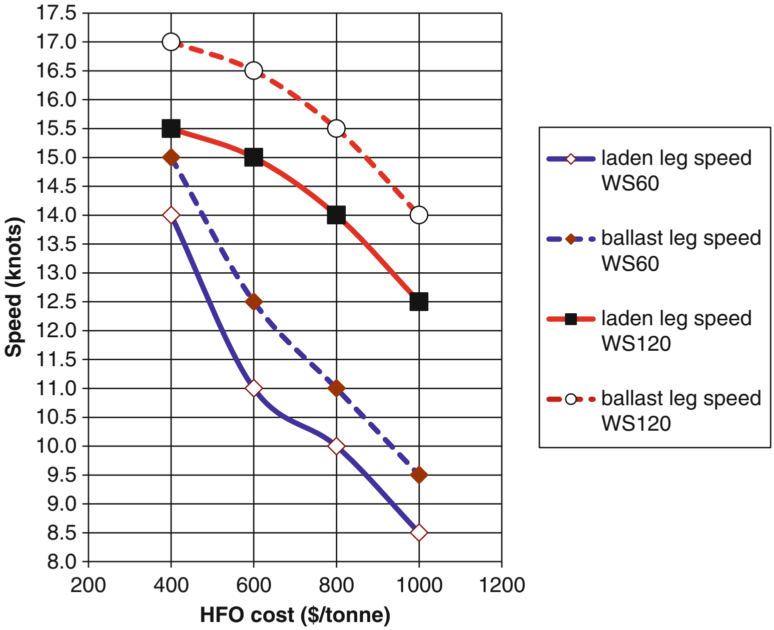

Fig. 9.3 Optimal VLCC speed as a function of spot rate and bunker price. Adapted from Gkonis and Psaraftis (2012)

both freight rate and bunker price on optimal speed can be quite dramatic, and that the range of optimal speeds can be very broad, depending on the combination of values of these two input parameters. It can be also observed that ballast speeds are typically higher than laden speeds by 1.0 knot in the lower rate scenario and by 1.5 knots in the higher rate scenario

In general there is wide variation on the input parameters that are assumed by the various models in the literature. In general these are problem-dependent. The taxonomy of the Appendix sheds some light on this issue, among others, for each of the papers in the taxonomy.

Other input parameters and model assumptions may be important in speed optimization. The following may or may not be true as regards assumptions that are used in a speed model:

(a) fuel consumption is a function of payload,
(b) fuel price is an input (explicit or implicit),
(c) freight rate is an input, and
(d) in-transit cargo inventory cost is considered.

Table 9.2 below lists a limited sample of papers of the taxonomy of the Appendix, including some of the most recent ones, and lists whether or not each of (a) to (d) above is true.

As argued throughout this chapter, inclusion of (a) to (d) above within a speed model's formulation can be important.

Table 9.2 Sample of papers and whether certain parameters are included in the model

Papers (listed chronologically)	Shipping market, logistical context	Fuel consumption a function of payload?	Fuel price explicit or implicit input?	Freight rate an input?	In-transit cargo inventory cost considered?
Ronen (1982)	Tramp, fixed route	No	Explicit	Yes	No
Perakis and Jaramillo (1991)	Liner, fleet deployment	No	Explicit	Yes	No
Devanney (2007)	World petroleum network	Only for laden and ballast conditions	Explicit	Equilibrium spot rate computed	Yes
Notteboom and Vernimmen (2010)	Container, fixed route	No	Explicit	No	No
Norstad et al. (2011)	Tramp, pickup and delivery	No	Implicit	No	No
Cariou and Cheaitou (2012)	Container, fixed route	No	Explicit	No	Yes
Gkonis and Psaraftis (2012)	Tanker, fixed route	Only for laden and ballast conditions	Explicit	Yes	Yes
Hvattum et al. (2013)	General, fixed route	No	Implicit	No	No
Fagerholt and Ronen (2013)	Tramp, pickup and delivery	No	Implicit	Only for spot cargoes[a]	No
Psaraftis and Kontovas (2014)	General, fixed or flexible route	For any loading condition	Explicit	Yes	Yes
Andersson et al. (2014)	Ro/Ro, fleet deployment	Only for laden and ballast conditions	Implicit	No	No
Doudnikoff and Lacoste (2014)	Liner, fixed route in SECAs	No	Explicit	No	No
Wang et al. (2014)	Container, schedule design	No	Explicit	No	Yes

[a]A known revenue is assumed for each of the spot cargoes, implying a freight rate for them

9.3 Factors that Affect Fuel Consumption

It is known from basic naval architecture that fuel consumption depends non-linearly on both ship sailing speed and ship payload. Many papers assume that fuel consumption per day is a *cubic function* of ship speed. The cubic approximation is reasonable for some ship types, such as tankers, bulk carriers, or ships of small size, but may not be realistic at slow or near-zero speeds and for some other ship types such as high-speed large container vessels. Even at zero speed the ship consumes some fuel, as its auxiliary engines are typically on to produce electricity. An exception is if electricity is provided to the ship by shore-side supply (also known as 'cold ironing'), but this is currently an exception rather than the rule. In-port fuel consumption is proportional to overall total port residence time.

A more serious assumption in many related models is that no dependency between fuel consumption and ship payload is considered. This assumption is reasonable in case ship payload is constant or does not change much. Cruise vessels, passenger vessels, and sometimes Ro/Ro carriers and Ro/Pax vessels belong to this category. However, if this assumption is not valid, it can cause serious under- or over-estimation of fuel costs. Ship resistance and hence fuel consumption at a given speed can be drastically different if the ship is full, empty or at an intermediate loading condition.

In tankers and bulk carriers we have a 'binary' situation, as the ship is typically either full or empty, and the difference in fuel consumption between these two extreme conditions can be quite substantial. In container vessels the ship is typically intermediately laden most of the time, but ships in some trunk routes (e.g. Far East to Europe) are mostly full in one direction and mostly empty in the opposite. This can come close to a binary situation and one would expect non-trivial differences in fuel consumption as a result.

In general, if a ship's loading condition varies along the legs of a ship's route (which is typical in pickup and delivery scenarios in which the ship is not fully laden all of the time), it is important that the dependency between ship load and fuel consumption along that route be realistically modeled. In an optimization setting, it would not make sense to claim solutions within, say, 1, 2 or 5 % from the optimal solution, or even solutions at the exact optimum, if the fuel consumption function, and hence fuel costs, are misrepresented by 10, 20 or 30 %.

In order to capture this dependency, it is useful to extend the previous formulation of the daily 'at-sea' fuel consumption of the ship $f(v)$ and assume that it is a known function $f(v,w)$ of both v, the ship's speed, and w, the ship's payload, which may actually vary along the ship's route. Function $f(v,w)$ depends on the ship, and essentially on the hull geometry-engine-propeller configuration. It can even be defined for $v=0$ (ship in port) and $w=0$ (ship going on ballast), and it need not be assumed in closed form, but could be given as a point/wise function, as a table, or even as the output of a relevant subroutine. Strictly speaking, f must also take into account the reduction of the ship's total displacement due to fuel being consumed along the ship's route. However, since displacement would not change much as a

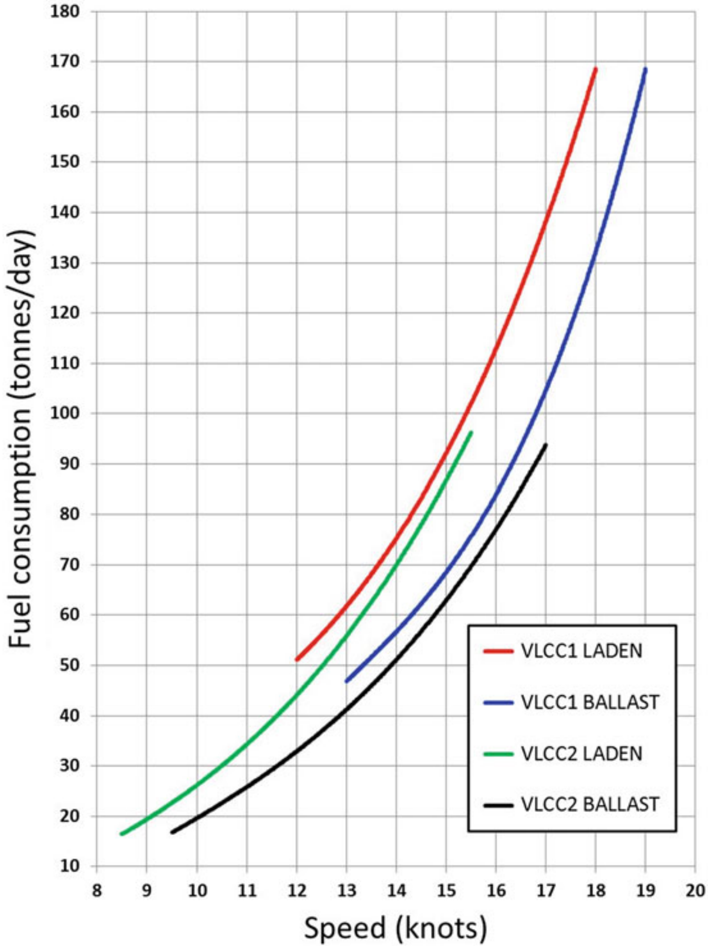

Fig. 9.4 Typical fuel consumption functions for two VLCCs for both the laden and ballast conditions. *Sources*: undisclosed

result of that consumption, one can practically assume f independent of en-route fuel consumption.

Figure 9.4 shows fuel consumption curves for two distinct Very Large Crude Carriers (VLCCs), for both the laden and ballast conditions. Relevant data was solicited and obtained for these ships under confidentiality conditions. It can be seen that the difference between laden and ballast fuel consumption at the same speed is on the order of 25–30 %.

