

Chapter 8. Tramp ship routing and scheduling: effects of market-based measures on CO₂ reduction

Xin Wang¹, Inge Norstad², Kjetil Fagerholt¹, and Marielle Christiansen¹

¹Department of Industrial Economics and Technology Management, Norwegian University of Science and Technology, Trondheim, Norway

²SINTEF Ocean, Trondheim, Norway

Abstract

In this chapter we examine, from a tramp ship operator's point of view, how potential CO₂ emission reduction measures impact the operational decisions and their economic and environmental consequences. Two market-based measures (MBMs) are discussed, the bunker levy scheme and the emission trading scheme, and we show that both can be incorporated in a similar way into a typical tramp ship routing and scheduling model. We also demonstrate with a computational study the environmental benefits of these CO₂ reduction schemes.

Abbreviations:

CO ₂	Carbon dioxide
CO ₂ e	Carbon dioxide equivalent
COA	Contract of affreightment
dwt	Deadweight tonnes
ETS	Emission trading scheme
EU	European Union
EU ETS	European Union Emissions Trading Scheme
GHG	Greenhouse gas
IMO	International Maritime Organization
LNG	Liquefied natural gas
M	Nautical mile
MBM	Market-based measure
OR	Operations research
t	tonnes

1 Introduction

Traditionally for ship operators, the reduction of maritime greenhouse gas (GHG) emissions might just be a “happy side-effect” of the increasing global competition in the shipping industry. While the thin profit margin generates the need to reduce bunker fuel consumption, through, e.g., better design of ship hulls, energy-saving engines, “slow steaming” (significantly reducing ship speed in response to depressed market conditions and/or high fuel prices, see [Maersk, 2011](#)) and more efficient deployment and operation of the fleet; it also contributes to less GHG produced, especially carbon dioxide (CO₂) emissions since they are directly proportional to fuel consumed.

However, as we marched into the second decade of the new millennium there had been much discussion of stricter and more direct regulations on CO₂ emissions in the shipping sector ([Buhaug et al., 2009](#); [Shi, 2016](#)), due to the urgency of combating global warming and meeting the “two-degrees goal” ([Rajamani, 2011](#)). Among those proposed regulations are the so-called market-based measures (MBMs), including bunker levy, emission trading and a variety of other schemes. We refer the readers to Chapter 11 for a discussion of MBMs in the shipping sector. A bunker levy scheme collects revenue from the sector in the form of a tax on fuel use, which may then be used to establish an international fund that invests in environmental causes. An emission trading scheme (ETS) sets a maximum quantity (cap) on emissions from the shipping sector, and employs a trading mechanism to facilitate emission reductions. Although the effectiveness of any of these schemes has been controversial and the assessment and comparison of different MBMs are far from completion ([Psaraftis, 2012](#)), it is useful to study how *ship operators* may react to different types of CO₂ emission reduction schemes.

In this chapter we examine, from a tramp ship operator’s point of view, how potential CO₂ emission reduction schemes impact the operational decisions and their economic and environmental consequences. To the best of our knowledge, this is the first study in the literature that approaches this issue from an operations research perspective and in the tramp shipping context. We start by presenting the classic tramp routing and scheduling model in maritime transportation, and extend the model to incorporate CO₂ reduction aspects under two scenarios: a bunker levy scenario and an ETS scenario. A computational study is then conducted on typical tramp shipping instances to show the effects of imposing these CO₂ reduction schemes.

The rest of this chapter is organized as follows. Section 2 introduces the tramp ship routing and scheduling problem and its mathematical models. Section 3 discusses the model extensions for incorporating two versions of CO₂ emission reduction scheme. Section 4 presents the computational study and we conclude in Section 5.

2 Tramp Ship Routing and Scheduling

This section introduces the tramp ship routing and scheduling problem and its mathematical models. We start in Section 2.1 by discussing the operational characteristics of tramp shipping that distinguish itself as an important sector in maritime transportation. We then state the problem and present its mathematical models in Section 2.2.

2.1 Operational characteristics of tramp shipping

In maritime transportation, ships are said to operate in the *tramp* mode if they do not have a fixed schedule or itinerary and do not expect repetition of voyages as a normal part of their operations. This is in contrast to the liner shipping business, characterized primarily by container shipping, which constitutes the provision of scheduled services with a fixed frequency over a pre-determined route.

