Chapter 11
Slow Steaming in Maritime Transportation: Fundamentals, Trade-offs, and Decision Models

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Abstract Slow steaming is being practised in many sectors of the shipping industry. It is induced principally by depressed shipping markets and/or high fuel prices. In recent years the environmental dimension of slow steaming has also become important, as ship emissions are directly proportional to fuel burned. The purpose of this chapter is to examine the practice of slow steaming from various angles. In that context, a taxonomy of models is presented, some fundamentals are outlined, the main trade-offs are analysed, and some decision models are presented. Some examples are finally presented so as to highlight the main issues that are at play.

11.1 Introduction

In recent times, increasing fuel prices and depressed market conditions have brought a new perspective to ship speed. For a variety of reasons, economic but also environmental, sailing at full speed may not necessarily be the best choice. In that sense, optimizing ship speed is receiving increased emphasis these days and is likely to do so in the years ahead.

Ships travel slower than the other transportation modes, but a basic premise has always been that there is value in ship speed. As long-distance trips may typically last one to two 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, this basic premise is being challenged whenever shipping markets are

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not very high and whenever fuel prices are not low. In addition, perhaps the most significant factor that is making a difference in recent years is the environmental one: a ship has to be environmentally friendly as regards air emissions. 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.

Even for the simple objective to reduce fuel costs (and by extension emissions) by reducing speed, this can be done at two levels. The first level is technological (strategic), that is, build future ships with reduced installed horsepower so that they cannot sail faster than a prescribed speed. However, the first cellular containerships that went up to 33 knots in the late 1960s when fuel was cheap are gone forever. Maersk's new 18,000 TEU 'Triple-E'[1] containerships have a design speed of 17.8 knots, down from the 22–25 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).

The second level is logistics-based (tactical/operational), that is, have an existing ship go 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[2]. 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 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 (Lloyd's 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 design speed of 16 knots was reduced to speeds 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

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[1] Triple-E stands for Economy of scale, Energy efficiency and Environmentally improved performance.

[2] Such a reconfiguration may involve dropping a cylinder from the main engine or other measures.

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 MTEU 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.

The purpose of this chapter is to examine the practice of slow steaming from various angles. In that context, some fundamentals are outlined, the main trade-offs are analysed, and some decision models are presented. Some examples are finally presented so as to highlight the main issues that are at play. Material in this chapter is mainly taken from various papers and other documents by the authors and their colleagues, including Gkonis and Psaraftis (2012), and Psaraftis and Kontovas (2013, 2014).

The rest of this chapter is organized as follows. Section 2 discusses a taxonomy of speed models. Section 3 presents the fundamentals of slow steaming. Section 4 discusses the impact of inventory costs. Section 5 summarizes results for VLCCs. Section 6 discusses the case of multiple optimal speeds. Section 7 discusses slow steaming vis a vis ports. Section 8 analyses combined speed and route models. Section 9 presents a case in which sailing the minimum distance route at minimum speed may not minimize fuel costs. Section 10 discusses policy implications. Last but not least, sect. 11 presents the chapter's conclusions.

11.2 Taxonomy of Speed Models

11.2.1 General

Determining the optimal speed of ships is not new in the literature. A first observation is that most of the models (at least implicitly) assume 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 in most instances and thus some of the models that optimize speed do not capture the trade-off between a higher speed to make more profit-earning trips per unit time and the impact of such higher speed on costs (mainly on fuel).

For problems in the liner market (served by containerships and ro/ro ships), a similar situation pertains. Ship owners who run liner services using their own ships want to maximize profits and the same trade-offs are at play. But also using chartered ships to provide liner services is not uncommon, as a liner company typically employs a mix of owned and chartered vessels.

For the so-called ‘industrial’ types of problems, in which a company (for instance, an oil company) uses its own ships to move its own cargoes, again the usual objective is cost minimization. What is not often mentioned however is that these companies always have the option to enter the market, by either offering excess capacity at the prevailing spot rate, or hiring extra capacity at such rate. Thus, in a boom period it may make sense for an oil company to run its ships at a higher speed, so as to offer the excess capacity obtained to the spot market. Of course, that this opportunity exists does not necessarily mean it will be used.

The other general observation is the scarcity of ‘dynamic’ speed models in the literature, even though a model that assumes no fixed cargo throughput within a certain time interval, but a rolling horizon in which costs or profits are optimized per unit time might want to consider ship speed as a key variable. However this is not necessarily the case: a recent paper that develops heuristics on dynamic ship routing and scheduling probems (Tirado et al. 2012) does not incorporate speed aspects. An exception concerns weather routing models, in which typically ship speed is dynamically updated.

There are many ways of classifying related papers and models in the literature. A first-order classification involves grouping references into two major categories:

a. Those that present models in which emissions are not considered, and
b. Those that present models in which emissions are considered (together with other considerations).

11.2.2 Non-emissions Speed Models

As expected, these are papers or other publications that chronologically constitute the oldest set of reviewed papers, in terms of average publication date, although some of them are relatively recent.

Alderton (1981) presents a variety of criteria to determine the speed that maximizes profit and discusses how sensitive these speeds are to such inputs as port time, voyage distance, freight rates and bunker costs. The influence of cargo inventory costs is also taken into account. He differentiates between what he terms "Least Cost Speed", the one that maximizes profit per tonne carried, and "Maximum Profit Speed", the one that maximizes profit per day.

Benford (1981) proposes a simple procedure to select the mix of available ships from a fleet and their speeds in order to achieve the best solution for a fleet owner. The approach is confined to non-liner trades (in fact his examples are from the coal trades in the Great Lakes). He assumes that the owner has only one contract, meaning that total revenues revenues are fixed, hence the objective is minimum cost.

Perakis (1985) relaxes some of Benford's fleet deployment model assumptions and arrives at an optimal solution that reduces by 15 % the operating costs vis-a-vis those of Benford's.

Ronen (1982) investigates the effect of oil prices on the optimal speed of ships and presents three models, namely for the ballast (or positioning) leg, the income generating (or laden) leg and a variant of the laden case for which a penalty/bonus is given for late/early arrival. He analyzes the tradeoff between fuel savings through slow steaming and loss of revenues due to the increase of voyage time.

Perakis and Papadakis (1987a, b) deal with fleet deployment and the optimal speed for ships operating between a single loading port and a single discharging port. In that problem laden and ballast speeds for each ship are treated as the decision variables. In their second paper a sensitivity analysis of the optimal solution is performed and for the longer term problem, a time-dependent cost function and probabilistic analysis is used.

An expanded model to address a set of loading and unloading ports is presented in Papadakis and Perakis (1989) under the same assumption as in their previous work that each ship returns to the loading port in ballast. The same authors address a weather routing problem in which the objective is to minimize transit time and in which using control theory it is proven that the maximum permissible speed is the optimal speed (Perakis and Papadakis 1989).

Another weather routing problem is examined in Lo and McCord (1998), who present a fuel consumption minimization approach that addresses the uncertainty that results from the time lags between the time to collect and process raw data on ocean currents and the delivery of the estimation. They formulate the routing problem as an adaptive, probabilistic dynamic program.

Brown et al. (1987) study a crude oil tanker routing and scheduling problem that takes into account cost components and generate feasible ship schedules with different speeds and alternate routes of the ballast legs. For the laden condition, speed is not a decision variable since it is implicitly determined by the given loading and discharging dates.

Perakis and Jaramillo (1991) develop a more complex fleet deployment model for the liner trades. The objective is to minimize costs. A linear programming formulation is developed and the speed problem is decomposed from the deployment problem.

The option to charter in additional vessels is also considered and the model includes port, canal and lay up costs.

Bausch et al. (1998) develop a spreadsheet-based interface for scheduling the fleet of tankers and barges. Embedded is a set partitioning model that optimizes cost. The model is used by dispatchers whose native language is not English but who communicate with one another via the model interface.

Fagerholt (2001) considers a flexible situation in determining the optimal speeds on the various legs of the schedule. This is the so-called ‘soft- time window’ case, in which penalties are imposed if the vessel arrives at a port outside a specified time window. It is motivated by the fact that allowing some customers to have controlled time violations for both loading and unloading of cargo it may be possible to obtain better schedules and high reductions in shipping costs.

An extensive discussion of the various aspects of speed in maritime transportation from various angles is in Stopford (2004), which is the well known seminal book on maritime economics. The basic model assumes a cubic speed function, although it is stated that other exponents may be applicable.

Alvarez (2009) presents a mixed integer programming (MIP) formulation for the joint optimization of routing and fleet deployment of container vessels. Speed is considered as a variable so that the sailing time between any two ports is assumed to be deterministic and the time in port is fixed for each port-ship combination. The model minimizes the operating expenses of a liner company over a tactical planning horizon and the algorithm includes the possibility of rejecting transportation demand on a selective basis, with lost revenue and some monetary penalty.

Notteboom and Vernimmen (2010) deal with the impact of high fuel costs on the design of liner services on the Europe–Far East trade and discuss the way that shipping lines have adapted their schedules in terms of speed and number of vessels deployed for each loop. Furthermore, a cost model is developed to estimate the impact of the additional bunker cost on the operational costs and cost comparisons for different vessel sizes and vessels speeds are presented.

Lang and Veenstra (2010) study the problem of container vessel arrival planning and in that context assume a linearized speed model in which fuel cost is to be minimized. Linearization takes place for computational purposes. Even though fuel price is not an explicit input, results are presented under high and low fuel price regimes, the price difference between these two scenarios being 35 %.

None of the surveyed models attempts to estimate the equilibrium spot rate that would be established as a function of the fuel price and the optimal speed that ships would choose as a result. Devanney (2010) presents such an approach for VLCCs, by looking at the interaction of the VLCC fleet supply and demand curves.

A more general model is presented in Devanney (2007), which models the world’s petroleum transportation network as a linear program, and simultaneously determines tanker optimal speeds in the laden and ballast legs, FOB and CIF prices of crude oil at origin and destination points, and the market equilibrium spot rates in various routes. The related software (termed Martinet) is only commercially available.

Norstad et al. (2011) present the tramp ship routing and scheduling problem with speed optimization, where speed is introduced as a decision variable. Although the main objective is to maximize profit by allowing the option of picking up spot cargoes, for the speed optimization subproblem the objective is to minimize costs on a certain leg of the route. The paper presents search heuristics to solve this problem and propose alternative algorithms. Various comparisons are also provided.

Ronen (2011) studies the effect of oil price on the trade-off between reducing sailing speed and increasing the fleet size for container ships and develops a procedure to indentify the sailing speed and number of vessels that minimize annual operating costs.

Meng and Wang (2011) proposes an optimal operating strategy problem arising in liner shipping industry that aims to determine service frequency, containership fleet deployment plan, and sailing speed for a long-haul liner service route. The problem is formulated as a mixed-integer nonlinear programming model and solved using an efficient and exact branch-and-bound based e-optimal algorithm. A case study based on an existing long-haul liner service route with fixed service frequency and fixed ship type is presented and the results for the optimisation in ship number and sailing speed are compared with Ronen (2011) and Gelareh and Meng (2010).