In Fig. 9.4 it can be seen that ship speeds have upper and lower bounds. Both bounds are dictated by the maximum power and technology of the engine, and by the ship's payload. The upper bound exists because of limits in the ship's power and the lower bound exists because it is simply impossible for a ship engine to run slower than a certain power. Modern, electronically controlled engines can run slower than older, camshaft controlled engines.

A realistic closed-form approximation of f that takes both v and w into account is $f(v,w) = k(p + v^q)(w + A)^{2/3}$ with k, p and q constants such as $k > 0$, $p \geq 0$ and $q \geq 3$. A is the 'lightship weight', that is, the weight of the ship if empty including fuel and other consumables (modified admiralty formula). The rationale for such a formulation is that fuel consumption is proportional to the wetted surface of the ship, which is crudely proportional to the displacement of the ship $\Delta = w + A$, raised to the power of 2/3; see also Barrass (2005).

As said earlier, most papers in the literature assume a cubic function, that is, $p = 0$ and $q = 3$ and no dependency on payload.

The fuel consumption function also depends on the prevailing weather conditions along the route, which may actually vary in time and space. The way weather conditions are treated in the literature ranges from non-treatment (implying that the *average* weather conditions the ship expects along its route are implicitly factored into the function f, perhaps by a '*sea margin*' coefficient), to more sophisticated approaches in which f depends on the specific weather conditions along the ship's route, including wave height, wave direction, wind speed, wind direction, sea currents, and possibly others. These factors, most of which may be stochastic, can significantly influence both wave and wind resistance and hence fuel consumption and cost. Weather routing models typically take the more sophisticated approach, whereas all other OR/MS models including ship routing and scheduling, fleet deployment, and other models typically follow the simpler one.

Hull condition can also be an important factor that influences the frictional resistance of a ship, and, as a result, its fuel consumption. A foul hull from seaweed and other sea organisms would entail a higher resistance (and hence fuel consumption) than a clean hull, and efforts are being made (via anti-fouling paints and hull cleaning at regular intervals) to maintain a clean hull. To our knowledge, no OR/MS model takes into account such factor, all assuming an average hull condition.

9.4 Impact of In-Transit Cargo Inventory Costs

Many of the reviewed speed models do not include *in-transit cargo inventory costs* as part of the cost function. These are inventory costs that accrue while the ship is in transit, and they can be a non-trivial component of the cost that the owner of the cargo bears if the ship will sail at a reduced speed. They can be important if timely delivery of the cargo is significant. They can also be important if the voyage time and/or the quantities to be transported are non-trivial. This can be the case in long-haul problems.

It is clear that in-transit inventory costs are important for the charterer, assuming that he is the owner of the cargo. These costs are also important for the ship owner, as a charterer will prefer a ship that delivers his cargo earlier than another ship that sails slower. Thus, if the owner of the slower ship would like to attract that cargo, he may have to rebate to the charterer the loss due to delayed delivery of cargo. In that sense, the in-transit inventory cost is very much relevant in the ship owner's profit equation, as much as it is relevant in the charterer's cost equation.

The same is the case if the charterer does not move his own cargo but uses the ship to move somebody else's cargo. This is a typical situation in liner trades, where a significant part of a liner company's fleet consists of chartered ships, owned by independent ship owners but operated by the liner company. As the cargo owner will prefer a ship that moves his cargo faster, his in-transit inventory costs are again very much part of the chartered ship's cost equation.

If we call β the per day and per tonne in-transit inventory cost of the cargo, it is straightforward to see that β is equal to $PR/365$, where P is the CIF value of the cargo (value of cargo at destination) and R the cargo owner's cost of capital. This represents the revenue that is lost due to a delayed delivery of 1 tonne of the cargo by 1 day. This means (as expected) that expensive cargoes are more costly than cheaper cargoes in terms of inventory cost. This also explains why expensive cargoes tend to get hauled by liner ships that go faster, whereas cheaper (bulk) cargoes go by tramp ships that go slower. Conversely, it also means that in periods of low interest rates this cost component is less important.

Cargo inventory costs can be important in the liner business which involves trades of higher valued goods than those in bulk trades. The unit value of the top 20 containerized imports at the Los Angeles and Long Beach Ports in 2004 varied from about \$14,000/tonne for furniture and bedding to \$95,000/tonne for optic, photographic and medical instruments (CBO, 2006). Delaying 1 tonne of the latter category of cargo by 1 week because of reduced speed would cost some \$91 if the cost of capital is 5 %. For a 80,000 tonne payload this would amount to some \$7.25 million. This may or may not be greater than the economic benefit of a reduced speed.

Psaraftis and Kontovas (2009b) assumed a hypothetical string of 100 identical Panamax container vessels, each with a payload of 50,000 tonne. If the fleet baseline speed is 21 knots (both ways) and the fuel consumption at that speed is 115 tonne/day, then for a fuel price of \$600/tonne (corresponding to a period of high fuel prices, before the slump of 2008), the daily fuel bill would be \$69,000 per ship. Running the same type of ship at a reduced speed of 20 knots (one knot down), and assuming a cube law the fuel consumption would drop to 99.34 tonnes/day and the daily fuel bill would drop to \$59,605 per ship.

Assume these 100 ships go back and forth a distance of 2,100 miles (each way) and are 100 % full in both directions. This is not necessarily a realistic operational scenario, as containerships visit many ports and as capacity utilizations are typically lower both ways, depending on the trade route. However, a generalization of this analysis to many ports and different capacity utilizations in each leg of the trip should be straightforward. For simplicity, also assume 365 operating days per year and zero port loading and unloading times. For non-zero port times and less than 365 days, the analysis will be more involved but will lead to similar results.

Then we will have two cases:

Case A: 100 Ships Going 21 Knots
Total fuel burned/year/ship: 115 tonnes/day*365 = 41,975 tonnes
For 100 ships = 4,197,500 tonnes
Transit time (one way) = 100 days
Total annual fuel cost (X$600) = $2,518,500,000.

Case B: 105 Ships Going 20 Knots
To reach the same throughput of cargo per year, we will need 105 ships.
Total fuel burned/year/ship: 99.34 tonnes/day*365 = 36,259 tonnes
For 105 ships = 3,807,256 tonnes
Transit time (one way) = 105 days
Total annual fuel cost for 105 ships (X$600) = $2,284,353,741 (reduced vis-à-vis Case A).
Reduction of CO_2 emissions (per year), vis-à-vis Case A: 1,237,073 tonnes.

Fuel cost difference (per year) = $234,146,259 for five more ships, that is, $46,829,252 per additional ship. Dividing by 365, this difference is $128,299 per day. This means that if the sum of additional cargo inventory costs plus other additional operational costs of these ships (including the time charter) is less than $128,299 a day, then case B is overall cheaper. One would initially think that such a threshold would be enough. But it turns out that this is not necessarily the case if in-transit inventory costs are factored in.

To compute in-transit inventory costs for this case, we hypothetically assume that cargo carried by these vessels consists of high value, industrial products (e.g., computers, luxury cars, or similar), whose average value at the destination (CIF price) is $20,000/tonne. We also assume the cost of capital being 4 %. This means that 1 day of delay of 1 tonne of cargo would entail an inventory cost of 20,000*0.04/365 = $2.19. This may not seem like a significant figure, but it is. Computing the in-transit inventory costs for this case gives a total annual difference of $200,000,000 ($4,200,000,000−$4,000,000,000) in favor of case A, which moves cargo faster. This figure is significant, of the same order of magnitude as the fuel cost differential.

Assuming also a time charter rate of $25,000 per day (typical charter rate for a Panamax containership in 2007), the total other operational costs of the reduced speed scenario are $958,125,000 per year for 105 ships, versus $912,500,000 for 100 ships going full speed. Tallying up we find a net differential of $11,478,741 per year in favor of Case 1, meaning that in-transit inventory and other operational costs offset the positive difference in fuel costs.

Of course, other scenarios may yield different results, and the reduced speed scenario may still prevail in terms of overall cost, under different circumstances. For instance, if the average value of the cargo is $10,000/tonne, and everything else is the same, then the difference in annual inventory costs drops to $100,000,000, rendering the reduced speed scenario a profitable proposition (with a total cost reduction of $88,521,259 per year). Actually, speed reduction remains profitable if

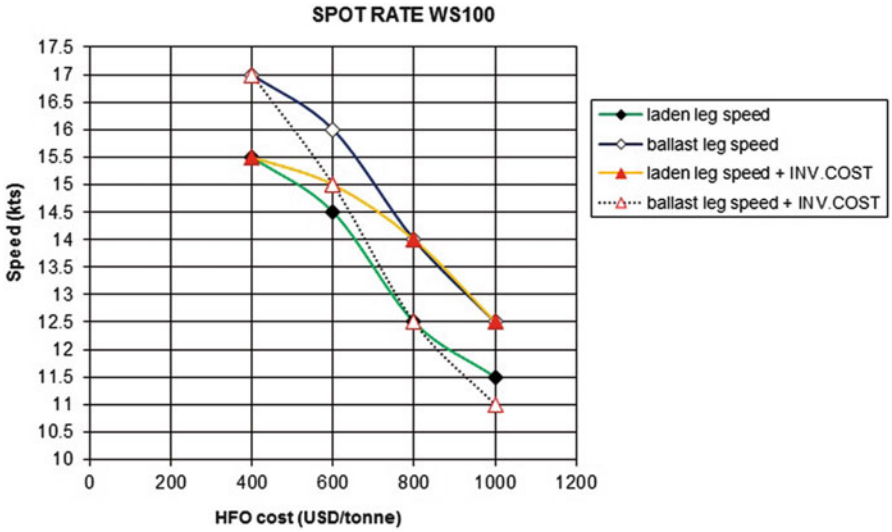

Fig. 9.5 Optimal VLCC speeds with and without inventory costs. *Source*: Gkonis and Psaraftis (2012)

the value of the cargo is no more than about $18,800/tonne (which can be considered as a break-even CIF price).