In tramp shipping, the sailings of a vessel follow the cargo commitments that vary with the vessel’s employment (like taxicabs), usually catering to both mandatory contractual cargoes and optional spot ones. The mandatory cargoes are usually based on long-term agreements between the ship operator and cargo owners, or contracts of affreightment (COAs) in shipping parlance, where the ship operator is obliged to transport specified quantities of cargo between specified ports during a specified time period. Some contracts (in, e.g., oil trades) also demand repetitious voyages at a certain frequency, but unlike liner shipping, such voyages are usually not actively advertised and the schedules are less strict. In addition to the mandatory contractual cargoes, a tramp operator often seeks optional cargoes from the spot market to better utilize their ship capacity and increase their revenue. Therefore, when planning for the routes and schedules of tramp ships in pursuit of maximized profits, the decisions regarding which optional cargoes to accept/reject are also non-trivial to the ship operator.

For the past two decades, there has been much work done in the operations research (OR) community towards the development of decision support tools in tramp shipping, where optimization theories and techniques are applied to achieve such as better routes and schedules, optimized speeds and improved composition of fleet. We refer the readers to [Christiansen et al. \(2004\)](#) and [Christiansen et al. \(2013\)](#) for surveys in ship routing and scheduling problems, and to [Christiansen and Fagerholt \(2014\)](#) for a review on tramp ship routing and scheduling in particular.

While it is common to distinguish between liner, industrial and tramp ([Lawrence, 1972](#)) when describing the mode of operation in maritime transportation, the line between the industrial and tramp shipping modes is narrow. A traditional industrial ship operator is considered to control its own “private” fleet that only provides transportation for its own cargoes. The recent trend, however, has been the shift from industrial to tramp

shipping, as many companies previously involved in industrial shipping have outsourced their transportation, while others have become more engaged in the spot market during the process of industrial shipping operations being transformed from “cost centers” into “profit centers”. From an OR perspective, the boundary between industrial and tramp shipping is even more obscure: essentially they are both defined around the principle of “following the available cargoes”. While an industrial operator minimizes the cost of a somewhat closed system with a given number of ships and cargoes, the tramp ship routing and scheduling problem may be seen as a generalization of its industrial counterpart, where optional cargoes are also considered to generate additional revenue and the objective becomes profit maximization. Together, industrial and tramp shipping are responsible for the transportation of most of the bulk cargoes in global trades, including wet (oil and gas, chemicals, etc.) and dry bulk products (iron ore, coal, grain, etc.). In 2016, these products account for over 60% of the total weight transported at sea ([UNCTAD, 2017](#)).

2.2 The tramp ship routing and scheduling problem

In tramp shipping, as previously mentioned, the cargoes are the source of revenue and the demands for transporting cargoes in a timely and efficient fashion are the main drivers for addressing tramp ship routing and scheduling problems. A cargo, mandatory or optional, represents the demand of a specified amount of product(s) to be loaded (picked up) at a specified origin port, transported, and unloaded (delivered) at a specified destination port. There usually is a time window associated with the pickup of each cargo during which the loading operations of the cargo must start. There sometimes are similar time windows for the delivery of the cargoes, but more often they are relatively wide (if any). Each optional cargo has a specified freight income rate that determines the revenue the ship operator will receive if the cargo is transported. The revenues from carrying the mandatory cargoes are also specified.

The ship operator controls a fleet of ships to service the cargoes. Such fleet is typically heterogeneous, in the sense that: (a) the ships can be of different load capacity, speed range, fuel efficiency and physical dimension (length, draft, etc.); and (b), more importantly, the initial locations of the ships are different, some ships may be at sea and others may be at dock in various sea areas and ports. A ship can sometimes carry multiple cargoes on board depending on the cargo sizes, although in several contexts, e.g., transporting major bulk commodities, a cargo is usually a full shipload. For various reasons there may also be compatibility constraints between ships and cargoes. For example, a small ship may not carry a cargo that is too heavy, and a large ship with deep draft may not carry a cargo because one of the associated ports of this cargo is too shallow.

In short, a typical tramp ship routing and scheduling problem is characterized by the simultaneous determination of acceptance/rejection of optional cargoes to service, assign-

ment of cargoes to specific ships, the sequence and times of port calls for all ships and, if variable speeds are applicable, the sailing speed during each voyage. The objective is to provide timely transportation services for all mandatory and accepted optional cargoes, while maximizing profit which is computed as the revenue from all serviced cargoes subtracted by the variable transportation costs. These costs mainly consist of: fuel costs, associated with sailing the ships; port and canal fees, dependent on the type and size of the ship when visiting a port and passing a canal; and sometimes also costs for spot charters (i.e., voyage/space charters from the spot market to service given cargoes).