Wang and Meng (2012a) investigate the optimal speed of a fleet of container ships on each leg of each ship route in a liner network using a mixed-integer nonlinear programming model while considering transshipment and container routing. Their model uses a power bunker consumption function which is calibrated using historical operating data from a global liner shipping company.

Wang and Meng (2012b) develop and solve a model for a proposed liner ship route schedule design problem with sea contingency and uncertain port time in order to minimize the ship cost and bunker cost, while fulfilling the port-to-port transit time constraints. For each leg of each ship route they solve the optimal sailing speed problem in order to identify the optimal bunker consumption function as a function of the available sailing time t. Then they solve the schedule design problem by determining the arrival time and the number of vessels for each route by minimizing the sum of ship cost and the expected total bunker cost while satisfying the transit time constraints. However, late arrival at a port is not allowed in their model.

Thus, Wang and Meng (2012c) present a robust schedule design problem which takes into account the penalty for late arrival or late container handling as a result from uncertain port time. The problem is formulated using a mixed-integer nonlinear stochastic programming model and solved using an algorithm that incorporates a sample average approximation method, linearization techniques, and a decomposition scheme. In addition, numerical results based on an Asia–America–Europe ship route are presented to demonstrate that the algorithm obtains near-optimal solutions.

Yao et al. (2012) perform a study on bunker fuel management for container trades in which ship speed and fuel purchase location are the main decision variables. Minimization of total bunker costs is the objective function.

Even though the above models do not consider emissions, possible extensions could examine what would happen if the social cost of emissions (and essentially CO_2) is incorporated into the cost functions assumed by these models. Doing so would internalize the external cost of these emissions, a central (although seldomly applied) environmental policy goal.

11.2.3 Emissions Speed Models

Speed models that also consider emissions in a logistical context are on the average more recent.

Psaraftis and Kontovas (2009a) investigate the simple scenario where a fleet of identical ships, each of which loads from a port A, travels to port B with a known speed, discharges at B and goes back to port A in ballast, with a known speed. A result of the analysis is that total emissions would be always reduced by slowing down, even though more ships would be used. Another result is that if speed is reduced in a Sulphur Emissions Controlled Area (SECA) in order to reduce SO_x emissions and this is compensated by a speed increase outside the SECA so that total transit time is the same, overall emissions increase.

Corbett et al (2010) develop equations relating speed, energy consumption, and total cost to evaluate the impact of speed reduction on emissions. They also explore the relationship between fuel price and optimal speed.

Du et al (2011) use a speed model in the context of a berth allocation problem, in which they assume that the ship operator acts so as to minimize per route leg fuel consumption. A non-linear and not necessarily cubic fuel consumption function is obtained by regression analysis. The regression coefficients are obtained from data provided by a major marine engine manufacturer. Wang et al (2013) improve this model so that general fuel consumption functions can be handled more tractably.

Eefsen and Cerup-Simonsen (2010) examine the tradeoffs between lower fuel costs and higher inventory costs associated with speed reduction, as well as their impact on emissions. The model was used to investigate the transport costs and carbon emissions on a particular container route from China to Europe on a 6,600 TEU containership.

Faber et al (2010) estimate that emissions of bulkers, tankers and container vessels can be reduced maximally by about 30 % in the coming years by using the current oversupply to reduce speed, relative to the situation in 2007.

Fagerholt et al. (2010) consider a single route speed optimization problem with time windows and proposed a solution methodology in which the arrival times are discretized and the solution is based on the shortest path of the directed acyclic graph that is formed. Reduction in ship emissions are also computed. For the same problem, and drawing also from the results of Norstad et al (2011), Hvattum et al (2012) show that if fuel cost is a convex function of vessel speed, optimal speeds can be found in quadratic time.

Qi and Song (2012) investigate the problem of designing an optimal vessel schedule in the liner shipping route to minimize the total expected fuel consumption (hence also emissions) considering uncertain port times and frequency requirements on the liner schedule. The general optimal scheduling problem is formulated and tackled by simulation-based stochastic approximation methods.

Cariou (2011) investigates slow steaming strategies especially in container shipping and measures the reduction of CO_2 achieved in various container trades. In addition, the paper concludes that for the main trades speed reduction is cost beneficial when bunker price is at least $ 350–$400 per tonne.

Kontovas and Psaraftis (2011) examine speed reduction as an operational measure to reduce fuel consumption with a focus on container vessels. Since time at sea increases with slow steaming, there is a parallel and strong interest to investigate possible ways to decrease time in port. To that effect, a related berthing policy was investigated as a measure to reduce waiting time.

Another aspect of the problem is studied in Psaraftis and Kontovas (2010), where the impact of speed reduction on modal split is investigated, in the sense that cargoes that go slower may choose alternative modes of transport, particularly if their inventory costs are high. This may be true not only for short sea trades, but for longer haul ones, for example using the Trans-siberian railway to move cargoes to or from the Far East. Multinomial logit models are introduced.

Lindstad et al (2011) present an analysis at the strategic level. They investigate the impact of lower speeds on the cost and emissions of the world fleet and argue that there is a significant potential for the reduction of GHGs if speed is reduced. They explore Pareto-optimal policies and recommend speed limits as a possible way to achieve speed reduction.

An opposing view is presented by Cariou and Cheaitou (2012), who 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 latter measure is counterproductive for two reasons. First, 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. Second, because it is sub-optimal compared to results obtained if an international bunker-levy were to be implemented.

Gkonis and Psaraftis (2012) develop a series of models that optimize speed in both the laden and ballast legs for several tanker categories (VLCC—ULCC, Suezmax, Aframax, product tankers, LNG and LPG carriers) and for a variety of scenarios. The modeling approach consists of two steps. The first step performs a speed optimization for both laden and ballast sailing. This is carried out over certain defined routes and for a certain ship. The second step calculates the annual emissions for the global tanker fleet, broken down into size brackets. The data used is based on actual speed-consumption curves, rather than theoretical or modelling approximations. The impacts of inventory costs, bunker costs, freight rates and other parameters on optimal speeds and emissions are estimated.

Fagerholt and Ronen (2013) develop speed models for a mixed chartering scenario, in which a fleet of ships have the obligation to carry some ‘mandatory’ cargoes under a contract of affreightment scenario, but also have the option to add ‘optional’ cargoes on a spot charter basis. Maximizing profit is the objective.

Last but not least, Psaraftis and Kontovas (2014) clarify some important issues as regards ship speed optimization at the operational level and develop models that optimize ship speed for a spectrum of routing scenarios in a single ship setting. The paper’s main contribution is the incorporation of those fundamental parameters and other considerations that weigh heavily in a ship owner’s or charterer’s speed decision and in his routing decision, wherever relevant. Various examples are given so as to illustrate the properties of the optimal solution and the various trade-offs that are involved.

11.2.4 Taxonomy

A finer-grain taxonomy classifies the literature of the previous two sections according to the following parameters (see also Psaraftis and Kontovas (2013)):

Optimization Criterion The main variants here are cost (to be minimized) and profit (to be maximized). Other variants include fuel consumption, transit time, or others. To be sure, some models in the literature are not cast as optimization problems. In these papers we set 'cost', 'profit', or other, depending on what the model described by the paper tries to measure.

What is the Shipping Market/Context of the Problem? This may be tankers, bulk carriers, containerships, or other ship types. It may even involve the whole commercial fleet.

Who is the Decision Maker? By this we mean who decides what the ship speed should be. This can be the ship owner or the charterer. For weather routing problems, it is typically the ship's master. An attempt to designate who is the decision maker is made even if the model is not an optimization model.

Fuel Price an Explicit Input? Yes if fuel price is explicitly included as one of the explicit inputs of the problem, no otherwise.

Freight rate an Input? Yes if freight rate (spot, or other) is explicitly included as one of the explicit inputs of the problem, no otherwise. There are also models that compute that rate as an equilibrium rate depending on supply and demand.

Fuel Consumption Function It could be cubic, non-linear, linearized, general or unspecified.

Optimal Speeds in Various Legs Whether or not the model computes optimal speeds for each leg of the route (versus a single optimal speed).

Optimal Speed as Function of Payload Whether or not the model can compute the optimal speed as a function of how much full or empty the ship is.

Logistical Context This could be a fixed route scenario, a ship routing and scheduling problem, a fleet deployment problem, or other.

Size of Fleet One ship, or many ships.

Adding more Ships an Option This is so if adding (or subtracting) ships is an option so as to maintain constant throughput.

Inventory Costs Included Yes if cargo carrying (inventory) costs are included in the model, no otherwise.

Emissions Considered Yes or no.

Modal Split Considered Yes if model calculates the split among alternative and competing modes of transport as a function of problem inputs.

Ports Included in Formulation Yes if port times, costs, congestion, port emissions or other port-related variables are included in the model.

The full taxonomy is presented in Psaraftis and Kontovas (2013). A sample table is presented in Table 11.1 below.

11.3 Slow Steaming Fundamentals

We now come to presenting what in our opinion are the fundamentals in slow steaming.

11.3.1 Is ship Speed Fixed?

The first fundamental is something that many papers in the literature seem to ignore: ships do not trade at predetermined speeds. Those who pay for the fuel, that is, a ship owner whose ship trades on the spot market, or a charterer if the ship is on time charter, may want to choose the ship speed as a function of (a) fuel price and (b) market spot rate. In periods of depressed market conditions, as is the typical situation these days, 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 case that the ship owner or the charterer can freely choose an optimal speed for the ship is in case the ship is *on spot charter* and speed is prescribed in the charter party contract, either explicitly (speed is, say, 15 knots) or implicitly (pickup and delivery dates are prescribed). In spot charters (rental of the ship for a single voyage) 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 spot rate, understanding of course that in this case he may lose the customer to a competitor ship, with which 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).

11.3.2 Who is the Speed Optimizer?

The second fundamental is perhaps not immediately obvious. This is that even though the owner's and time charterer's speed optimization problems appear at first glance different, the optimal ship speed for both problems turns out to be the same. A proof

Table 11.1 Taxonomy—a sample table. Source: Psaraftis and Kontovas (2013)

Taxonomy parameter paper	Fagerholt (2001)	Kontovas and Psaraftis (2011)	Lindstad et al. (2011)	Notteboom Vernimmen (2013)	Ronen (2010)
Optimization criterion	Cost	Cost	Pareto analysis	Cost	Cost
Shipping market	General	Container	All major ship types	Container	Container
Decision maker	Owner	Charterer	Owner	Owner	Owner
Fuel price an explicit input	No	Yes	Yes	Yes	Yes
Freight rate an input	No	Input	No	No	No
Fuel consumption function	Cubic	Cubic	Cubic	Unspecified	Cubic
Optimal speeds in various legs	Yes	Yes	No	No	No
Optimal speeds as function of payload	No	Yes	Yes	No	No
Logistical context	Pickup and delivery	Fixed route	Fixed route	Fixed route	Fixed route
Size of fleet	One ship	Multiple ships	Multiple ships	Multiple ships	Multiple ships
Add more ships an option	No	Yes	Yes	Yes	Yes
Inventory costs included	No	Yes	Yes	No	No
Emissions considered	No	Yes	Yes	No	No
Modal split considered	No	No	No	No	No
Ports included	No	Yes	Yes	Yes	Yes

is in Devanney (2010) for a rudimentary scenario of a ship hauling cargo from port 1 to port 2 and returning to port 1 on ballast (empty), and goes roughly as follows.