But the liner market is not the only one in which inventory costs are important. Figure 9.5 shows that optimal VLCC speeds vary, depending on whether or not in-transit inventory costs are taken into account. Including that cost component would generally increase the optimal speed. The example is for a given VLCC and assumes that the market spot rate is WS 100. Per earlier considerations, if no inventory costs are factored in, ballast speeds are uniformly above laden speeds, by 1.0–1.5 knots. But in case inventory costs are factored in, this is not necessarily the case. In the example, one can observe that if fuel (HFO) prices are higher than about $600/tonne (a break-even price), optimal laden speeds are higher than the equivalent ballast speeds.

For crude oil tankers, and in working with curves such as in Fig. 9.5, another effect should also be taken into account, which is not immediately obvious. If fuel prices change, the same in general will happen to the value of the crude oil that is carried, although there may not be a direct mapping between the two values. So in-transit inventory costs if HFO price is 800 $/tonne may be higher than those if HFO price is 400 $/tonne. We found that a higher value of the cargo while at the same time fuel prices increase will make the ship sail slightly faster (no more than 0.5 knots) than if the value of the cargo is kept fixed.

9.5 Speed Optimization in Mixed Chartering Scenarios

There are a number of papers in the OR/MS literature that examine ‘mixed’ chartering scenarios (see for instance Norstad, Fagerholt, and Laporte (2011) and Fagerholt and Ronen (2013), among others). In such scenarios, a number of the cargoes are labeled ‘*mandatory*’ cargoes, to be moved under COA (contract of affreightment) terms, and the rest are ‘*optional*’ cargoes, to be moved under spot charter terms. A COA contract is a voyage charter in which the ship owner undertakes the obligation to carry specified cargoes between specified ports at some point in the future, without naming the ships which will undertake the assignment. This gives flexibility to the ship owner in fulfilling his obligation, and in fact at time of COA signature he may not even have control of the ships that will be eventually used. He can use his own ships, or he can use ships from the charter market for that purpose.

Optional (spot) cargoes in such a mixed scenario mean that the owner has the option whether or not to embed these cargoes within his service plan, in addition to the COA cargoes which are considered mandatory. Adding spot cargoes would generate *additional revenue* for the ship owner, whereas the revenue of the mandatory cargoes is considered fixed and therefore does not impact the optimization problem. Given this additional potential revenue from the optional spot cargoes, it may make sense for some ships in the fleet to pick up some of these cargoes along their route. It may also make sense for the ships to sail at a higher speed in order to accommodate these optional spot cargoes and not violate time window constraints or other contractual obligations that may exist for the mandatory cargoes.

Such scenarios are encountered in the OR/MS maritime logistics literature but may actually be more complex than a first glance would suggest. A first observation is that the distinction between mandatory and optional cargoes may be, in many ways, artificial. Any cargo, including the COA cargoes, is optional until the ship owner and the charterer decide to enter into a mutually binding contract for that cargo. After COA contract signature, serving the COA cargo in question becomes mandatory. The same is true for the spot cargoes: they are only optional until an agreement to carry them is reached, and if so they become mandatory as well. What really distinguishes these two types of cargo is the timing of contract signature, which is presumably different: signature of the COA precedes that of the spot cargoes. The period during which the COA cargoes are mandatory and the spot cargoes are optional is the period between the signatures of the two contracts, and hence is only a transient period.

It is known that a COA does not require a ship owner to name a ship at the time of contract signature. But as the contract will specify the size of the shipments, the size of the ships that will carry them under the COA is likely to be more or less indirectly implied, usually leaving little or no extra space for spot cargoes, if the latter would have to be on the ship together with the COA cargoes. Fulfilling the COA with ships larger than required so as to allow space for potential spot cargoes is always an option. But assigning larger ships for the COA *before* potential spot cargoes are known may entail a financial risk and a potential loss to the ship owner. Even though several papers in this area also deal with uncertainty, we have seen no models that try to capture this specific risk as part of their formulation. One way to avoid such risk altogether is if the decision which spot cargoes to serve and at what speed is made *simultaneously* with the decision which ships to assign to fulfill the COA obligations. Another way is if the spot cargoes are served separately from the COA cargoes, for instance on the return leg of the COA route. However, this is likely to involve delays for the COA cargoes.

Another issue that is not often mentioned but may further complicate things is that the owner who has signed a COA may have to obtain the permission of the COA charterer to serve the additional spot cargoes. This may involve amending the COA itself, not necessarily an easy proposition, unless commitment to both the COA and spot cargoes happens at roughly the same time (something that would eliminate the distinction between mandatory and optional cargoes). The permission of the COA charterer may be warranted because adding spot cargoes may imply delayed delivery of the COA cargoes and also may involve liability issues, for instance in case the spot cargoes are dangerous or semi-dangerous and the ship (together with the COA cargoes) is lost or damaged.

Irrespective of the above, in mixed scenarios such as the above, ship payload will generally vary along the ship's route. Note however that, to our knowledge, all papers in the literature that deal with such mixed scenarios assume fuel consumption functions that are independent of ship payload. For reasons outlined earlier, this may misrepresent the fuel costs along the route and hence may lead to suboptimal solutions.

9.6 Selected Results for Tankers and Bulk Carriers (Fixed Route)

In addition to VLCCs (tankers over 250,000 DWT), Gkonis and Psaraftis (2012) developed speed optimization models for several other tanker classes, such as Suezmax (120,000–200,000 DWT), Aframax (80,000–120,000 DWT), Panamax (65,000–80,000 DWT) & product tankers (above 10,000 DWT), as well as Liquefied Natural Gas (LNG) and Liquefied Petroleum Gas (LPG) ships. Also Kapetanis et al. (2014) developed similar models for Handymax bulk carriers (54,000 DWT). In this section we reproduce some of the results of these models, referring the reader to the above papers for more details.

Figure 9.6 depicts the effect of varying freight rates and fuel prices on annual CO_2 emissions for a specific VLCC running the route Ras Tanura-Yokohama. It can be seen that as the freight rate level decreases from WS120 to WS60, emissions decrease by 29–64 %, depending on the fuel price (higher reductions for higher fuel prices). This sharp reduction in emissions is of course due to speed reduction.

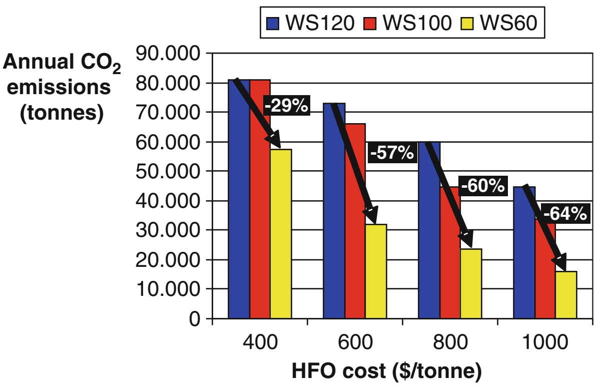

Fig. 9.6 Reduction in annual CO_2 emissions (single VLCC) for a 50 % reduction in freight rates. *Source*: Gkonis and Psaraftis (2012)

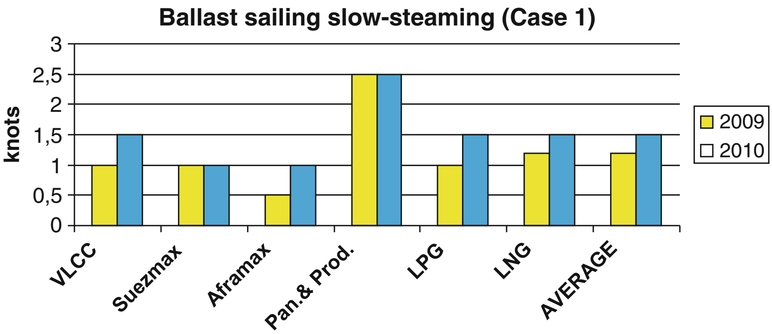

Fig. 9.7 Difference between laden and ballast speeds in Case 1 for several tanker types. *Source*: Gkonis and Psaraftis (2012)

Figure 9.6 can also be used to assess the effect of a levy (or tax) on ship emissions. If the fuel price is (say) 600 $/tonne and a levy of 200 $/tonne is applied on bunker fuel, the reduction of annual CO_2 emissions can be computed from the figure (for WS120 the drop is from approximately 73,000 to 60,000 tonnes a year, or some 18 %). This can attest to the usefulness a Market Based Measure (MBM) can have on emissions reduction (more on MBMs in Chap. 8).

Figure 9.7 shows for each tanker type examined in Gkonis and Psaraftis (2012) and for the reference years 2009 and 2010, how much slower is the ship's ballast speed versus its laden speed, assuming that laden speed is (per chartering agreement) constrained to about 90 % of MCR speed ±1 knot, and that only the ballast speed is allowed to be free (this is denoted as Case 1). The resulting slower-steaming in ballast is on average of the order of 1.5 knots, but can vary from 0.5 to 2.5 knots.

In addition to Case 1, Case 2 is the scenario when both speeds, laden and ballast, are free to be optimized. In Fig. 9.8, we see (again for each tanker category and for both 2009 and 2010), the difference between the Case 2 laden speed and the Case 1 laden speed. One can see that if laden speed is allowed to be free (Case 2), that

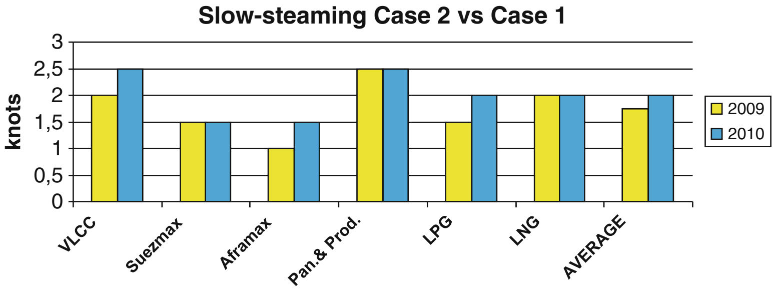

Fig. 9.8 Difference between Case 2 vs. Case 1 laden speeds for several tanker types. *Source*: Gkonis and Psaraftis (2012)

speed is generally lower than the laden speed of Case 1, and the difference is of the order of 2 knots on the average.