The tramp ship routing and scheduling problem has many similarities with the so-called *multiple-vehicle one-to-one pickup and delivery problem with time windows* that arises in road-based transportation (Battarra et al., 2014). In the context of passenger transportation, it is often called the Dial-a-Ride problem (Doerner and Salazar-González, 2014). In these land-based problems each customer request also consists of transporting a load (goods or people) from one pickup vertex to one destination vertex. The differences are, however, equally significant. In tramp shipping the fleet is usually heterogeneous (even if the ships are of similar physical characteristics), the ships have different initial positions and they generally do not have a common depot. In addition, since the transport distance is generally longer at sea than on land, the ships operate around the clock and their voyages span days or weeks.

In the following we first give the mathematical formulation of a classic tramp ship routing and scheduling problem in Section 2.2.1, in which the sailing speed between a pair of ports for a given ship is fixed, and the fuel consumption is not dependent on ship payload. The model takes the form of a mixed integer linear programming problem. We then show in Section 2.2.2 the non-linear extension of the model that incorporates variable speeds and the dependency of fuel consumption on ship speed and payload. These models are based on Norstad et al. (2011) and Christiansen and Fagerholt (2014).

2.2.1 The basic linear model

Let there be n cargoes that might be transported during the planning horizon. Let each of the n cargoes be represented by an index i . Associate to cargo i a loading port node i and an unloading port node $n + i$. Note that different nodes may correspond to the same physical port. Let $N^P = \{1, 2, \dots, n\}$ denote the set of pickup nodes, and $N^D = \{n + 1, n + 2, \dots, 2n\}$ the set of delivery nodes. The set of pickup nodes is partitioned into two subsets, N^C and N^O , where N^C is the set of pickup nodes for the mandatory contracted cargoes and N^O is the set of pickup nodes for the optional cargoes.

Let V be the set of ships. A network (N_v, A_v) is associated with each ship v . Here, N_v is the set of nodes that can be visited by ship v , including the origin and an artificial destination for ship v , $o(v)$ and $d(v)$, respectively. Geographically, the origin can be either

a port or a point at sea, while the artificial destination is the last planned unloading port for ship v . If the ship is not used, $d(v)$ will represent the same location as $o(v)$. From this, we can extract the sets $N_v^P = N^P \cap N_v$ and $N_v^D = N^D \cap N_v$ consisting of the pickup and delivery nodes that ship v may visit, respectively. The set A_v contains all feasible arcs for ship v , which is a subset of $N_v \times N_v$.

For each ship $v \in V$ and each arc $(i, j) \in A_v$, let T_{ijv}^S be the sailing time from node i to node j , while T_{iv}^P represents the service time in port at node i with ship v . The variable transportation costs C_{ijv} consist of the sum of the sailing costs from node i to node j and the port costs of node i for ship v . It is also assumed that a (contractual) cargo i can be serviced by a ship chartered from the spot market at a given cost, C_i^S . Further, let $[\underline{T}_{iv}, \overline{T}_{iv}]$ denote the time window for ship v associated with node i , where \underline{T}_{iv} is the earliest time for start of service and \overline{T}_{iv} is the latest. Each cargo i has a quantity Q_i and generates a revenue R_i per unit if it is transported. Let K_v be the capacity of ship v .

We also define the following decision variables. Let binary variable x_{ijv} be equal to 1 if ship v sails directly from node i to node j , and 0 otherwise. Let t_{iv} represents the time for start of service for ship v at node i , and l_{iv} the load (weight) on board ship v when leaving node i . To ease the reading of the model, we assume that each ship is empty when leaving the origin and when arriving at the artificial destination, i.e., $l_{o(v)v} = l_{d(v)v} = 0$. Let binary variable z_i be equal to 1 if cargo i is serviced by a ship from the spot market, and 0 otherwise. Finally, let binary variable y_i be equal to 1 if optional cargo i is transported, and 0 otherwise.