For a given ship, a ship owner in the spot market should operate at a speed that maximizes profit per day. Then his speed optimization problem is the following:

$$\max_v \{sC/(d/v) - pf(v) - E\} \tag{11.1}$$

where

s is the spot rate received by the owner (in \$/tonne)
C is the ship's cargo capacity (in tonnes)
d is the roundtrip distance (in nautical miles)

v is the sailing speed in nautical miles per day[3]
p is the bunker price (in \$/tonne)
f(v) is the daily fuel consumption function at speed v (t/day) and
E are the operating expenses borne by the ship owner other than fuel costs, including crew wages, insurance, etc (in \$/day).

In the above scenario, time in port has been ignored, although including it is a straightforward extension. Also the function f(v) is assumed to be the same in both directions (laden and ballast), although having different functions and different speeds on each leg is also a straightforward extension.

For a time charterer who has chartered the same ship, and who is the effective owner of the vessel during the period of the contract (also known in shipping parlance as the "disponent owner") faces the following problem:

$$\min_v \{s[R - Cv/d] + pf(v) + T\} \tag{11.2}$$

where

R is how much cargo needs to be moved (t/day)
T is the time charter rate paid to the owner (\$/day)

Equation (11.2) above assumes that any difference between the cargo capacity required by the time charterer (R) and what the chartered ship can provide if sailing at speed v (Cv/d) can be chartered in the spot market at a spot rate of s. If the difference [R-Cv/d] is positive (meaning that the chartered ship sailing at speed v cannot fully satisfy the charterer's needs), then additional capacity is chartered in at a rate of s, assuming the spot chartered ship sailing at the same speed v. If this difference is negative (meaning that there is spare capacity in the time chartered ship), then that spare capacity can be chartered out at the same spot rate s.

It can be seen easily that problems (11.1) and (11.2) are mathematically equivalent. In fact, in (11.1) the term E does not depend on speed and can be discarded from the objective function, leading to

$$\max_v \{sC/(d/v) - pf(v)\} \tag{11.3}$$

In (11.2), one can separate the term (sR + T) which does not depend on speed and thus can be discarded as well. What is then left is

$$\min_v \{pf(v) - sCv/d\} \tag{11.4}$$

Problems (11.3) and (11.4) are essentially the same, thus leading to the same optimal speed.

Factoring out the spot rate s, both problems can be rewritten as follows:

$$\min_v \{(p/s)f(v) - Cv/d\} \tag{11.5}$$

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[3] This is 24 times the speed in knots. We use this unit to avoid carrying the number 24 through the calculations.

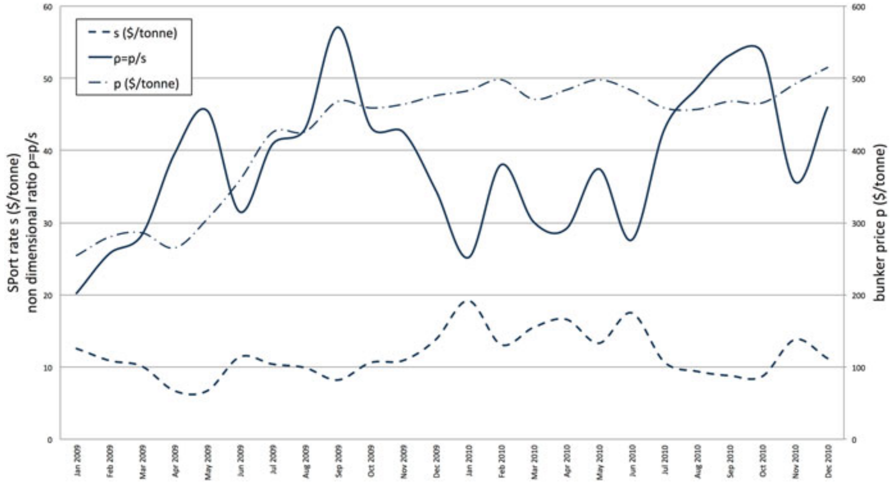

Fig. 11.1 Evolution of bunker price p, spot rate s and their ratio ρ = p/s. Data Source: Drewry Shipping Consultants

Equation (11.5) shows that for both problems, a key determinant parameter of the speed optimization problem is the *nondimensional ratio* ρ = p/s of the bunker price divided by the spot rate, since for a given ship and route the optimal speed will be the same as long as ρ remains constant. Higher ρ ratios will generally induce lower speeds than lower ρ 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.

Figure 11.1 shows a typical evolution of p, s and ρ for the tanker market. The period is 2009–2010, the route is Persian Gulf to Japan. HFO is the fuel and the fuel supplier is in the Persian Gulf.

11.3.3 Fuel Consumption Functions

The third fundamental of slow steaming is that fuel consumption (and hence fuel costs and emissions) depend non-linearly on ship sailing speed. The simplest model is to assume one type of fuel consumed on the ship, available at a known price of p (in $/tonne). Then the daily *at sea* fuel cost of a ship sailing from port i to port j is equal to $pf(v_{ij}, w_{ij})t_{ij}$, where $f(v_{ij}, w_{ij})$ is the ship's daily fuel consumption at sea (in t/day), a known function of the ship's speed v_{ij} and payload w_{ij} from i to j, and t_{ij} is the ship's sailing time from i to j, given by the ratio (d_{ij}/v_{ij}), sailing distance divided by speed. Function f depends on many ship parameters, such as type and size of power plant, including main and auxiliary engines, geometry of ship hull, propeller design, and other parameters (weather conditions for instance). It can even be defined for $w_{ij} = 0$ (ship going on ballast). *In port* fuel costs are proportional to overall total port residence time, and these depend on per day fuel consumption of the ship's auxiliary engines while in port. In case the ship uses different fuels for its main engine and auxiliary engines (for instance Heavy Fuel Oil-HFO and Marine Diesel Oil- MDO, respectively), total fuel cost is the summation of all relevant fuel types.

The fact that function f can be a complex function which may not even be defined in closed form does not prevent us from considering some modeling approximations. A usual approximation is that function f is equal to $A + Bv_{ij}^{n}$ with A, B and n input parameters such as $A \geq 0$, $B > 0$ and $n \geq 3$. Another approximation is that for a given speed, f is proportional to $(w_{ij} + L)^{2/3}$, where L is the weight of the ship if empty plus fuel on board and consumables (modified admiralty formula, see also Barass (2005)[4]. A combination of these two approximations can also be considered. Most papers in the literature assume a cubic function, that is, $A = 0$ and $n = 3$ and no dependency on payload. $n = 3$ is usually a good approximation for tankers and bulk carriers and for the range of typical operational speeds of these vessels. A basic drawback of a cubic function is that it is invalid for very low speeds. In fact this function gives zero fuel consumption at zero speed, which is not the case in practice, as a ship, even stationary, consumes some fuel. Another drawback of a cubic function is that it may not be a good approximation for some ship types, containerships being the most notable example. For these ships, exponent n can be 4 or 5 or conceivably even higher.

Figure 11.2 below shows two typical fuel consumption curves for a VLCC, one for the laden condition and one for the ballast condition. Consumption of auxiliary engines is included. The functions in the figure are general and based on real data. Notice also that the curves are not defined below some minimum speed levels (on which more later).

With the above fundamentals in mind, we next examine a basic side effect of slow steaming, the impact of in-transit inventory costs.

11.4 Impact of In-Transit Inventory Costs

Problem (11.2) of the previous section does not include the in-transit inventory costs of cargo, to be borne by the charterer and due to the fact that the cargo is in transit for d/2v days (again, d is the roundtrip distance and cargo travels only one way). These costs depend on transit time and hence on speed, a lower speed entailing higher such costs. If these costs are not already factored in the negotiated market spot rate s, they are equal to $\beta C/2$ (\$/day) if β is the per day and per tonne inventory cost of the cargo. The latter is equal to PR/365 if P is the CIF value of the cargo in \$/tonne and R is the charterer's cost of capital.

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[4] A first order approximation is that f does not take into account the reduction in the ship's total displacement due to fuel, lubricating oil or other consumables (such as fresh water) being consumed along the ship's route, since displacement would not change much as a result of that consumption.

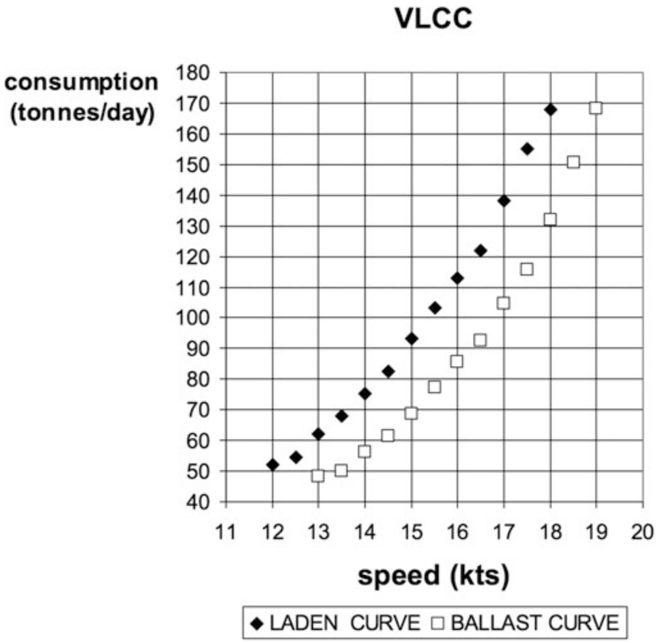

Fig. 11.2 Fuel consumption versus speed (in knots) for a VLCC. (Source: Gkonis and Psaraftis (2012))

Cargo inventory costs can be important, mainly in the liner business which involves trades of higher valued goods than 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/t for furniture and bedding to \$ 95,000/t for optic, photographic and medical instruments (CBO 2006). Delaying one tonne of the latter category of cargo by one week because of reduced speed would cost some \$ 91 if the cost of capital is 5 %. For a \$ 75,000/t payload this would amount to some \$ 6.8 million. This may or may not be greater than the reduction of cost due to reduced speed (see Kontovas and Psaraftis (2011) for some examples).

It is straightforward to check that if inventory costs are included, equation (11.4) can be modified by replacing the spot rate s by (s-βd/2v). This problem is tantamount to the owner's problem (11.3) if the spot rate s is replaced by (s-βd/2v), if in fact cargo inventory costs are not factored in when the ship owner negotiates the spot charter with the charterer.

We mention these rudimentary problems because many models that we have reviewed assume (explicitly or implicitly) a fixed revenue for the ship owner and hence ignore the first term in (11.3). This is typically the case for routing and scheduling models in which the set of cargoes is fixed. If the amount of cargo to be transported in a year or within a given time period is fixed, then the ship owner's revenue is also fixed and then obviously the speed optimization problem of the ship owner is a cost minimization problem, subject to the constraint that this fixed quantity of cargo should be hauled. However, a ship owner may like to take advantage of high spot rates by hauling as much cargo as possible within a given period of time. In that case, the set of cargoes is not fixed. Conversely, if the market is low, ships tend to slow steam, as the additional revenue from hauling more cargo is less than the additional cost of the fuel. Even a charterer or an industrial shipping company may conceivably want to take advantage of such opportunities. Not factoring in the state of the market in a speed model means that the model may not capture one of the fundamental facets of shipping industry behavior, according to which the state of the market, along with the price of fuel, are the two main determinants of the speed of vessels.