Kapetanis et al. (2014) performed a similar analysis for Handymax bulk carriers and investigated the effect of a bunker levy on optimal speed and emissions. As per Chap. 8, one of the effects of a bunker levy would be speed reduction. Among other results, they found that a $200/tonne levy on bunker fuel would reduce laden speed from 14 to 12 knots and CO_2 emissions by 9.1 % for the Handymax world fleet (2,119 ships in 2010), even though 214 more ships would be needed to produce the same amount of transport work.

9.7 Combining Speed and Routing Decisions

9.7.1 General Considerations

Speed optimization can be extended into combined ship routing and speed scenarios. A number of papers in the literature have looked at such combined scenarios, see for instance Hvattum, Norstad, Fagerholt, and Laporte (2013) and Fagerholt and Ronen (2013), among others. The considerations of Chap. 7 of this book on green vehicle routing can be considered as a parallel here, although obviously the cost functions in a maritime setting are very different from those in a road setting.

In the following we examine combined single-ship scenarios in which the fuel consumption function depends on both ship speed and payload and in which fuel price, charter rate and inventory costs are also taken onboard. By increasing order of complexity, these scenarios include (see Psaraftis and Kontovas (2014) for more details):

- Fixed-route scenarios: A ship going from port A to port B, or even on a multiple leg route in which the sequence of port visits is already determined at a higher level, but ship payload varies along the route.

- Feeder scenarios: A feeder ship collecting cargoes from several ports and bringing them into a hub port or vice versa.
- Combined pickup and delivery scenarios: A ship picking up cargoes from distinct origins and delivering them to distinct destinations. The route and sequence of pickups and deliveries has to be determined, along with the ship speed at each leg of the route.

The latter scenario is actually a generalized version of the feeder scenario and includes several sub-scenarios itself, depending on whether each port has one or multiple pickup cargoes, to be delivered to one or several delivery ports.

Whatever the scenario, assume we are given a set of ports $N = \{0, 1, 2, \ldots, n\}$. Inter-port distances are known and equal to s_{ij} ($i \in N, j \in N$), in nautical miles. Also we are given an origin/destination (O/D) matrix $[d_{ij}]$, representing the weight of cargo that has to go from port i to port j ($i \in N\backslash 0$, $j \in N\backslash 0$, $i \neq j$), in thousands of tonnes. This matrix is not necessarily symmetric. We assume that the set of cargoes is fixed and that each cargo is considered a distinct commodity and cannot be split.

In all scenarios the ship is assumed to be initially located at port *0* (home port), and has to: (a) pick up from each port the cargoes destined to other ports, (b) deliver to each port the cargoes originating from other ports, and, optionally, depending on the scenario, (c) return to port 0. Ship capacity is Q and cannot be exceeded. It is assumed that $Q \geq max_{(i,\, j)}\, d_{ij}$, otherwise the problem is infeasible.

In all scenarios we need to decide on the appropriate sailing speeds for each leg of the route, as well as the route itself, if the latter is not fixed.

The chartering context assumed is that of a *time charter*, and the assumption is that the charterer of the ship is also the cargo owner. The charterer would like to minimize the total cost of the trip, which has the following three components: (a) fuel cost, (b) time charter cost, and (c) cargo inventory cost, as further elaborated below.

Fuel cost: Since in a time charter the charterer pays for the fuel, a basic tradeoff for the charterer is whether he should complete the trip as soon as possible, so as to reduce the charter paid to the ship owner (see below), or go slower so as to reduce fuel cost. Fuel is assumed to be purchased at a known fuel price of P_{FUEL} ($/tonne). The default scenario ignores port-related costs to be borne by the charterer, even though including these costs is a straightforward extension (see Psaraftis and Kontovas (2014)).

The daily at sea fuel consumption of the ship sailing from i to j is equal to $f(v,w)$ (tonnes/day), which is assumed a known function of the ship's speed v and payload w from i to j ($0 \leq w \leq Q$). In-port fuel costs are assumed proportional to overall total port residence time, but as the latter is a constant proportional to total cargo moved, they can be ignored. In general, different speeds can be chosen for different legs of the route, so long as they are within the speed window $[v_{LB}(w), v_{UB}(w)]$, where $v_{LB}(w)$ and $v_{UB}(w)$ are lower and upper bounds (respectively) on the speed.

Time charter cost: In a time charter, the charterer pays to the ship owner a known freight rate of F ($/day), with F being an exogenous variable mainly determined by market conditions. It can be high in boom periods or low in depressed market periods. It is assumed that the time charter ends with the termination of the route and that the value of F is independent of charter duration and is agreed upon before the voyage commences.[4]

Cargo inventory cost: The third component of the cost that we assume the charterer bears is the inventory cost of the cargo. Per earlier considerations, we consider this cost irrespective of whether or not the charterer is the cargo owner. In addition to the per unit volume and per unit time in-transit inventory cost of β, as defined earlier, we assume that the per unit volume and per unit time cargo inventory cost of the cargo awaiting to be picked up at the port of origin is equal to α (cost accrues from time 0 until cargo is on the ship). Both α and β are known constants ($/tonne/day), and both are non-negative.

Coefficient α may be different from β for various reasons. For instance, the case $\alpha = 0$ assumes that cargo is available at the loading port in a 'just-in-time' fashion and related waiting or delay costs are zero. Also, these costs would generally depend on whether the cargo is at the origin's warehouse or inside the ship. The case $\alpha = \beta = 0$ means that inventory costs are insignificant or are ignored altogether.

It can be seen that even for each of the scenarios described earlier, several variants of the problem may exist, depending on the objective function. It turns out that these variants can be defined by an appropriate choice of the inputs.

The **minimum trip time problem** is tantamount to setting $P_{FUEL} = \alpha = \beta = 0$ and leaving F as the only nonzero cost coefficient.

At the other extreme, the **minimum emissions problem** is tantamount to setting $\alpha = \beta = F = 0$ and leaving P_{FUEL} as the only nonzero cost coefficient.

It is important to realize that different objective functions will generally produce different solutions, as will be seen in some examples that will be presented in the sections that follow.

9.8 Decomposition Property

Whatever the scenario, be it fixed route or flexible route, a property of the optimal solution is that the speed decision at each route leg can be decomposed from speed and (if applicable) routing decisions at subsequent route legs. Looking at an individual leg of the route, and assuming the ship is at port i and wants to sail to the next port j, the total cost on leg (i, j) is equal to

$$COST(i,j) = (P_{FUEL} f(v,w) + \alpha u + \beta w + F) \cdot \frac{s_{ij}}{v}$$

[4] The assumption that F is independent of charter duration is valid if the charter duration is within a reasonably narrow range. For large variations of time charter duration (e.g. a few months versus a multi-year charter), we expect that F will generally vary with charter duration.

with

v: ship speed during leg
w: ship payload during leg
u: total weight of cargo not yet picked up while ship sails on leg

This cost can be minimized with respect to speed v. As we can factor out the leg distance s_{ij}, the leg's optimal speed is the solution of the following problem:

$$C* = \min_{v \in V} \left\{ \frac{P_{FUEL} f(v, w) + au + \beta w + F}{v} \right\}$$

with

$$V = \{v : v_{LB}(w) \leq v \leq v_{UB}(w)\}$$

$C*$ is the minimum per mile cost of the leg. We note that it is independent of leg distance s_{ij}. In addition, and other than the fact that it depends on variables w and u, which depend on the ship's entire route history up to i, this minimum per mile cost is also independent of either i or j, that is, is independent of which is the route leg under consideration.

It is also important to realize that, in the absence of time windows, the speed decision on leg (i, j) has no repercussion on subsequent routing or speed decisions, as it does not affect the subsequent values of the parameters w or u at port j. The speed decision on this leg depends on the values of w and u at port i, on the fuel price P_{FUEL} and the charter freight rate F. It also depends on coefficients α and β, as well as the function f. Generally, high values for F, α and β and/or low values for P_{FUEL} would induce higher speeds than if the opposite is the case.

This means that, provided we know the parameters w and u at port i, the speed optimization problem for any specific leg can be solved in a stand-alone mode, the solution method depending on the form of function f. If a general form is given, the problem can be solved by complete enumeration, perhaps over a finite set of discrete speed values. As these results are not leg-specific, all of these calculations can be carried out in advance only once, and the results can even be tabulated in an appropriate parametric form and be ready for subsequent use. We note that this is true independent of the algorithm that is used for the routing part, be that exact or heuristic.

We can also explore special cases if a mathematical form is given for function f. Then a closed-form solution can be given.

As an example, assume that $f(v, w) = g(p + v^q)(w + A)^{2/3}$
with g, p, q and A known constants.
Then we want to minimize with respect to v the function

$$H(v) = \frac{P_{FUEL}\left(g(p+v^q)(w+A)^{2/3}\right) + \alpha u + \beta w + F}{v} = k_1 v^{q-1} + \frac{k_2}{v}$$

with $k_1 = P_{FUEL} g(w+A)^{2/3}$
and $k_2 = P_{FUEL} g p (w+A)^{2/3} + \alpha u + \beta w + F$
Let $v^* = \left(\frac{k_2}{k_1(q-1)}\right)^{1/q}$
(this is the speed that sets the first derivative of $H(v)$ equal to zero)

Note that

$$\frac{k_2}{k_1} = \frac{P_{FUEL} g p (w+A)^{2/3} + \alpha u + \beta w + F}{P_{FUEL} g (w+A)^{2/3}} = p + \frac{\alpha u + \beta w + F}{P_{FUEL} g (w+A)^{2/3}} \tag{9.5}$$

Then if $v_{LB}(w) \leq v^* \leq v_{UB}(w)$, $v_{OPT} = v^*$
If $v^* < v_{LB}(w)$, $v_{OPT} = v_{LB}(w)$
If $v^* > v_{UB}(w)$, $v_{OPT} = v_{UB}(w)$

For the minimum emissions (or minimum fuel consumption) speed, one can set $\alpha = \beta = F = 0$ and $H(v)$ is as follows:

$$\begin{aligned} H(v) &= \frac{CARB \cdot P_{FUEL}\left(g(p+v^q)(w+A)^{2/3}\right)}{v} \\ &= CARB \cdot P_{FUEL}\left[g\left(\frac{p}{v} + v^{q-1}\right)(w+A)^{2/3}\right] \end{aligned} \tag{9.6}$$

with *CARB* being the "carbon coefficient", tonnes of emissions per tonne of fuel burned. For CO_2 emissions and fossil fuels, *CARB* is between 3.02 and 3.11.