The basic tramp ship routing and scheduling problem can now be formulated as follows:

$$\max \sum_{i \in N^C} R_i Q_i + \sum_{i \in N^O} R_i Q_i y_i - \sum_{v \in V} \sum_{(i,j) \in A_v} C_{ijv} x_{ijv} - \sum_{i \in N^C} C_i^S z_i \quad (1)$$

subject to

$$\sum_{v \in V} \sum_{j \in N_v} x_{ijv} + z_i = 1, \quad i \in N^C, \quad (2)$$

$$\sum_{v \in V} \sum_{j \in N_v} x_{ijv} - y_i = 0, \quad i \in N^O, \quad (3)$$

$$\sum_{j \in N_v} x_{o(v)jv} = 1, \quad v \in V, \quad (4)$$

$$\sum_{j \in N_v} x_{ijv} - \sum_{j \in N_v} x_{jiv} = 0, \quad v \in V, i \in N_v \setminus \{o(v), d(v)\}, \quad (5)$$

$$\sum_{i \in N_v} x_{id(v)v} = 1, \quad v \in V, \quad (6)$$

$$l_{iv} + Q_j - l_{jv} - K_v(1 - x_{ijv}) \leq 0, \quad v \in V, (i, j) \in A_v | j \in N_v^P, \quad (7)$$

$$l_{iv} - Q_j - l_{n+j,v} - K_v(1 - x_{i,n+j,v}) \leq 0, \quad v \in V, (i, n+j) \in A_v | j \in N_v^P, \quad (8)$$

$$\sum_{j \in N_v} Q_i x_{ijv} \leq l_{iv} \leq \sum_{j \in N_v} K_v x_{ijv}, \quad v \in V, i \in N_v^P, \quad (9)$$

$$0 \leq l_{n+i,v} \leq \sum_{j \in N_v} (K_v - Q_i) x_{n+i,jv}, \quad v \in V, i \in N_v^P, \quad (10)$$

$$t_{iv} + T_{iv}^P + T_{ijv}^S - t_{jv} - M_{ijv}(1 - x_{ijv}) \leq 0, \quad v \in V, (i, j) \in A_v, \quad (11)$$

$$\sum_{j \in N_v} x_{ijv} - \sum_{j \in N_v} x_{n+i,jv} = 0, \quad v \in V, i \in N_v^P, \quad (12)$$

$$t_{iv} + T_{iv}^P + T_{i,n+i,v}^S - t_{n+i,v} \leq 0, \quad v \in V, i \in N_v^P, \quad (13)$$

$$\underline{T}_{iv} \leq t_{iv} \leq \bar{T}_{iv}, \quad v \in V, i \in N_v, \quad (14)$$

$$l_{iv} \geq 0, \quad v \in V, i \in N_v, \quad (15)$$

$$x_{ijv} \in \{0, 1\}, \quad v \in V, (i, j) \in A_v, \quad (16)$$

$$y_i \in \{0, 1\}, \quad i \in N^O, \quad (17)$$

$$z_i \in \{0, 1\}, \quad i \in N^C. \quad (18)$$

The objective function (1) maximizes the profit from operating the fleet. The four terms are: the revenue gained by transporting the mandatory contracted cargoes, the revenue from transporting the optional cargoes, the variable transportation costs, and the cost of using spot charters. The fixed revenue for the contracted cargoes can be omitted, but is included here to obtain a more complete picture of the profit. Constraints (2) state that all mandatory contract cargoes are transported, either by a ship in the fleet or by a spot charter. The corresponding requirements for the optional cargoes are given by constraints (3). Constraints (4) - (6) describe the flow along the sailing route used by ship v . Constraints (7) and (8) keep track of the load on board at the pickup and delivery nodes, respectively. Constraints (9) and (10) represent the ship capacity constraints at the loading and discharging nodes, respectively. Constraints (11) ensure that the time

of starting service at node j must be greater than or equal to the departure time from the previous node i , plus the sailing time between the nodes. The big M coefficient in constraints (11) can be calculated as $M_{ijv} = \max(0, \bar{T}_{iv} + T_{iv}^P + T_{ijv}^S - \underline{T}_{jv})$. Constraints (12) ensure that the same ship v visits both loading node i and the corresponding discharging node $n + i$. Constraints (13) force node i to be visited before node $n + i$, while constraints (14) define the time window within which service must start. If ship v is not visiting node i , we will get an artificial starting time within the time windows for that (i, v) -combination. The non-negativity requirements for the load on board the ship are given by constraints (15). Constraints (16), (17) and (18) impose the binary requirements on the flow, optional cargo and spot charter variables, respectively.