The above simple model can be extended to the case in which speeds are optimized separately for the laden and ballast legs of a route, assuming different fuel consumption functions for each leg, and port times and costs are included. Figure 11.3 shows how optimal speeds in the laden and ballast leg conditions may vary as a function of fuel price and market rate for a modern VLCC operating from the Persian Gulf to Japan. Spot rates are expressed in terms of World Scale (WS) equivalents[5]. In-transit inventory costs are being included as an option in Fig. 11.4.

One can observe that optimal ballast speeds are typically higher (by 1–1.5 knots) than optimal laden speeds, except if cargo inventory costs are accounted for, in which case laden speeds can be higher than ballast speeds (depending on fuel price). In practice however, many tankers sail faster on the laden leg than on the ballast leg, which is sub-optimal. The reason for this is more likely to be attributed to charter party speeds than inventory costs (Devanney 2011).

In an even more general case, in which the ship is intermediately full at each route leg (a typical situation with containerships), different speeds can be chosen for different legs of the route, so long as they are within a "speed window" $[v_{LB}(w_{ij}), v_{UB}(w_{ij})]$, where $v_{LB}(w_{ij})$and $v_{UB}(w_{ij})$ are lower and upper bounds (respectively) on ship speed if the ship's payload from i to j is w_{ij}. Typically both bounds are dictated by the maximum power and technology of the engine and by the ship's payload when sailing from i to j. Practically both speed bounds are decreasing functions of w_{ij} (a more heavily loaded ship is not able to run as fast as an emptier ship). The upper bound exists because of limits in the ship's power. The lower bound exists because it is simply impossible for a ship engine to run lower than a certain power, below which the engine simply stalls. For a given payload, modern, electronically controlled engines, possibly equipped with 'slow steaming kits', generally have a lower v_{LB} than older, mechanical camshaft engines. Weather also plays a role in both bounds, with a usual approximation involving a 'speed margin' for anything else than calm weather.

Other model formulations do not optimize on a per day basis, but in terms of total costs or profits for a prescribed set of cargoes, for instance on a fixed route scenario or even in a routing and scheduling problem for which the ship route needs to be optimized.

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[5] For a certain tanker route, WS is defined as 100 times the ratio of the prevailing spot rate on that route divided by the 'base rate' on that route (see Stopford (2004)).

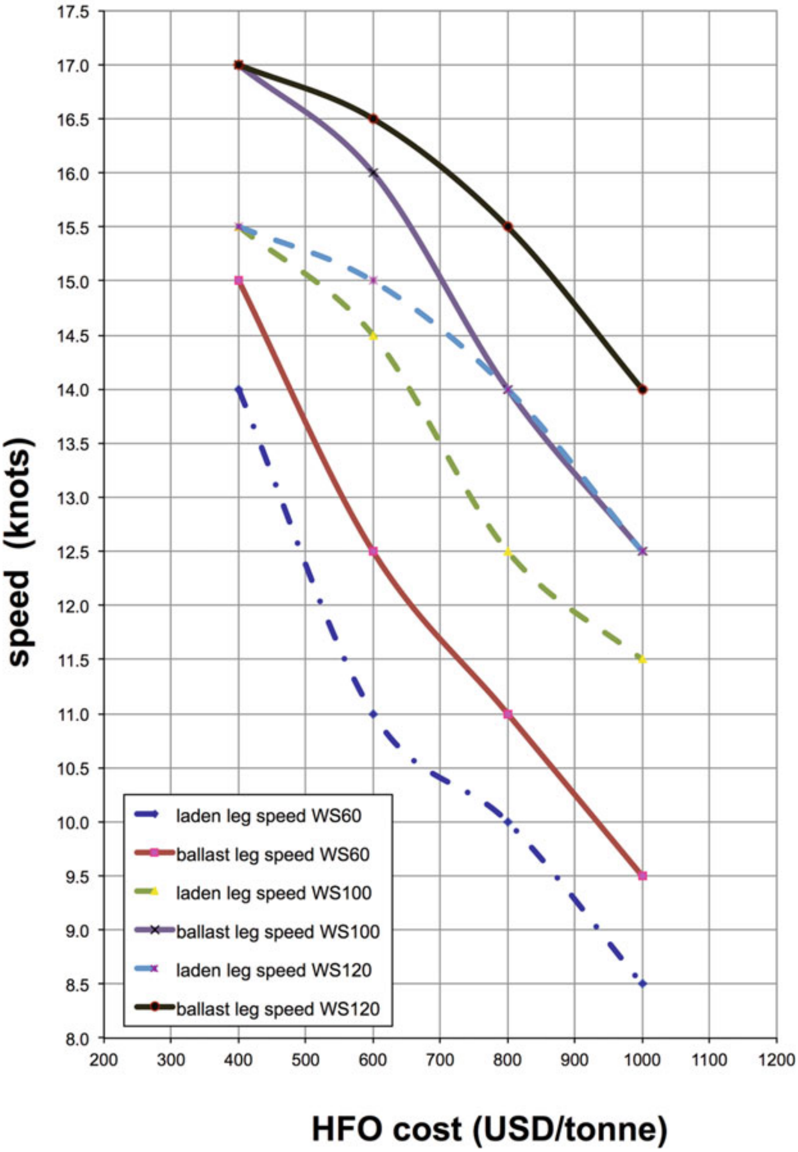

Fig. 11.3 Optimal VLCC laden and ballast speeds as functions of fuel price and spot rate. Spot rates are in WS. (Source: Gkonis and Psaraftis (2012))

Take for instance the case in which a ship on a fixed route wants to minimize costs over a specific route leg of length d. If v is the ship speed (miles per day), w is the ship payload during the leg (tonnes), p is the fuel price ($/tonne), f(v, w) is the fuel consumption function (t/day), T is the time charter rate the charterer is paying ($/day),

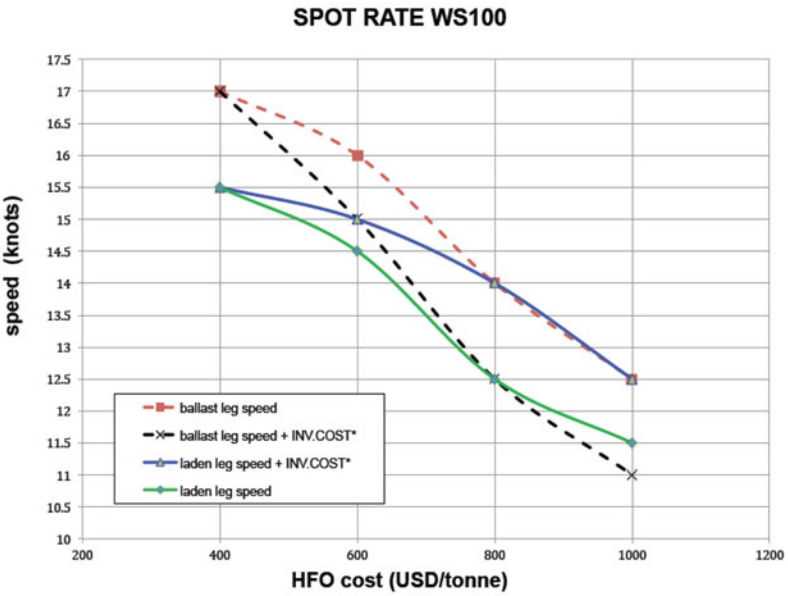

Fig. 11.4 Optimal VLCC laden and ballast speeds with and without inventory costs. (Source: Gkonis and Psaraftis (2012))

β is the inventory cost of the cargo (\$/tonne/day), and $V = \{v: v_{LB}(w) \le v \le v_{UB}(w)\}$ is the set of allowable speeds, then the speed optimization problem for the charterer (who is the party paying for the fuel) for the specific leg is

$$\min_{v \in V} \{[pf(v, w) + \beta w + T](d/v)\}$$

As d is constant, this problem reduces to

$$\min_{v \in V}\{[pf(v, w) + \beta w \ + T]d/v\}$$

If function f is general (for instance given as a pointwise function), this problem can be solved by complete enumeration over all feasible values of v. If function f is given by a mathematical expression (cubic or other), more can be said.

Assuming for instance that $f(v, w) = (A + Bv^n)(w + L)^{2/3}$, the problem's objective function becomes

$$\{[pf(v, w) + \beta w + T\,]/v\}=\{[\,p(A + Bv^n)(w + L)^{2/3} + \beta w + T]/v\} = K/v + Mv^{n-1} \tag{11.6}$$

with $K = pA(w + L)^{2/3} + \beta w + T$

and $M = pB(w + L)^{2/3}$

Define v* the speed that makes the 1st derivative of expression (11.8) with respect to v equal to zero.

Then $v^* = \{K/[M(n-1)]\}^{1/n}$
If U is the optimal speed, then
If $v^* \le v_{LB}(w)$, $U = v_{LB}(w)$
If $v_{LB}(w) \le v^* \le v_{UB}(w)\}$, $U = v^*$
If $v_{UB}(w) \le v^*$, $U = v_{UB}(w)$

Even though this is a different model than the previous one, here too it can be seen that the higher the freight rate T, the lower the fuel price p, and the higher the value of the cargo (and hence β), the higher is the optimal speed U. This would seem to fit the pattern observed in many container trades. For instance, in the Far East to Europe trunk route, the busiest in the world, freight rates and average value of cargo are about double in the westbound direction than in the eastbound direction. This is reflected in the operational speeds, as most of slow steaming can be observed eastbound (Journal of Commerce 2010).

11.5 Speed Models for VLCCs

Reference was made in the previous section to the work of Gkonis and Psaraftis (2012), in which speed models were developed for several tanker classes, including Very Large Crude Carriers (VLCCs). These models pertain to both the single ship scenario and the fleet segment scenario. In this section we describe these models in more detail.

11.5.1 The Single Tanker Tool

The objective of this tool is the speed optimization for a known single crude oil tanker over a defined route. This follows the rationale outlined below:

- Typical route(s) per tanker segment are considered, where a typical size ship operates and to which some "average characteristics" are attributed
- The tool is run for the considered route and associated typical ship, under the defined assumptions and scenario (e.g. regarding freight rate levels & bunker prices)
- Output of the tool is the set of laden and ballast leg speeds for the considered route and associated typical ship, and also several emissions statistics.

The model is established in Microsoft Excel^{TM} and structurally consists of a number of main sections or "sheets", see Fig. 11.5.

A variety of runs and sensitivity analyses have been made, see Gkonis and Psaraftis (2012) for more details.

Figure 11.6 below 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, the emissions decrease, as they are proportional to fuel consumption.