In this case $\frac{k_2}{k_1} = p$ (=0 if f is cubic) and $v^* = (p(q-1))^{1/q}$

For minimum emissions, quite likely $v_{OPT} = v_{LB}(w)$ (this is surely so if f is cubic).

From the above it can be seen that F and other input parameters such as P_{FUEL}, α and β can influence the speed decision at each leg. In particular, the optimal speed is a non-decreasing function of α, β and F, and a non-increasing function of P_{FUEL}. High rates, expensive cargoes and cheap fuels will induce higher speeds than low rates, cheaper cargoes and more expensive fuels.

As a parenthesis we note that such a property is also valid in a multiple ship setting. If which ship serves which set of cargoes and which route is known, and if the objective is the same as above for the fleet as a whole, a similar speed selection rationale should be applied for each of the ships in the fleet.

Table 9.3 Interport distances (nautical miles)

i\j	0	1	2	3
0	–	200	180	360
1	200	–	160	180
2	180	160	–	200
3	360	180	200	–

9.8.1 Freight Rate and Other Input Parameters May Influence the Routing Decision

What is less obvious is that input parameters such as the above may also influence the routing decision. This is indeed the case and it can be shown by a rudimentary example as follows.

A cargo ship of lightship weight equal to $A = 5$ and capacity equal to $Q = 11$,[5] loads two cargoes of sizes 10 and 1 (all sizes in 1,000 tonnes) at hypothetical port 0, and has to deliver them to hypothetical ports 1 and 2 respectively, and then proceed to port 3 on ballast. Interport distances are given by Table 9.3.

For simplicity assume port dwell times are zero. Note that the route of the ship in this example is an open path as the ship does not return to port 0, but this causes no loss of generality as the path and tour problems are reducible to one another (or one could assume that the ship after visiting port 3 returns to port 0).

Assume that daily fuel consumption (in tonnes) is equal to $FC = kv^3(w + A)^{2/3}$, where v is the ship speed, w is the payload and k is a constant such that at full capacity and at a speed of 14 knots fuel consumption is 30 tonnes/day. For simplicity also assume that the ship's maximum and minimum speeds are 14 and 8 knots respectively, and are independent of payload. Assume finally that $P_{FUEL} = \$600$/tonne and that $\alpha = \beta = 0$ (ignore cargo inventory costs).

In case the ship wants to minimize total emissions (or equivalently minimize total fuel consumed or total fuel cost), it is straightforward to see that all legs should be sailed at the minimum speed (8 knots) and that the optimal route is 0-1-2-3. This is so even though total distance sailed (560 nautical miles) is longer than that of the alternative route 0-2-1-3 (520 nautical miles). The reason that 0-1-2-3 is better than 0-2-1-3 is because in 0-1-2-3 the heavier cargo is delivered first, which makes the ship consume less fuel in subsequent legs (and in total). Table 9.4 shows these calculations.

However, if the objective is to minimize total cost, including cost paid for chartering the ship at a rate of F (\$/day), then if F is high enough the ship would follow the shorter route 0-2-1-3, even though in this case the heavier cargo

[5] In terms of ship size, this corresponds roughly to a feeder containership of about 1,000 TEU capacity. It could also be a product carrier or a small bulk carrier.

Table 9.4 Minimum emissions solution (optimal speed = 8 knots)

	Fuel consumption (tonnes)	Fuel cost ($)	Trip time (days)
Route 0-1-2-3			
Leg 0–1 (200 nm)	5.83	3,499	1.04
Leg 1–2 (160 nm)	2.43	1,455	0.83
Leg 2–3 (200 nm)	2.69	1,611	1.04
Total (560 nm)	10.94	6,565	2.92
Total CO_2 emissions (tonnes)	34.02		
Route 0-2-1-3			
Leg 0–2 (180 nm)	5.25	3,149	0.94
Leg 2–1 (160 nm)	4.47	2,681	0.83
Leg 1–3 (180 nm)	2.42	1,450	0.94
Total (520 nm)	12.13	7,280	2.71
Total CO_2 emissions (tonnes)	37.72		

Table 9.5 Minimum total cost solution

	Optimal speed (knots)	Fuel consumption (tonnes)	Fuel cost ($)	Chartering cost ($)	Total cost ($)	Trip time (days)
Route 0-1-2-3						
Leg 0–1 (200 nm)	10.46	9.96	5,977	11,954	17,931	0.80
Leg 1–2 (160 nm)	13.00	6.41	3,845	7,690	11,536	0.51
Leg 2–3 (200 nm)	13.54	7.69	4,616	9,231	13,847	0.62
Total (560 nm)		24.06	14,438	28,876	43,314	1.93
Total CO_2 emissions (tonnes)		74.83				
Route 0-2-1-3						
Leg 0–2 (180 nm)	10.46	8.97	5,379	10,759	16,138	0.72
Leg 2–1 (160 nm)	10.61	7.86	4,714	9,427	14,141	0.63
Leg 1–3 (180 nm)	13.54	6.92	4,154	8,308	12,462	0.55
Total (520 nm)		23.75	14,247	28,494	42,741	1.90
Total CO_2 emissions (tonnes)		73.86				

would be delivered last. Table 9.5 summarizes the cost components for both routes if $F = \$15{,}000$/day. The table also shows the optimal ship speed in all legs of the route.

9.8.2 Multiple Optimal Speeds

If ship payload varies along the ship's route, optimizing ship speed at each leg of the route is better than finding a single optimal speed, the same for all legs. This is of

Table 9.6 Results of the variable speed scenario

Leg	Distance (nm)	Payload (000 tonnes)	Speed (knots)	Fuel cost ($)	Charter cost ($)	Total cost ($)	Trip time (days)
0–1	396	0	13.54	9,139	18,278	27,417	1.22
1–2	165	5	11.61	4,442	8,884	13,326	0.59
2–3	191	6	11.36	5,252	10,504	15,756	0.70
3–4	201	8	10.95	5,736	11,472	17,208	0.76
4–5	508	11	10.46	15,182	30,364	45,545	2.02
Total	1,461			39,751	79,502	119,253	5.30

Adapted from Psaraftis and Kontovas (2014)

course to be expected, as the feasible solution space of the single speed case is a subset of the feasible solution space of the multiple speed case.

Consider a fixed-route situation with the ship of the previous scenario assumed to be visiting, *in this order*, ports 0, 1, 2, 3, 4 and 5.

Assume the ship starts empty at port 0 and has to collect cargo shipments of sizes 5,000, 1,000, 2,000 and 3,000 tonnes at ports 1, 2, 3, and 4 respectively and deliver all of them to port 5. Inter-port distances for legs (0,1), (1,2), (2,3), (3,4) and (4,5) are respectively 396, 165, 191, 201 and 508 nautical miles. As before, assume that P_{FUEL} is $600/tonne, that F is $15,000/day and that port dwell times and inventory costs can be ignored ($\alpha = \beta = 0$).

Note that in this scenario, if the fuel consumption function was assumed independent of ship payload, the ship's computed optimal speed would be the same on each leg of the route. However, with a payload-dependent fuel consumption function, different speeds on each leg would generally be warranted.

Table 9.6 shows the results of the variable speed scenario.

A pertinent question is, with the same fuel consumption function, if for whatever reason the ship is to keep the same speed along the route, can we at least find the common speed that minimizes total cost? It turns out that this speed is 11.375 knots, as shown in Fig. 9.9.

Table 9.7 shows detailed results of this scenario.

In comparing Tables 9.6 and 9.7, and as expected, the results of Table 9.6 are better for the objective to be optimized (total cost in this case). But it happens that in this instance better results are also obtained with respect to total fuel cost, total charter cost and total trip time. Note also that the single optimal speed (11.375 knots) is lower than the average speed of the multiple optimal speed scenario (11.48 knots). The difference in total costs depends on the scenario. For this one, it is not that pronounced.

If the charter rate F is higher, optimal speeds will tend to increase, and this is true for both the single optimal speed and for the multiple optimal speed scenarios. Figure 9.10 shows such a behavior, by plotting the optimal (single) speed as a function of the charter rate.