Note that in the industrial shipping context (which may be seen as a special case of tramp shipping as discussed earlier), the objective will be to minimize the variable transportation costs, which correspond to the third and fourth terms in objective function (1), while constraints (3) and variable y_i are no longer required since in industrial shipping all cargoes are mandatory.

2.2.2 The extended non-linear model with speed optimization

Most of the earlier studies in the tramp ship routing and scheduling literature, e.g., [Brown et al. \(1987\)](#), [Korsvik et al. \(2010\)](#), [Malliappi et al. \(2011\)](#) and [Lin and Liu \(2011\)](#) among others, assume a fixed and known speed for every ship in the fleet, which usually is the service speed traditionally used when the shipping company makes its planning. In reality, the ship can of course sail at other speeds as well. Normally, a ship has a minimum and a maximum cruising speed which define the range of speeds at which it can actually travel. The option of speeding up affords the ship operator operational flexibility to absorb delays at ports and handle schedule disruptions. On the other hand, the shipping industry has seen significant economic savings by prevailing the practice of slow steaming in almost every commercial ship sector.

As shown by [Ronen \(1982\)](#), a cubic function provides a good estimation of the relationship between fuel consumption per time unit and speed for cargo ships. The impact of a change in ship speed on both fuel costs and emissions can therefore be quite dramatic. In fact, as a response to the growing awareness of the economic and environmental benefits brought by planning with variable speeds, in recent years many studies have been dedicated on speed optimization on given routes or have included speeds as decision variables in their routing and scheduling models ([Psaraftis and Kontovas, 2013, 2014](#)). Some examples are [Fagerholt et al. \(2010\)](#), [Gatica and Miranda \(2011\)](#), [Norstad et al. \(2011\)](#) and [Hvattum et al. \(2013\)](#).

Another important but often overlooked consideration when determining the fuel costs along a ship route is that the payload of the ship varies, especially in pickup and delivery

situations, and that the fuel consumption, other than being a non-linear function of speed, is also a function of ship payload (Psaraftis, 2017). According to Barrass (2004), a common approximation is that for a given speed, fuel consumption is proportional to $(l + L)^{2/3}$, where l is the payload and L is the lightship weight of the ship. Also as suggested in Psaraftis and Kontovas (2016), the difference between laden and ballast fuel consumption at the same speed for a specific ship type can be as high as 40%. It is therefore inspiring to see that, recently, some studies have taken payload dependency into account (only for laden and ballast conditions in some case) in the tramp routing and scheduling context, e.g., Wen et al. (2016) and Vilhelmsen et al. (2017), and in other contexts too, e.g., Andersson et al. (2015) and Wen et al. (2017).

In the following we show that the basic model presented above in Section 2.2.1 can be modified to incorporate speed optimization, where the fuel consumption rate of each ship can be a specific function of its speed and payload. Let D_{ij} be the sailing distance from node i to node j . The variable s_{ijv} defines the speed of travel from node i to node j with ship v . Thus the time it takes to sail along arc (i, j) can be computed by D_{ij}/s_{ijv} . The non-linear function $C_v(s, l)$, defined on the speed interval $[\underline{S}_v, \bar{S}_v]$, represents the variable transportation costs per unit of distance for ship v sailing at speed s with load l on board. The cost of sailing an arc (i, j) with ship v departing node i with load l_{iv} at speed s_{ijv} is then $D_{ij}C_v(s_{ijv}, l_{iv})$.

The model for the basic tramp ship routing and scheduling problem (1) – (18) can now be adjusted as follows:

$$\max \sum_{i \in N^C} R_i Q_i + \sum_{i \in N^O} R_i Q_i y_i - \sum_{v \in V} \sum_{(i,j) \in A_v} D_{ij} C_v(s_{ijv}, l_{iv}) x_{ijv} - \sum_{i \in N^C} C_i^S z_i, \quad (19)$$

subject to (2) – (10), (12), (14) – (18) and

$$t_{iv} + T_{iv}^P + D_{ij}/s_{ijv} - t_{jv} - M_{ijv}(1 - x_{ijv}) \leq 0, \quad v \in V, (i, j) \in A_v, \quad (20)$$

$$t_{iv} + T_{iv}^P + D_{i,n+i}/s_{i,n+i,v} - t_{n+i,v} \leq 0, \quad v \in V, i \in N_v^P, \quad (21)$$

$$\underline{S}_v \leq s_{ijv} \leq \bar{S}_v, \quad v \in V, (i, j) \in A_v. \quad (22)$$

The objective function (19) has now become a non-linear function because of the non-linear relationships between fuel consumption and speed and payload. Constraints (20) and (21) correspond to constraints (11) and (13) in the original formulation. These constraints are also non-linear because the sailing time depends on the speed variable. The new constraints (22) define the lower and upper bounds for the speed variables.