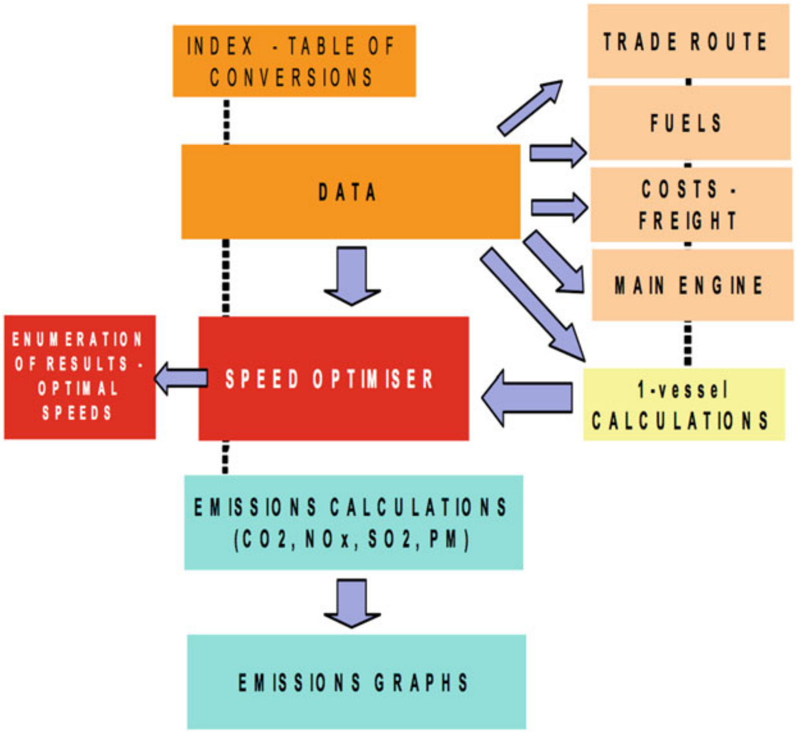

Fig. 11.5 Single tankers speed optimization tool structure. (Source: Gkonis and Psaraftis (2012))

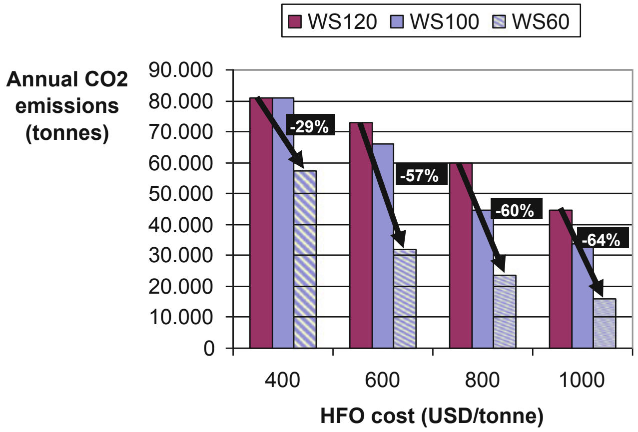

Fig. 11.6 Reduction in annual CO_2 emissions (single VLCC tanker) for a 50 % reduction in freight rates. (Source: Gkonis and Psaraftis (2012))

11.5.2 The Fleet Segment Tool

This tool has as main objective the calculation of emissions for the global fleet of the tanker segment in question (VLCC in our case). By fleet segment we mean the collection of ships that can be characterized as VLCCs, that is, tankers of 200,000 DWT and above. There were 525 such ships in the Lloyd's SeaWeb database in 2010. The tool works as follows.

- For the tanker segment in question, the "tanker segment emissions calculator" tool is run. This is a modified version of the single ship model, so that it does not refer to a specific route, but having as a constraint the annual tonne*miles throughput of a fleet of the typical ship considered.
- The laden & ballast leg speed input is taken from the single ship model.
- The output is annual emissions and operational characteristics (e.g. fuel consumption, operational days) for the tanker segment in question.

This model structurally resembles the previous one, but it is simpler as it does not perform any sort of optimization, see Fig. 11.7. It basically calculates emissions and related indices for the VLCC fleet segment.

As with the single ship tool, a variety of runs has been carried out. One is shown in Fig. 11.8 below.

In the above figure, Case 1 involves speed optimization only in the ballast leg, with the laden leg speed in the neighborhood of the recorded average service speed and assumed fixed in the charter party agreement. In Case 2, both speeds are free to be optimized. In all cases, upper and lower bounds on speeds are applicable. It can be seen that taking on board inventory costs generally reduces emissions for Case 1 (or leaves them constant) and increases emissions for Case 2. In all cases, Case 1 emits more than Case 2, which is something to be expected.

11.6 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.

Assume a cargo ship of lightship weight equal to $A = 6$ and capacity equal to $Q = 12$ (in thousands of tonnes), whose 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 35 t/day. For simplicity also assume that the ship's maximum and minimum speeds are 16 and 9 knots respectively, and are independent of payload. Assume that P_{FUEL} = \$ 800/t and that $\beta = 0$.

Consider a fixed-route scenario in which the above ship visits, in this order, ports 1–6.

Assume the ship starts empty at port 1 and has to collect cargo shipments of sizes 3, 2, 2 and 5 (in thousand tonnes) at ports 2,3,4 and 5 respectively, and deliver all of

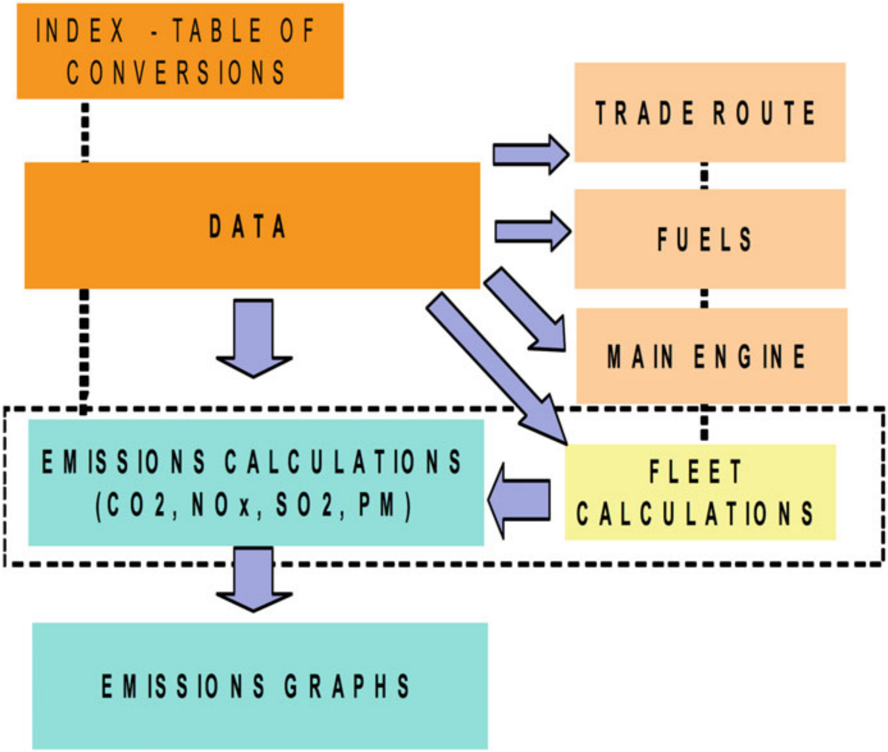

Fig. 11.7 "Fleet segment emissions calculator" tool structure. (Source: Gkonis and Psaraftis (2012))

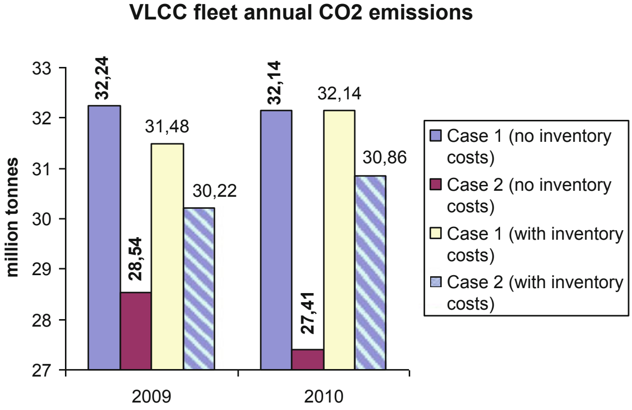

Fig. 11.8 VLCC fleet annual CO_2 emissions, with and without cargo inventory costs. (Source: Gkonis and Psaraftis (2012))

Table 11.2 Results of the variable speed per leg scenario

Leg	Distance (nm)	Speed (knots)	Fuel cost ($)	Charter cost ($)	Total cost ($)	Trip time (days)
1–2	400	13.17	9,494	18,989	28,483	1.27
2–3	150	12.03	3,896	7,792	11,688	0.52
3–4	200	11.51	5,432	10,863	16,295	0.72
4–5	250	11.09	7,046	14,093	21,139	0.94
5–6	300	10.31	9,090	18,179	27,269	1.21
TOTAL	1300	–	*34,958*	*69,916*	*104,874*	*4.66*

Table 11.3 Results of the fixed speed scenario

Leg	Distance (nm)	Speed (knots)	Fuel cost ($)	Charter cost ($)	Total cost ($)	Trip time (days)
1–2	400	11.541	7,296	21,661	28,957	1.44
2–3	150	11.541	3,585	8,123	11,708	0.54
3–4	200	11.541	5,465	10,830	16,295	0.72
4–5	250	11.541	7,636	13,538	21,174	0.90
5–6	300	11.541	11,383	16,245	27,628	1.08
TOTAL	1300	–	*35,365*	*70,397*	*105,762*	*4.69*

them to port 6. As before, assume that P_{FUEL} is $ 800/t, that F is $ 15,000/day and that port dwell times can be ignored.

Note that in this scenario, if the fuel consumption function is assumed independent of ship payload, the ship's optimal speed will 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. For the particular assumed fuel consumption function, the ship consumes about half the fuel in the ballast condition vis-a-vis that consumed in the fully laden condition if sailing at the same speed.

Table 11.2 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 11.541 knots. Table 11.3 shows detailed results of this scenario.

11.7 Slow Steaming and Ports

This section discusses the possible role of ports in slow steaming.

11.7.1 The Role of Ports in the Supply Chain

As mentioned earlier, speed reduction seems to be an easy fuel cost (and hence emission) reduction measure that can be implemented. A pertinent question is whether this is overall cost-effective or not. When talking about a single roundtrip, a delayed delivery of cargo will distort the current status-quo and may cause inventory costs to the shipper. In the case of containers and passenger vessels this may also lead to a modal shift (cargoes from sea to land) and may put the shipping company in an unfavorable competitive position. This is especially true for short sea shipping, but may also be true for longer distances, at least in principle. Although this may be far-fetched, one would not want to see, for instance, some cargoes from the Far East to Europe being shifted to rail, or (even worse) to road or air, as a result of a drastic speed reduction in the maritime mode. See Psaraftis and Kontovas (2010) for an example. Furthermore, to maintain constant annual throughput, in most of the cases, more ships will have to be used.