Figure 9.10 captures a typical market behavior in shipping: ships tend to speed up when the market is up, and slow down when the market is down. Also it can be

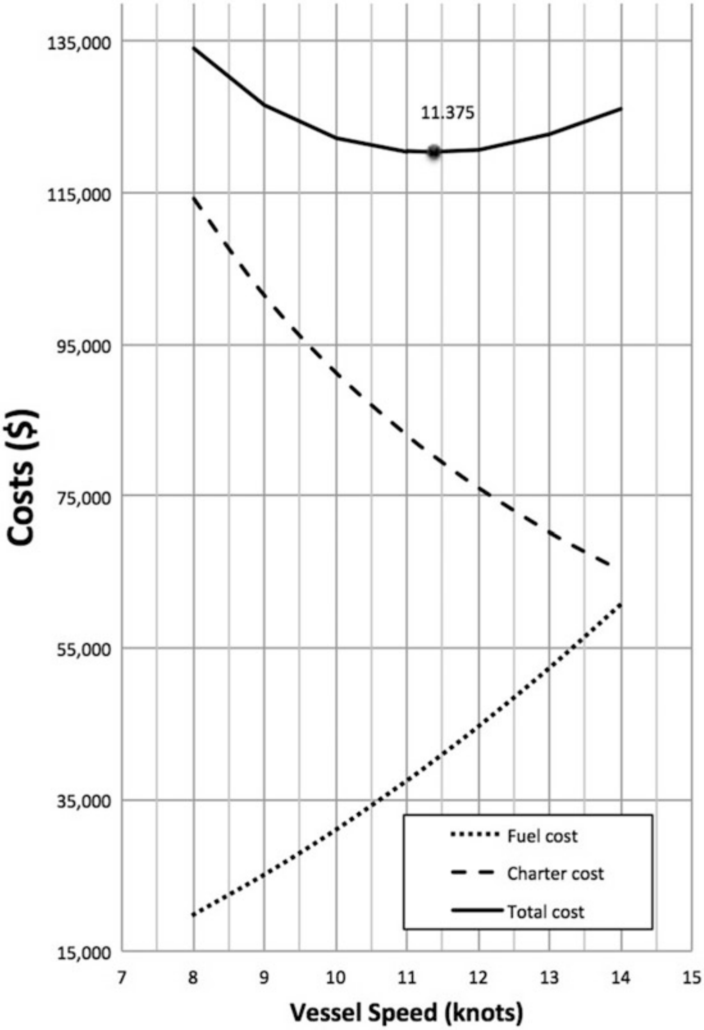

Fig. 9.9 Fuel, Charter and Total costs as functions of vessel speed. *Source*: Psaraftis and Kontovas (2014)

seen that above or below certain charter rates, the speed hits its upper or lower bounds respectively.

A similar behavior also pertains to variations in fuel price. For this particular form of fuel consumption function, keeping the ratio of fuel price to charter rate constant would result in the same speeds.

Table 9.7 Results of the fixed speed scenario

Leg	Distance (nm)	Payload (000 tonnes)	Speed (knots)	Fuel cost ($)	Charter cost ($)	Total cost ($)	Trip time (days)
0–1	396	0	11.375	6,449	21,758	28,207	1.45
1–2	165	5	11.375	4,266	9,066	13,332	0.60
2–3	191	6	11.375	5,262	10,495	15,756	0.70
3–4	201	8	11.375	6,190	11,044	17,233	0.74
4–5	508	11	11.375	17,966	27,912	45,878	1.86
Total	1,461			40,132	80,275	120,407	5.35

Adapted from Psaraftis and Kontovas (2014)

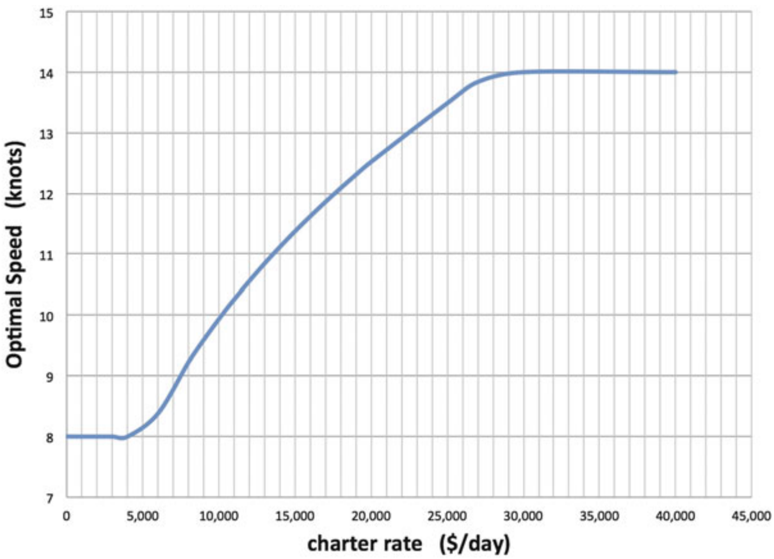

Fig. 9.10 Optimal speed as a function of the charter rate. *Source*: Psaraftis and Kontovas (2014)

The above results also tend to confirm those of Gkonis and Psaraftis (2012), to the effect that, in the absence of constraints on laden speed, if one wishes to reduce fuel costs and by extension emissions, it is better to apply speed reduction in the laden condition than in the ballast condition. Extending this argument, the more loaded the ship is, the lower its speed should be. In practice however, the opposite is often the case, as many ships maintain a constant speed and tend to sail faster when laden than in ballast. This behavior can be explained if there are contractual obligations or other constraints that force the ship to sail at the laden condition faster than in the ballast condition, or if cargo inventory costs are taken into account. This point is further elaborated next.

Table 9.8 Variation of optimal speed with value of cargo

Value of cargo ($/tonne)		Payload (000 tonnes)	0	5,000	10,000	15,000	20,000	25,000
			Speed (knots)					
Leg	0-1	0	13.54	13.54	13.54	13.54	13.54	13.54
	1-2	5	11.61	12.12	12.58	13.02	13.43	13.81
	2-3	6	11.36	11.96	12.49	12.99	13.45	13.88
	3-4	8	10.95	11.70	12.36	12.96	13.51	14.00
	4-5	11	10.46	11.42	12.24	12.96	13.61	14.00
Fuel cost ($)			39,751	44,433	48,808	52,945	56,890	59,854
Charter cost ($)			79,502	75,324	72,136	69,580	67,461	65,996
Inventory cost ($)			0	13,542	25,480	36,310	46,318	56,189
Total cost ($)			119,253	133,299	146,424	158,835	170,669	182,039
CO_2 emitted (tonnes)			206.04	230.31	252.99	274.43	294.88	310.24
Trip time (days)			5,30	5,02	4,81	4,64	4,50	4,40

Adapted from Psaraftis and Kontovas (2014)

9.8.3 Expensive Cargoes Sail Faster and Induce More CO_2

If we take cargo inventory costs into account in the previous example, optimal per leg speeds will change. The more expensive the cargo, the higher the optimal speed will be. If we assume that $\alpha = 0$ (just-in-time availability of cargoes at loading ports) and $\beta = PR/365$ with P the CIF value of the cargo and R the cargo owner's cost of capital, Table 9.8 exhibits the optimal speeds per leg for various values of the cargo, assuming $R = 3$ %. The zero value case corresponds to the case that cargo inventory costs are not factored in. The table also shows all cost components, total tonnes of CO_2 emitted and trip time in each case.

One can observe that, with the exception of the first leg, which is in ballast, all other legs are sailed at a higher speed for more expensive cargoes. In fact, even though there is an initial downward trend in speed along the route as the ship becomes more heavy with cargoes loaded on to it, above a certain value of cargo (about $15,000/tonne here) this trend is reversed and speed increases with payload, hitting its upper bound of 14 knots in the last two legs of the trip if the value of the cargo is $25,000/tonne. Further increases in the value of the cargo would set all leg speeds (except that of the first leg) to this upper bound.

One can also observe that expensive cargoes induce more CO_2, as they encourage higher speeds for the ship.

9.8.4 Sailing the Minimum Distance Route at Minimum Speed May Not Minimize Emissions

In the quest for environmentally optimal solutions, one might assume that if the minimum distance route is sailed at the minimum possible speed in all legs, this

Table 9.9 Interport distances (nautical miles)

i\j	0	1	2	3
0	–	255	175	10
1	255	–	200	250
2	175	200	–	170
3	10	250	170	–

Table 9.10 Cargo O/D matrix [d] (1,000 tonnes)

i\j	1	2	3
1	–	5	3
2	2	–	4
3	11	1	–

Table 9.11 Minimum trip time solution

Port stop	Pickup and delivery operations	Next leg	Payload at beginning of leg (000 tonnes)	Speed (knots)	Distance (nm)	Trip time (days)
0	–	0–3	0	14.00	10	0.03
3	P31	3–1	11	14.00	250	0.74
1	D31, P12, P13	1–3	8	14.00	250	0.74
3	D13, P32	3–2	6	14.00	170	0.51
2	D12, D32, P21, P23	2–1	6	14.00	200	0.60
1	D21	1–3	4	14.00	250	0.74
3	D23	3–0	0	14.00	10	0.03
0	–	–	–	–	–	
Total					1,140	3.39

Source: Psaraftis and Kontovas (2014)

would minimize emissions. After all, daily emissions are an increasing function of ship speed, and more days at sea would seem to imply more emissions. However, it turns out that this is not necessarily the case, as shown in the rudimentary example below, involving a pickup and delivery scenario.

Assume a 4-port problem (the home port 0 plus 3 other ports) with the distance matrix given by Table 9.9 as follows:

Also assume an asymmetric O/D table for six cargoes to be transported among ports 1–3 as given by Table 9.10:

We again assume the same feeder ship of the previous examples. The ship starts and ends at port 0, and has to visit the three ports as many times as necessary in order to carry all cargoes as shown in the O/D table. Note that one of the cargoes (from port 3 to port 1) is of size equal to the capacity of the ship. In this example we ignore cargo inventory costs, meaning that $\alpha = \beta = 0$.