Psaraftis and Kontovas(2009b) investigated the simple scenario where a fleet of N identical ships (N: integer), each of capacity (payload) W loads from a port A (time in port $T_{A,}$, days), travels to port B with known speed V_1, discharges at B (time in port T_B, days) and goes back to port A in ballast, with speed V_2. The main result of the analysis was that total emissions would be always reduced by slowing down, even though more ships would be used. Psaraftis et al. (2009) focused on the case where total trip time was kept constant. Given the fact that time at sea increases with slow steaming, possible ways to decrease time in port were investigated. Emissions can be reduced even further if port time can be reduced so that there is no need for additional vessels. But this may be a more difficult proposition. For instance, in the example illustrated above, when speed is reduced by 5 %, time in port has to be reduced by 11 % to maintain a constant total trip time. If this sounds feasible, it is non-trivial nonetheless. For a speed reduction of 15 % the total time in port has to be reduced from 10.8 days down to 6.81, which is almost a 37 % reduction. This is a much more difficult proposition, possibly entailing drastic port re-engineering and/or infrastructure improvements. Obviously speed reductions of more than 5–10 % cannot be implemented without the need of adding more ships to maintain same service level.

Port time is only a small portion of the total turnaround time and reducing port time is not as easy as with time in sea. In the following section, a closer look at container terminal operations will be presented in order to identify areas that can be optimized so that we can easily implement speed reduction scenarios.

There has been tremendous growth in the worldwide container transshipment. Up to 2008, the top 10 container terminals in the world have shown an average relative increase of more than 10 % per year with respect to the total number of TEUs handled. However, in light of the severe negative ongoing economic crisis, the outlook for global container trade has darkened after mid 2008. The overall picture that emerges after the crisis is that while Asia continues to lead the global demand for container port services, growth is slowing.

While most of the top 10 ports experienced an increase in throughput during the last decade, there exists high competition among terminals even within the same geographical region, see for example the European ports of Antwerp, Rotterdam, Bremen and Hamburg and the Asian ports of Shanghai, Busan and Hong Kong. Seaports compete for ocean carrier patronage and feeders as well as land-based carriers (trucks and railways). According to Muller (1995) and Steenken et al. (2004), the most crucial competitive advantage of a terminal is the rapid turnover of container vessels, thus the key factors are low transshipment times combined with high rates for loading and unloading operations.

Usually container traffic networks overlay with each other and terminals can be part of more than one network. Containers can be transshipped between different modes of transport. Forwarding a container from a shipper to a recipient requires the use of one or more traffic networks and a transshipment of the container in a CT in the case where different transport vehicles are involved. The main purpose of seaport container terminals is to serve container vessels, put is simply, that is loading and unloading containers. Beside the large ocean-going container vessels, terminals also serve barges and feeder vessels. Barges are used for the container transport on inland waterways and feeder vessels connect ports with low transport volume or insufficient accessibility for large vessels to so-called hub ports.

According to Steenken et al. (2004) the four major areas of a seaport CT are:

Quay area for berthing container vessles

Transport area where internal transportation of containers takes place

Yard area where containers are transferred to and stored

Truck and train area for service the land-based vehicles

For more information on container terminal operations the reader is referred to Vis and de Koster (2003); Steenken et al.(2004) and Agerschou (1983, 2004), among others.

11.7.2 Bottlenecks in Container Operations

As discussed above, identifying ways to reduce time in port is crucial in order to be able to implement speed reduction measures that are necessary to reduce emissions. The tasks performed vis-a-vis the four major areas described above are definitely time consuming. In a liner service, vessels follow a predefined schedule that gives the order of ports to visit and the calling times. Which ports to connect on a route and how to design the liner network is part of the decision problem of the liner company. Furthermore, by deciding on the frequency of port calls within a schedule (e.g., on a weekly basis, or other) the number of vessels to deploy on a route is determined. More on this subject can be found in Agarwal and Ergun (2008); Notteboom and Vernimmen (2010); and Alvarez (2009) among others. A review of these problems is presented in Meng et al. (2013).

Assuming that the number of vessels deployed and the ports to be visited are known, the total time of the route can be estimated. Laine and Vepsalainen(1994)

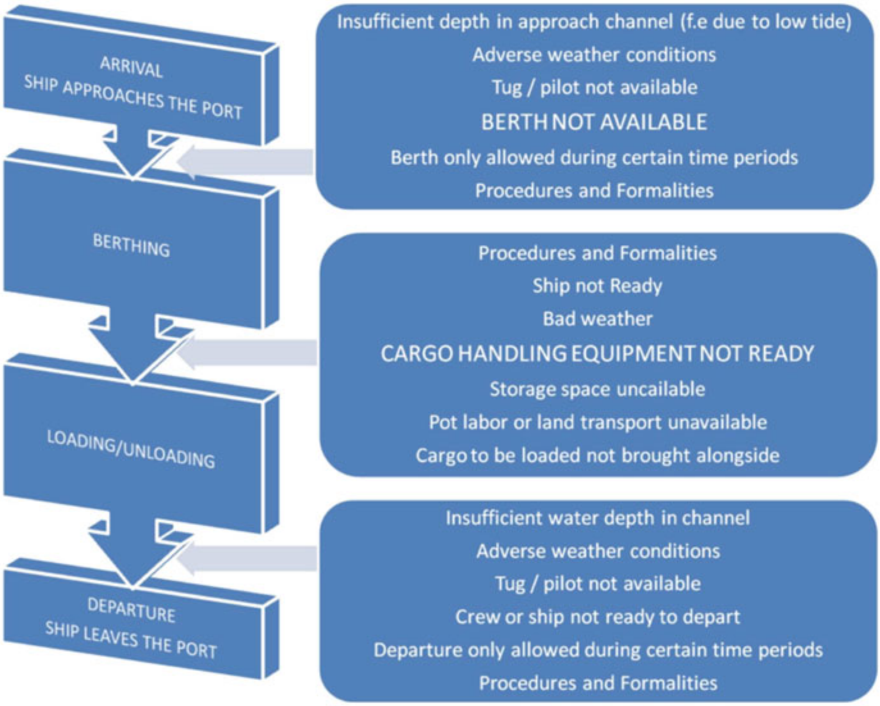

Fig. 11.9 Phases of operations and related problems

state that a high revenue can basically be obtained by an increase in the travel speed. However, they conclude that speed up of cargo handling seems to be more profitable compared to the increase in travel speed. Consequently, the performance of terminal operations is crucial for the profitability of liner services. This is in line with Notteboom (2006), who states that unexpected waiting times of vessels before berthing and unexpected low transshipment productivity at terminals are responsible for about 86 % of liner schedule disturbances.

In order to identify areas and operations that are time consuming, we shall graphically list the sequence of operations that usually take place from the time that a ship approaches a terminal until its departure. The list of procedures is mainly based on Agreschou (1981). There are four possible states for a vessel: arriving, berthing, loading and unloading and, finally, departing. When a vessel that carries cargo is approaching the port, she may berth immediately or wait for one of the reasons illustrated in Fig. 11.9, the most important of which is that the berth may not be available. After berthing, there are also several reasons that can prevent the immediate start of loading or unloading operations. One of them is related to the cargo handling equipment, which may be allocated elsewhere. Cargo handling equipment plays also an important role in the loading/unloading operation itself. Laine and Vepsalainen (1994) and Notteboom (2006) note that the most feasible way to reduce time in port is through operational decisions regarding quayside operations (berth allocation, quay cranes scheduling and vessel stowage).

11.7.3 The Time Factor in Port

Depending on the state of port congestion, the ship may or may not have to wait in an anchorage area outside the port, and the amount of total waiting time is t_W. After berthing, containers are unloaded/loaded from/onto the ship. Finally, when service is completed, the ship leaves the port. The amount of time that the vessels spends from berthing to departure is called service time (t_S).

According to Notteboom (2006), unexpected waiting times of vessels before berthing and unexpected low transshipment productivity at terminals are responsible for about 86 % of liner schedule disturbances. Furthermore, waiting time due to weather, procedure and formalities, canal transits etc will be assumed as constant before and after implementing a speed reduction measure and therefore they do not play any substantial role in the analysis.

We now perform a more detailed analysis of the total port time. In the scope of this work the main time components are the waiting time before berthing (t_w) and the service time (t_s). The average time that ships spend in port is defined as the sum of the average waiting time and average service time, i.e. $t_{ws} = t_w + t_s$.

First of all, the waiting time as seen by the view of port planners and constructors is analyzed. The occupancy rate of a group of berths expresses the percentage of time that berth positions are occupied by ships being serviced. The effect of berth occupancy on waiting time depends on the probability distributions of arrivals and of servicing times as well as on the number of berths available.

According to Tsinker (2004), the assumption that is usually made for container terminals is that the time intervals between successive vessel arrivals do not follow the negative exponential distribution applicable to general cargo terminals, but rather follow an Erlang distribution, with $K = 2$, because of the regularity of container ship arrivals. Furthermore, Agerschou (2004) states that arrival rates for container ports which are used by more than one shipping lines conform to Poisson distribution. He presents waiting time to service time ratios assuming $\mathrm{K} = 4$ and ∞ distributions for multi-user container terminal. The ratios are empirical values resulting from economic feasibility studies and are in general lower than those for general cargo ports due to the value of time for container ships. For example, for more than four berths the ratios for container terminals are 0.12 and 0.10 in the case of $\mathrm{K} = 4$ and $\mathrm{K} = 2\infty$ distributions respectively. Finally, Thoresen (2003) assumes a ratio of the average waiting time or congestion time to the average berth service rime of not higher than between 5–20 %.

On the other hand, Dragović et al. (2005) uses Queuing Theory (QT) models to analyse movements of ships in port. According to the authors and the studies that were analyzed the types ($\mathrm{M/M/n_b}$) and ($\mathrm{M/E_k/n_b}$) of queuing models were most practical to explain ship movements in port. Note that M denotes the Poisson distribution of arrivals. Furthermore, input data for both the simulation and analytical models were based on the actual ship arrivals at the Pusan East Container Terminal (PECT) for the six-month period from 6 September 2004 to 27 February 2005 -that is approximately 711 ship calls. The ships were categorized into the following three classes according to the number of lifts: under 500 lifts; 501–1000 lifts; and over 1000 lifts per ship. Ship arrival probabilities were as follows: 28.1 % for first class, 42.3 % for second and 29.6 % for third class of ships and an average ship arrival rate of $\lambda = 0.175$ ships/hour. The following table 11.4 presents the results of the work of Dragović et al. (2005) including the calculation of the waiting time to service time ratios for each ship category.

The above results are found to be in line with those of Agerschou (2004) and Thoresen (2003). Also, the berthing/unberthing time of ships was assumed to be one hour (Dragović et al. 2005). The total time at port is the sum of service time and waiting time plus this one hour. As a result, large container vessels (belonging to III class) spend at about 10 % of their total time in port waiting to occupy a berth. For all classes, the time waiting represents about 13 % of the total time in port.

11.7.4 Berthing Priority Policies: An Alternative Approach

Port managers in container terminals attempt to reduce costs by efficiently utilizing resources, including berths, yards, cranes, yard equipment and human personnel. Among all the resources, berths are the most important resources and good berth scheduling improves customers' satisfaction and increases port throughput, thus, leads to higher revenues. The usage of berths is scheduled by an intuitive trial-and-error method and varies from terminal to terminal.