If the objective is minimum trip time (this is achieved if we set $P_{FUEL} = 0$), all legs are sailed (as expected) at the maximum speed of 14 knots, and the ship makes a total of 6 port calls (once at port 2, twice at port 1 and three times at port 3) as follows (Table 9.11):

Table 9.12 Minimum emissions solution

Port stop	Pickup/delivery operations	Next leg	Payload at beginning of leg (000 tonnes)	Speed (knots)	Distance (nm)	Trip time (days)
0	–	0–3	0	8.00	10	0.05
3	P31	3–1	11	8.00	250	1.30
1	D31, P12	1–2	5	8.00	200	1.04
2	D12, P21	2–1	2	8.00	200	1.04
1	D21, P13	1–3	3	8.00	250	1.30
3	D13, P32	3–2	1	8.00	170	0.89
2	D32, P23	2–3	4	8.00	170	0.89
3	D23	3–0	0	8.00	10	0.05
0	–	–	–	–	–	
Total					1,260	6.56

Source: Psaraftis and Kontovas (2014)

Table 9.13 Solutions for non-zero fuel price and varying freight rates

Port stop	Pickup & delivery operations	Next leg	Payload at beginning of leg (000 tonnes)	Speed (knots)		Trip time (days)	
				F = \$5,000 per day	F = \$20,000 per day	F = \$5,000 per day	F = \$20,000 per day
0	–	0–3	0	9.39	14.00	0.04	0.03
3	P31	3–1	11	8.00	11.51	1.30	0.91
1	D31, P12, P13	1–3	8	8.00	12.05	1.30	0.86
3	D13, P32	3–2	6	8.00	12.51	0.89	0.57
2	D12, D32, P21, P23	2–1	6	8.00	12.51	1.04	0.67
1	D21	1–3	4	8.24	13.08	1.26	0.80
3	D23	3–0	0	9.39	14.00	0.04	0.03
0	–	–	–	–	–	–	–
Total						5.87	3.87

Source: Psaraftis and Kontovas (2014)

In Tables 9.11, 9.12 and 9.13, by “Pxy” we mean “at port x pick up cargo destined to port y,” and by “Dxy” we mean “at port y deliver cargo originating from port x.”

In this case total distance traveled is also minimized and equal to 1,140 nautical miles, and total CO_2 emitted is 260 tonnes. Total trip time is equal to 3.39 days. This solution is independent of F, so long as F is not zero.

At the other extreme of this example is if we examine the minimum emissions (or minimum fuel consumption) solution. We can do this by setting $F = 0$ and assuming any nonzero fuel price. If this is the case, the ship will make 7 port calls instead of 6 (twice at ports 1 and 2 and three times at port 3), and will sail all legs at the minimum speed of 8 knots. The solution will be as follows (Table 9.12):

Total distance traveled in this case will be 1,260 nautical miles and total trip time will be 6.56 days, both higher than before. But total CO_2 emitted will only be

80 tonnes, much lower. Obviously the lower emissions are mainly due to the lower speed. However, it is interesting to note that the amount of CO_2 emitted in this case is lower than the 84.90 tonnes of CO_2 that would be emitted if the ship had sailed the minimum distance route of Table 9.11 at the minimum speed of 8 knots (for a cubic fuel consumption function, total fuel consumed, and hence CO_2 produced, are proportional to the square of the speed, everything else, including payloads at each leg, being equal. Then $260(8/14)^2 = 84.90$).

The reason that sailing the minimum distance route at minimum speed is suboptimal with respect to emissions is that it involves more legs in which the ship is more laden as compared to the case it sails the alternate, longer route. A heavier load profile results in higher fuel consumption (and emissions) overall, even though the route is shorter. So in this case what would intuitively seem like an optimal policy is actually suboptimal.

Other solutions may be produced for different values of the input data. Table 9.13 shows two cases where $P_{FUEL} = \$600$/tonne (in both cases) and F is either \$5,000/day or \$20,000 day. Both cases produce the same optimal route as that of Table 9.11, but speeds along the legs of the route will vary for different values of F.

As expected, the ship goes faster when F is higher, with the lower speed bound active in 4 legs of the $F = \$5,000$/day case and the upper speed bound active in 2 legs of the $F = \$20,000$/day case.

In all of the above cases the combined speed-routing problem is solved by Dynamic Programming, as an extension of the approach of Psaraftis (2011). Details can be found in Psaraftis and Kontovas (2014).

9.9 Conclusions and Possible Extensions

This chapter has examined speed optimization in maritime transportation from various angles, including its interaction with route optimization. It has confirmed, among other things, that solutions for optimal environmental performance are not necessarily the same as those for optimal economic performance. Also policies that may seem at first glance optimal from an environmental viewpoint may actually be suboptimal. As a private operator would most certainly choose optimal economic performance as a criterion, if policy-makers want to influence the operator in his decision so as to achieve results that are good from a societal point of view, they could play with parameters that would internalize the external costs of CO_2 produced and move the solution closer to what is deemed more appropriate for the environment and for the benefit of society.

To that effect, a levy on bunker was seen as something that can be used to produce such a result, and in fact induce a lower speed and therefore reduced emissions. This confirms the assertion of Chap. 8 of this book, to the effect that the GHG Fund is the only among the MBM proposals submitted to the IMO that can have such impact on slow steaming in an ‘automatic’ fashion. This means with no additional information needed for the person responsible for the speed decision (other than the information on the fuel price including the levy).

A related policy issue is that mandating direct speed limits. If emissions can be reduced by reducing speed, can someone achieve this desirable outcome by imposing speed limits? This is an argument that is heard frequently these days. Among various lobbying groups, the Clean Shipping Coalition, a Non-Governmental Organization, advocated at IMO/MEPC 61 that "*speed reduction should be pursued as a regulatory option in its own right and not only as possible consequences of market-based instruments or the EEDI*." However, that proposal was rejected by the IMO. In spite of this decision, lobbying for speed limits has continued by CSC and other groups. Recipients of this lobbying activity have included the IMO and the European Commission.

Our own position on this issue is not in favor of speed limits. It is clear that slow steaming and speed limits are two different things, as the first is a voluntary response and the second is a mandated measure. If the speed limit is above the optimal speed that is voluntarily chosen, then it is superfluous. If it is below, it will cause (perhaps massive) distortions in the market, particularly in boom periods, and costs that may exceed the benefits of speed reduction. Possible side-effects include, among others, building more ships to match demand, with possible increase of emissions during shipbuilding and recycling, increasing cargo inventory costs, producing more GHGs if low-powered ships are forced to speed up in boom periods, and having adverse implications on ship safety.

We have seen no comprehensive analysis of the possible market distortions of a speed limit. But in a recent paper, Cariou and Cheaitou (2012) investigate policy options contemplated by the European Commission and compare speed limits versus a bunker levy as two measures to abate GHGs, with a scenario from the container trades. They conclude that the former measure is counterproductive because it may ultimately generate more emissions and incur a cost per tonne of CO_2 which is more than society is willing to pay and because it is sub-optimal compared to results obtained if an international bunker-levy were to be implemented.

We have also seen in previous sections that if laden leg ship speeds are not constrained by charter party speed clauses, lower emissions are likely to occur. Conversely, a charter party agreement specifying a prescribed speed, explicitly or implicitly, might entail significant costs, both in terms of additional fuel (which is a private cost matter) and in terms of additional emissions (which is a cost to society). Our analysis strongly suggests that regulatory action to prevent such clauses in charter party agreements could very well be worth looking into as a policy alternative.

Psaraftis and Kontovas (2015), among other things, provide a discussion on the possible impact of slow steaming on port operations. If a port is congested, it would clearly make no sense to sail there at full speed, wasting money on fuel and producing emissions that can be avoided if ship speed were slower. A recent initiative is the so-called 'Virtual Arrival', which has been employed firstly by tankers in order to manage the vessels' arrival time based on the experience of congestion at some discharging ports. This initiative recognizes known inefficiencies in the supply chain, such as waiting to discharge because of port delays and reduces fuel consumption and, consequently, emissions by implementing a mutually-agreed reduction in a vessel's speed in order to achieve an agreed arrival time at a port. This scheme in order to work needs a mutual agreement by both the owner and charterer to agree a speed to meet the terminal booking that maximizes fuel efficiency and minimizes port waiting time. To ensure the accuracy and independence of the calculations and to avoid the risk of disputes, it is proposed to use a weather routing analysis company. After the agreement of both parties the ship slows to the economical speed based on the revised arrival time. Once the voyage is completed, demurrage is calculated based on the original plans and bunker savings are spilt between the parties.

'Virtual Arrival' seems profitable especially given the fact that there are indeed serious delays in discharging in some ports in the world. According to the Global Ports Congestion Index (GPCI) and its weekly newsletter publication that provides details on berthing delays at the major coal and ore ports worldwide, the average delay can be as high as 5 days. Obviously there is no point for vessels to steam at full speed when the have to wait a couple of days in order to discharge. Sailing at a slower speed and arriving on time entails benefits both for the owner and the charterer but also for the environment.

In another direction, Magirou, Psaraftis, and Bouritas (2015) have recently developed models that optimize speed in a dynamic and stochastic setting. It was found that for freight rates that depend on a state of the market Markovian random variable, economic speed depends on the market state as well, with increased speed corresponding to good states of the market. Also, the authors and their colleagues have extended the combined speed and routing approach of Psaraftis and Kontovas (2014) into a multiple ship scenario. The results of this analysis were still incomplete as this book was being finalized and will be reported in future publications.

Last but not least, and as already mentioned earlier, in the Appendix we update the taxonomy of Psaraftis and Kontovas (2013) and display an amended set of speed models, classified according to a set of criteria.[6]

Acknowledgments Work on this chapter has been supported in part by various sources, including the Lloyd's Register Foundation (LRF) in the context of the Centre of Excellence in Ship Total Energy-Emissions-Economy at the National Technical University of Athens (NTUA), the authors' former affiliation. LRF helps to protect life and property by supporting engineering-related education, public engagement and the application of research. This work has also been supported in part by an internal grant at the Technical University of Denmark (DTU).

[6] As this book was being finalized, an unprecedented decrease in oil prices was taking place. However, as charter rates fell too, a definitive statement on the effect of this development on average ship or fleet speeds was not possible.