The traditional birth allocation problems (BAP) focuses on the First-Come-First-Served (FCFC) policy. However, lately, many customers have contracts with the terminal operators that ensure them guaranteed berth-on-arrival (BOA) service—that is the actual berthing occurs within two hours of arrival. In this case, the objective of berth scheduling is to minimize the penalty cost resulting from delays in the departures of those vessels and the additional handling costs resulting from non-optimal locations of vessels. Carriers usually inform the terminal operator on the expected arrival time (ETA) and the requested departure time of vessels. Based on the information, the terminal operator tries to meet the requested departure time of all other vessels.

A related strategy is a policy in which a line could book a berthing time slot in advance and guaranteed service in that slot. In a seminal paper Psaraftis (1998) describes his experience from the real world when he was pulled out of the classroom and put in charge of the Piraeus Port Authority (PPA). Back in 1998, he proposed a scheduling berthing priority reform that he as a general manager of the port was thinking to implement. The original motivation was that this system would streamline utilization of cranes during peak periods and would effectively increase the capacity of the terminal. This scheme is referred to as "*Booking by rendez vous*".

Table 11.4 Average service and wait time ships—(Adopted from Dragović et al. 2005)

		(All classes)			(II class)			(III class)		
Results	ρ	t_s	t_w	*tw/ts*	t_s	t_w	*tw/ts*	t_s	t_w	*tw/ts*
Real data	0.643	15.200	2.443	0.161	13.550	2.470	0.182	22.990	2.451	0.107
Simulation	0.641	15.120	2.438	0.161	13.500	2.467	0.183	22.170	2.445	0.110
Analytical	0.720	16.080	3.211	0.200	13.210	3.306	0.250	21.920	5.033	0.230

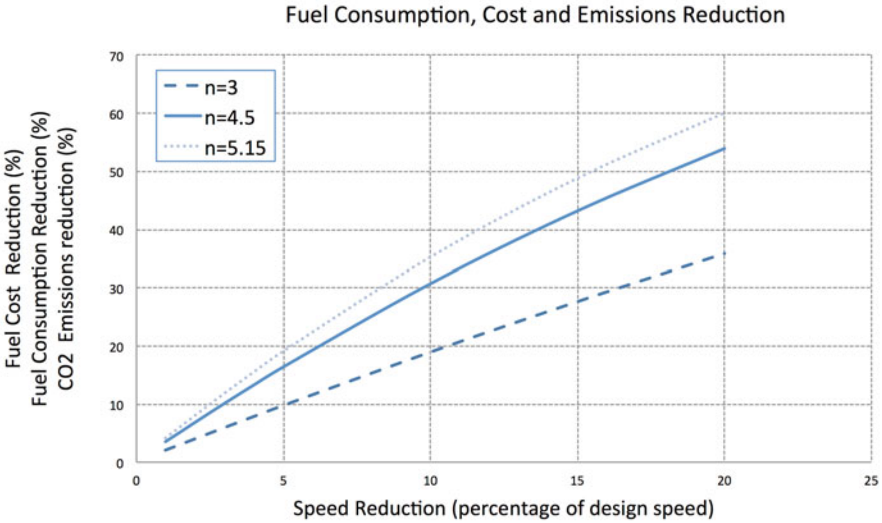

Fig. 11.10 Reduction percentage due to speed reduction

We present the following rudimentary example: A vessel employed in the Far East-Europe AE1 route served by CKYH, will decrease its speed in the Singapore-Rotterdam leg (that is the last asian port—first european port route). We also assume that the manoeuvering time and canal transit time (Suez) will be constant before and after the implementation of speed reduction[6].

The inputs are as follows:

Distance Singapore-Rotterdam: L = 8353 nm
Average Speed: Vo = 23 kn
Fuel consumption: at sea Fo = 150 t/day and in port f = 8.4 t/day and
Time in port of Rotterdam: to = 1.93 days

For reasons of simplicity we omit the detailed calculations and we illustrate the results in the following figures.

Figure 11.10 presents the percentage of reduction in fuel consumption and cost, and CO_2 emissions for the whole trip from Singapore to Rotterdam. As discussed in Sect. 3.2 the power requirement P is proportional to the speed V to the power of n. In the above figure the results are shown for $n = 3$ (cubic relation), $n = 4.5$ (according to MAN Diesel (2006)) and $n = 5.15$ as proposed by the regression analysis that we performed. In most of these cases, the implementation of speed reduction will lead in such an increase of total time that extra ships will be needed.

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[6] Ships transiting Suez are grouped in convoys that transit the canal every several hours, therefore in practice this assumption may not always be correct.

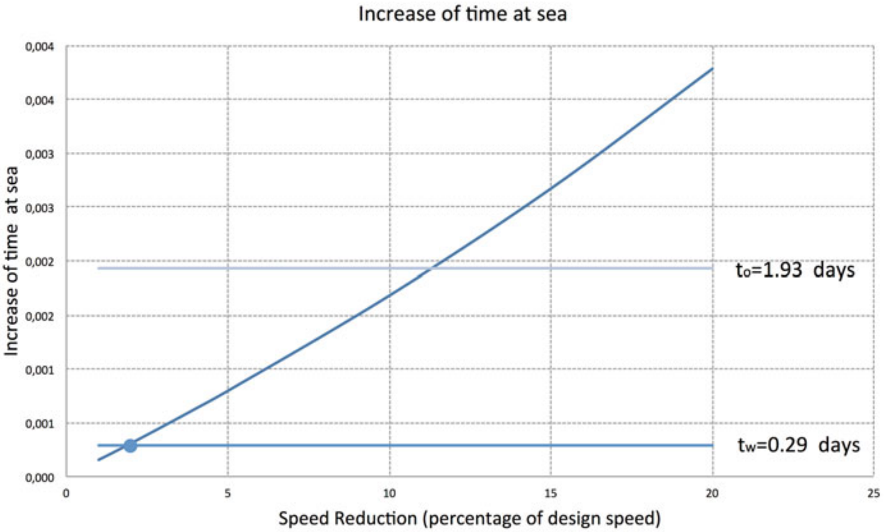

Fig. 11.11 Time implications of speed reduction

As discussed in the previous sections, a speed reduction will lead to an increase in the time at sea but some scenarios can be implemented without the need to add more ships to maintain the same throughput. The scenario of not adding extra vessels is the case when the total turnaround time can be kept constant. Here comes the role of the port in making this scenario feasible.

The waiting and service times for each port vary. For the sake of simplicity, suppose that in the same time we investigate the role of a single port in the route –that is of the first European destination, the Port of Rotterdam. We assume a port time (including service and waiting time) in the Port of Rotterdam equal to 1.93 days based on Notteboom and Vernimmen (2010). Optimizing the port operation in just this one port a speed reduction of 5 % sound realistic and can be implemented without the need to add extra ships.

Now, assume there is no congestion at the port and that service time is the same. By implementing a "booking by rendezvous" system, the vessel will berth as soon as it will arrive. No waiting time is equal to a reduction of 10–15 % of the total port time, that is $t_w = 0.193–0.29$ days (or about 4.6 to 7 h). In the best case scenario of the "booking by rendezvous" scheme, speed reductions of less than 2 % can be implemented without the need to add more ships (see Fig. 11.11). If this 2 % speed reduction sounds small, just imagine if we could introduce this scheme into every port. The potential savings in absolute numbers are great. Just a single figure: when fuel is expensive, let's say 600 $/t, a 5 % reduction saves a total of more than 200 thousand USD per route.

One initiative that is related to the scheme described above 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, see Kontovas and Psaraftis (2013) for more. This initiative recognises 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 mutually agreement by both the owner and charterer to agree a speed to meet the terminal booking that maximises fuel efficiency and minimises 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 split 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.

11.8 Combined Speed and Route Decisions

For pickup and delivery scenarios, the decomposition property of the optimal solution identified in sect. 4.1 is valid whatever the scenario and whetever algorithm is used to produce the ship's route, either exact or heuristic. Even if a heuristic algorithm is used, it would not make sense for the ship that sails a specific leg of the route to have an operating speed that is different from the optimal speed for that leg, as computed in sect. 4.1. A fortiori, the same is true if an exact algorithm is used.

An exact algorithm that can easily embed the above property, along with all other input parameters, and is flexible enough to allow for the spectrum of variants as regards the possible objective functions is one that is based on dynamic programming, and is a straightforward extension of the approach developed in Kontovas and Psaraftis (2011). That paper had assumed a general pick up and delivery setting with known and fixed arc traversal costs and times, zero dwell times and vehicle speed was not a decision variable. Further, there was no effect of F to be taken into account.

The approach goes as follows (see also Psaraftis and Kontovas (2014)).

Define the matrix $[k_{ij}]$ and optimal value function V as follows:

$$k_{ij} = \begin{cases} 3 \text{ if cargo from } i \text{ to } j \text{ has not been picked up yet} \\ 2 \text{ if cargo from } i \text{ to } j \text{ is on board the ship} \\ 1 \text{ if cargo from } i \text{ to } j \text{ has been delivered.} \end{cases}$$

$V(L, [k_{ij}])$ = Minimum possible total cost to complete the trip from port L to port 0, by executing all pending actions on pickup and delivery of the cargoes, choosing optimal speeds and observing capacity constraints, given that the current status of the cargoes is described by matrix $[k_{ij}]$.

Define M = large number.
For a specific state $(L, [k_{ij}])$, define set $R = \{(i, j) : \ i \neq j, \ k_{ij} \neq 1\}$
If $R = \emptyset$, then

$$V(L, [k_{ij}]) = s_{L0} \, \underset{v \in S}{min} \left\{ \frac{P_{FUEL} f(v, 0) + F}{v} \right\}$$

(boundary condition: ship returning to home port)

$$\text{If } R \neq \emptyset, \text{then} V\left(L, \left[k_{ij}\right]\right) = \begin{cases} M \quad if \ w > Q \\ \underset{(x,y)\hat{I}R}{\min} \left\{ s_{LL} C^* + \lambda d_{xy}(\alpha u + \beta w) + V\left(L', \left[k'_{ij}\right]\right) \right\} \\ otherwise \ (11.1) \end{cases} \tag{11.7}$$

where C^* is the optimal value of the optimization problem defined by

$$C^* = \underset{v \in S}{min} \left\{ \frac{P_{FUEL} f(v, w) + \alpha u + \beta w + F}{v} \right\}$$

with $S = \{v : v_{LB}(w) \leq v \leq v_{UB}(w)\}$
In the above recursion,

$$u = \sum_{(i,j):k_{ij}=3} d_{ij}$$

$$w = \sum_{(i,j):k_{ij}=2} d_{ij}$$

λd_{xy} is the port dwell time,
and for all pairs (i, j) with $i \neq j$, it is:

$$k'_{ij} = \begin{cases} k_{ij} - 1 \ if \ i = x \ and \ j = y \\ k_{ij} \quad otherwise \end{cases}$$

$$L' = \begin{cases} x \ if \ k_{xy} = 3 \\ y \ \ if \ k_{xy} = 2 \end{cases}$$

To solve the problem, the recursion is executed backwards, by lexicographic ordering of the state variable vector and solving by moving to lexicographically increasing states. An alternative is to solve the recursion stage by stage, by defining an appropriate stage variable m as follows:

Ship is at port 0 (start), $m = 0$
Ship is port 0 (end), $m = 2n(n - 1) + 1$
Ship is at any intermediate port, $m = 3n(n - 1) - \sum_{\text{(i,j): i} \neq \text{j}} \text{kij}$

The stage-by-stage method is computationally more cumbersome than the lexicographic approach (in which m is not necessary) and as a result we have not used it. The algorithm was coded in Fortran 95 and implemented on a PC.

As in Kontovas and Psaraftis (2011), the computational effort of this method is as follows. Regarding memory, L grows as $O(n)$, and the number of possible combinations of values of the $[k]$ matrix is $O(3^{\text{r}})$, where r is the number of non-zero O/D pairs, hence memory grows as $O(n3^{\text{r}})$. For a complete graph, $r = n(n - 1)$. Each iteration of the recursion takes $O(r)$ time, bringing the total computational effort to $O(r^2 3^{\text{r}})$. This can be as high as $O(n^4 3^{\text{n2}})$ in the most general case. An exception is if both α and β are zero, in which case there are no summations to be taken. In this case the computational effort reduces to $O(n^2 3^r)$.

It can be seen that it is mainly r, the number of cargoes, rather than n, the number of ports, that dictates computational effort. Obviously such effort is on the high side for anything but small values of r, especially if matrix $[d]$ is complete. Lower computational times can be achieved in special cases, for instance in sparse graphs or for low values of Q.

Extensions The following extensions should be straighforward to implement:

1. Include cargo handling costs: Assuming that these are proportional to port dwell time, one can add a term equal to $C_p \lambda d_{xy}$ within the large bracket in recursion (1), where C_p is the per unit time cargo handling cost. However, as total port dwell time is proportional to total cargo volume and therefore fixed, adding this cost component will not change the optimal solution.
2. Include per call port costs: If there is a fixed component to port cost, say a per call cost of CC_K, then one can add this term within the large bracket in recursion (1), but only whenever $L' \neq L$, in the sense that this cost is accounted for only if the state transition involves moving from port to port. If $L' = L$, the state transition involves loading or unloading cargo and this cost should not be accounted for.
3. Include different loading and unloading rates λ, different cargo handling costs C_p and different per port call costs CC_K at each port.
4. Include different inventory coefficients α and β for each cargo, if for instance the cargoes have different values.
5. Last but not least, one can even include different fuel consumption functions for different legs of the route, say, due to different average weather conditions, sea currents, etc.

Table 11.5 Interport distances (in 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 11.6 Cargo O/D matrix [d] (in thousand tonnes)

i\j	1	2	3
1	–	5	3
2	2	–	4
3	11	1	–

11.9 Sailing the Minimum Distance Route at Minimum Speed may not Minimize Fuel Costs

In the quest for reducing fuel costs but also obtaining environmentally optimal solutions, one might assume that if the minimum distance route is sailed at the minimum possible speed in all legs, this 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 11.5 as follows:

Also assume an asymmetric O/D table for six (6) cargoes to be transported among ports 1–3 as given by Table 11.6:

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 11.7):

In Tables 7 to 12, 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 t. 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.

Table 11.7 Minimum trip time solution

Port stop	Pickup & delivery operations	Next Leg	Payload w at beginning of leg (000 t)
0	–	0–3	0
3	P31	3–1	11
1	D31, P12, P13	1–3	8
3	D13, P32	3–2	6
2	D12, D32, P21, P23	2–1	6
1	D21	1–3	4
3	D23	3–0	0
0	–	–	–

Table 11.8 Minimum emissions solution

Port stop	Pickup/ delivery operations	Next Leg	Payload w at beginning of leg (000 t)
0	–	0–3	0
3	P31	3–1	11
1	D31, P12	1–2	5
2	D12, P21	2–1	2
1	D21, P13	1–3	3
3	D13, P32	3–2	1
2	D32, P23	2–3	4
3	D23	3–0	0
0	–	–	–

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 11.8):

Total distance traveled in this case will be 1260 nautical miles and total trip time will be 6.56 days, both higher than before. But total CO_2 emitted will only be 80 t, 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 t of CO_2 that would be emitted if the ship had sailed the minimum distance route of Table 11.10 at the minimum speed of 8 knots*[7]. The reason that sailing the minimum distance route at minimum speed is suboptimal with respect to

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[7] For a cubic fuel consumption function, total fuel consumed (and hence CO_2 produced) is proportional to the square of the speed, everything else (including payloads at each leg) being equal. $260(8/14)^2 = 84.90$.

Table 11.9 Solutions for non-zero fuel price and varying freight rates

Port stop	Pickup & delivery operations	Next Leg	Payload w at beginning of leg (000 t)	Optimal speed (knots)	
				F = $ 5,000/day	F = $ 20,000/day
0	–	0–3	0	9.39	14.00
3	P31	3–1	11	8.00	11.51
1	D31, P12, P13	1–3	8	8.00	12.05
3	D13, P32	3–2	6	8.00	12.51
2	D12, D32, P21, P23	2–1	6	8.00	12.51
1	D21	1–3	4	8.24	13.08
3	D23	3–0	0	9.39	14.00
0	–	–	–	–	–

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 11.9 shows two cases where $P_{FUEL} = \$\ 600/t$ (in both cases) and F is either $ 5,000/day or $ 20,000 day. Both cases produce the same optimal route, 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.

We mention that the above examples were solved by dynamic programming, in a straightforward extension of the algorithm of Kontovas and Psaraftis (2011), so as to embed speed optimization.

11.10 Policy Implications

In this section we discuss slow steaming from a policy perspective.

11.10.1 The Adoption of EEDI

Perhaps the most sweeping piece of regulation that will have an impact on ship speeds (and in fact at the strategic level) is the recent adoption of Energy Efficiency Design Index (EEDI) by the IMO. Indeed, after years of discussion and intensive and highly

Table 11.10 Parameters for determination of EEDI reference values for different ship types

Ship type	a	c
Bulk carrier	961.79	0.477
Gas carrier	1120.00	0.456
Tanker	1218.80	0.488
Container ship (65 % DWT)	186.52	0.200
General cargo ship	107.48	0.216
Reefer	227.01	0.244
Combination carrier	1219.0	0.488

political debate between developed and developing countries, the finalization of the regulatory text on the EEDI for new ships was agreed upon at the 62nd session of IMO's Marine Environment Protection Committee—MEPC 62 in July 2011.

For a given ship, the EEDI is provided by a complex formula, of which the numerator is a function of all power generated by the ship (main engine and auxiliaries), and the denominator is a product of the ship's deadweight (or payload) and the ship's 'reference speed', defined as the speed corresponding to 75 % of MCR, the maximum power of the ship's main engine. The units of EEDI are grams of CO_2 per tonne mile. The EEDI of a new ship is to be compared with the so-called "EEDI (reference line)," which is defined as EEDI (reference line) = aDWT^{-c}, where DWT is the deadweight of the ship and a and c are positive coefficients determined by regression from the world fleet database, per major ship category.

For a given ship, the attained EEDI value should be equal or less than the required EEDI value which is provided by the following formula.

$$\text{Attained EEDI} \leq \text{Required EEDI} = (1 - X/100)\mathrm{aDWT}^{-\mathrm{c}} \tag{11.8}$$

where X is a "reduction factor" specified for the required EEDI compared to the EEDI Reference line[8].

The reference line parameters a and c in (11.9), which have been finalized by regression analysis after a long debate within the IMO are presented in Table 11.10 below, although they are subject to revision.

It is interesting to note that Ro/ro vessels are thus far excluded from EEDI, because no adequate regression coefficients have been obtained for this class of vessels. This is an open subject that the IMO hopes to close in the foreseeable future.

A basic problem with EEDI is that compliance effectively imposes a limit on a ship's *design speed*, as the left-hand side of inequality (11.9) is a polynomial function of the design speed whereas the right-hand side is independent of speed. Thus,

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[8] The values of X specified by the IMO are 0 % for ships built from 2013–2015, 10 % for ships built from 2016–2020, 20 % for ships built from 2020–2025 and 30 % for ships built from 2025–2030. This means that it will be more stringent to be EEDI compliant in the years ahead.

whereas the real goal of EEDI is to design ships with better hulls, engines and propellers so as to be more energy efficient, an easy solution might be to reduce design speed, and, as a consequence, installed power. This may have negative ramifications on ship safety. It may also have negative effects on total CO_2 emitted, as an unde-powered ship would burn more fuel and hence emit more CO_2 at the same speed, particularly if it tries to maintain speed in bad weather.

11.10.2 Market Based Measures

A parallel effort at the IMO concerns the so-called Market Based Measures, or MBMs. MBMs are economic instruments that entice the ship owner to adopt measures to make the ship emit less CO_2. MBMs are also used to raise money to invest in carbon-reducing technologies outside the shipping sector.

At this point there are 10 distinct MBM proposals before the IMO. An Expert Group has been formed and some initial discussions have been held, but no final decision has been reached as of yet. These MBMs include a levy on fuel, an emissions trading scheme, various hybrid proposals based on EEDI, and others.

In terms of what has been described in this chapter, it is interesting to note that among the various MBM proposals, the levy proposal is perhaps the only one that can handle slow steaming automatically. In the short run, a levy on fuel would effectively raise the price of fuel and as a result would make the ship go slower. If the levy is equal to the social cost of CO_2, this would fully internalize its external cost. In the long run, the same measure would encourage a ship owner to invest in technologies that would make the ship burn less fuel. For an analysis of the MBMs of the table at the IMO, see IMO (2010) and Psaraftis (2012a).

11.10.3 Instituting Speed Limits?

Realizing that reducing speed also reduces emissions, some researchers and some lobbying groups have recommended instituting speed limits on shipping. Among the researchers, see Lindstad et al. (2011) for an argument and Cariou and Cheaitou (2012) for a counter argument. Among the lobbying groups, the Clean Shipping Coalition (CSC), 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.

It is clear that slow steaming and speed limits are two different things, as the first is a voluntary response and the second is an imposed measure. If the speed limit is above the optimal speed that is voluntarily chosen, then it is superfluous. If it is below, it may cause distortions in the market and costs that exceed the benefits of speed reduction. Possible side-effects include

- Building more ships to match demand throughput, with more CO_2 associated with shipbuilding and recycling
- Increasing cargo inventory costs due to delayed delivery
- Increasing freight rates due to a reduction in tonne-mile capacity
- Inducing reverse modal shifts to land-based modes (mainly road) that would increase the overall CO_2 level
- Implications on ship safety

It is clear that imposing speed limits, either on a global or on a regional level, is an emissions abatement measure that should be studied very carefully in terms of its possible side effects, as it is quite conceivable that its overall costs might exceed its benefits.

11.11 Conclusions

This chapter has examined the practice of slow steaming from various angles. In that context, a taxonomy of models was presented, some fundamentals were outlined, the main trade-offs were analysed, and some decision models were presented. Some examples were finally presented so as to highlight the main issues that are at play.

The chapter has confirmed 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.

In the quest for a balanced economic and environmental performance of maritime transport, we think that this chapter can provide useful insights.

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