Appendix: Taxonomy of Speed Papers, Amended from Psaraftis and Kontovas (2013)

Table has 7 parts, of 7 entries each. Two entries have two references each. Total references: 51

Taxonomy part I

Taxonomy parameter\ paper	Alderton (1981)	Alvarez (2009)	Andersson, Fagerholt, and Hobbesland (2014)	Bausch, Brown, and Ronen (1998)	Benford (1981)	Brown, Graves, and Ronen (1987)	Cariou (2011)
Optimization criterion	Profit	Cost	Cost	Cost	Cost	Cost	Cost
Shipping market	General	Liner	Ro/Ro	Tanker/barge	Coal	Tanker	Container
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	Yes	Yes	No	Yes	No	No	Yes
Freight rate an input	Input	No	Implicit	No	No	No	No
Fuel consumption function	Cubic	Cubic	General	Unspecified	Cubic	Unspecified	Cubic
Optimal speeds in various legs	Yes	Yes	Yes	No	No	Only ballast	No
Optimal speeds as function of payload	Yes	Yes	Yes	No	No	No	No
Logistical context	Fixed route	Joint routing and fleet deployment	Fleet deployment	Routing and scheduling	Fleet deployment	Routing and scheduling	Fixed route
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	Yes	No	Yes	No	No	No	Yes
Inventory costs included	Yes	No	No	No	No	No	No
Emissions considered	No	No	No	No	No	No	Yes
Modal split considered	No	No	No	No	No	No	No
Ports included	Yes	Yes	No	Yes	No	No	No

Taxonomy part II

Taxonomy parameter\ paper	Cariou and Cheaitou (2012)	Chang and Wang (2014)	Corbett, Wang, and Winebrake (2010)	Devanney (2007)	Devanney (2010)	Doudnikoff and Lacoste (2014)	Du, Chen, Quan, Long, and Fung (2011) / Wang, Meng, and Liu (2013a, b)
Optimization criterion	Cost	Cost	Profit	Profit	Cost or profit	Cost	Fuel consumption
Shipping market	Container	General	Container	Tanker	Tanker (VLCC)	Liner	Container
Decision maker	Owner	Owner	Owner	Owner	Owner or charterer	Owner	Owner
Fuel price an explicit input	Yes	Yes	Yes	Yes	Yes	Yes	No
Freight rate an input	No	Yes	Input	Computed	Computed	No	No
Fuel consumption function	Cubic	Cubic	Cubic	Cubic	General	Cubic	Non-linear
Optimal speeds in various legs	No	No	No	Yes	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No
Logistical context	Fixed route	Fixed route	Fixed route	World oil network	Fixed route	Fixed route in SECAs	Berth allocation
Size of fleet	Multiple ships	One ship	Multiple ships	Multiple ships	One ship	Multiple ships	Multiple ships
Add more ships an option	Yes	No	Yes	Yes	Yes	No	No
Inventory costs included	Yes	No	No	Yes	Yes	No	No
Emissions considered	Yes	No	Yes	No	No	Yes	Yes
Modal split considered	No	No	No	No	No	No	No
Ports included	Yes	Yes	No	Yes	No	No	No

Taxonomy part III

Taxonomy parameter\ paper	Eefsen and Cerup-Simonsen (2010)	Faber, Freund, Köpke, and Nelissen (2010)	Fagerholt (2001)	Fagerholt, Laporte, and Norstad (2010)	Fagerholt, Gausel, Rakke, and Psaraftis (2015)	Fagerholt and Ronen (2013)	Gkonis and Psaraftis (2012)
Optimization criterion	Cost	N/A	Cost	Fuel consumption	Cost	Profit	Profit
Shipping market	Container	Various	General	Liner	Ro/Ro	Tramp	Tanker, LNG, LPG
Decision maker	Owner	N/A	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	Yes	No	No	No	Yes	No	Yes
Freight rate an input	No	No	No	No	No	Implicit	Input
Fuel consumption function	Cubic	Cubic	Cubic	Cubic	Cubic	General	General
Optimal speeds in various legs	No	No	Yes	Yes	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No
Logistical context	Fixed route	Fixed route	Pickup and delivery	Fixed route	Route & speed selection in SECAs	Pickup and delivery	Fixed route
Size of fleet	Multiple ships	Multiple ships	Multiple ships	One ship	One ship	Multiple ships	Multiple ships
Add more ships an option	Yes	Yes	No	No	No	No	Yes
Inventory costs included	Yes	No	No	No	No	No	Yes
Emissions considered	Yes	Yes	No	Yes	Yes	No	Yes
Modal split considered	No	No	No	No	No	No	No
Ports included	Yes	No	No	No	No	No	Yes

Taxonomy part IV

Taxonomy parameter\ paper	Hvattum et al. (2013)	Kapetanis et al. (2014)	Kontovas and Psaraftis (2011)	Lang and Veenstra (2010)	Lindstad, Asbjørnslett, and Strømman (2011)	Lo and McCord (1998)	Magirou et al. (2015)
Optimization criterion	Fuel consumption	Profit	Cost	Fuel costs	Pareto analysis	Fuel consumption	Profit
Shipping market	General	Drybulk	Container	Container	All major ship types	General	General
Decision maker	Owner	Owner	Charterer	owner	Owner	Ship's master	Owner
Fuel price an explicit input	No	Yes	Yes	No	Yes	No	Yes
Freight rate an input	No	Yes	Input	No	No	No	Yes
Fuel consumption function	Convex	General	Cubic	linearized	Cubic	Cubic	Cubic
Optimal speeds in various legs	Yes	Yes	Yes	No	No	N/A	Yes
Optimal speeds as function of payload	No	Yes	Yes	No	Yes	No	No
Logistical context	Fixed route	Fixed route	Fixed route	Vessel arrival planning	Fixed route	Weather routing	Fixed route
Size of fleet	One ship	Multiple ships	Multiple ships	Multiple ships	Multiple ships	One ship	One ship
Add more ships an option	No	Yes	Yes	No	Yes	No	No
Inventory costs included	No	Yes	Yes	No	Yes	No	No
Emissions considered	Yes	Yes	Yes	No	Yes	No	No
Modal split considered	No	No	No	No	No	No	No
Ports included	No	Yes	Yes	Yes	Yes	No	

Taxonomy part V

Taxonomy parameter\ paper	Meng and Wang (2011)	Norlund and Gribkovskaia (2013)	Norstad et al. (2011)	Notteboom and Vernimmen (2010)	Perakis and Papadakis (1989)	Perakis (1985)	Perakis and Jaramillo (1991)
Optimization criterion	Cost	Cost	Cost	Cost	Cost	Cost	Cost
Shipping market	Liner	Offshore supply vessels	Tramp	Container	Tramp	Tramp	Liner
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	Yes	No	No	Yes	Yes	No	Yes
Freight rate an input	No	No	No	No	No	No	Yes
Fuel consumption function	Cubic	Cubic	Cubic	Unspecified	General	Cubic	Cubic
Optimal speeds in various legs	No	Yes	Yes	No	Yes	No	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No
Logistical context	Fleet deployment	Set covering	Pickup and delivery	Fixed route	Fleet deployment	Fleet deployment	Fleet deployment
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	No	No	No	Yes	No	Yes	Yes
Inventory costs included	No	No	No	No	Yes	No	No
Emissions considered	No	Yes	No	No	No	No	No
Modal split considered	No	No	No	No	No	No	No
Ports included		No	No	Yes	Yes	No	No

Taxonomy part VI

Taxonomy parameter\ paper	Perakis and Papadakis (1987a, b)	Perakis and Papadakis (1989)	Psaraftis and Kontovas (2009b)	Psaraftis and Kontovas (2010)	Psaraftis and Kontovas (2014)	Qi and Song (2012)	Ronen (1982)
Optimization criterion	Cost	Time	Cost	Cost	Cost	Fuel consumption	Profit
Shipping market	Tramp	General	Tramp	General	General	liner	Tramp
Decision maker	Owner	Ship's master	Charterer	Charterer	Charterer	Owner	Owner
Fuel price an explicit input	Yes	No	Yes	No	Yes	No	Yes
Freight rate an input	No	No	Input	Input	Input	No	Input
Fuel consumption function	General	N/A	Cubic	General	General	cubic	Cubic
Optimal speeds in various legs	Yes	N/A	Yes	No	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	Yes	No	Yes	No	No
Logistical context	Fleet deployment	Weather routing	Fixed route	Fixed route	Fixed or flexible route	Scheduling	Fixed route
Size of fleet	Multiple ships	One ship	Multiple ships	Multiple ships	One ship	Multiple ships	One ship
Add more ships an option	No	No	Yes	Yes	No	No	No
Inventory costs included	Yes	No	Yes	Yes	Yes	No	No
Emissions considered	No	No	Yes	No	Yes	Yes	No
Modal split considered	No	No	No	Yes	No	No	No
Ports included	Yes	Yes	No	No	No	Yes	Yes

Taxonomy part VII

Taxonomy parameter\paper	Ronen (2011)	Stopford (2009)	Wang and Meng (2012a)	Wang and Meng (2012b)	Wang and Meng (2012c)	Wang et al. (2014)	Yao, Ng, and Lee (2012)
Optimization criterion	Cost	Profit	Cost	Total cost and fuel cost	Cost	Cost	Fuel cost
Shipping market	Container	General	Container	Liner	Liner	Container	Container
Decision maker	Owner	Owner	Owner	Owner	Owner	Owner	Owner
Fuel price an explicit input	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Freight rate an input	No	Input/ computed	No	No	No	No	No
Fuel consumption function	Cubic	Cubic	linearized	cubic	linearized	General	cubic
Optimal speeds in various legs	No	No	Yes	Yes	Yes	Yes	Yes
Optimal speeds as function of payload	No	No	No	No	No	No	No
Logistical context	Fixed route	Fixed route	Scheduling	Scheduling	Scheduling	Schedule design	Bunker fuel management
Size of fleet	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	Yes	No	No	No	No	No	No
Inventory costs included	No	Yes	No	No	No	Yes	No
Emissions considered	No	No	No	No	No	No	No
Modal split considered	No	No	No	No	No	No	No
Ports included	Yes	Yes	Yes	Yes	Yes	Yes	Yes

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