3 Modeling the Emission Reduction Schemes

In this section we present and discuss the model extensions for incorporating two versions of CO₂ emission mitigation strategy: a bunker levy scheme in Section 3.1; and an Emission Trading Scheme (ETS) in Section 3.2. The bunker levy and ETS proposals are both market-based measures (MBMs) that can potentially help meet global climate goals through a more flexible approach than the traditional regulatory measures (“command-and-control”, where public authorities mandate the performance to be achieved or the technologies to be used). On the one hand, the MBMs can be used to establish an international fund to invest into emission reduction projects outside the marine sector. They are also economic (or “price-based”) instruments that, on the other hand, potentially provide the required incentives to ship owners for enhancing their energy efficiency and reducing “in-sector” emissions, through the adoption of long-term technological measures (e.g., more efficient engines or ships) and short-term logistical measures (e.g., slow steaming, optimal fleet management).

3.1 Model with bunker levy

Bunker levy, or “carbon tax”, is a measure of collecting revenue from the shipping sector in the form of a tax on fuel use. The scheme may also be enforced as a percentage on fuel price. The bunker levy scheme has gained much favor with researchers compared with other emission mitigation solutions (European speed limit, ETS, etc.), mainly because it is easy to implement and provides price certainty in terms of increase in fuel costs to which shipping companies can respond proactively (Cariou and Cheaitou, 2012; Psaraftis, 2012; Kapetanidis et al., 2014). There are also concerns on the resulting modal shifts and that the extra costs will only be passed along the supply chain (GSF, 2012).

In a tramp ship routing and scheduling problem, the bunker levy scheme can be modeled as an extra charge on every tonne of fuel consumed. In terms of mathematical formulation, the model incorporating a bunker levy requires the following modifications. Similar to the non-linear function $C_v(s, l)$ in Section 2.2.2., we let $F_v(s, l)$ denote the amount of fuel consumed (in tonnes) per unit of distance for ship v sailing at speed s with load l . The total fuel consumption, represented by FUEL, can then be written as

$$\text{FUEL} = \sum_{v \in V} \sum_{(i,j) \in A_v} D_{ij} F_v(s_{ijv}, l_{iv}) x_{ijv}. \quad (23)$$

Let LEVY be the tax imposed on every tonne of fuel consumed. The objective function (19) is then modified as follows to account for the extra fuel costs:

$$\begin{aligned}
\max \quad & \sum_{i \in N^C} R_i Q_i + \sum_{i \in N^O} R_i Q_i y_i - \sum_{v \in V} \sum_{(i,j) \in A_v} D_{ij} C_v(s_{ijv}, l_{iv}) x_{ijv} - \sum_{i \in N^C} C_i^S z_i \\
& - \text{LEVY} \times \text{FUEL}.
\end{aligned} \tag{24}$$

3.2 The Emission Trading Scheme

To provide a basis for considering a potential ETS in our model on tramp shipping, we look at the European Union Emissions Trading System (EU ETS) for some details of the mechanism. The EU ETS has been in operation from 2005 and was the first large GHG emission trading scheme in the world. The scheme now covers more than 11,000 factories, power stations, and other installations in 31 countries – all 28 EU member states plus Iceland, Norway, and Liechtenstein. In 2012, the EU ETS was extended to the airline industry. **In November 2017 the European Parliament and EU member states agreed on a revision of the EU ETS that excludes shipping for the time being, but “will include shipping in the trading system from 2023 if IMO progress in a CO₂ strategy is considered insufficient” (The Maritime Executive, 2017).**

The ETS functions under the “cap and trade” principle, where a maximum (cap) is set on the total amount of CO₂ that can be emitted by all participants in the system. “Allowances” for emissions are created equal to the size of the cap, which are measured in units where one unit corresponds to the right to emit one tonne of carbon dioxide equivalent (CO₂e). The allowances are allocated for free or auctioned off to the emitters, and can subsequently be traded among them. If emission exceeds what is permitted by its allowances, an emitter must purchase allowances from others. Conversely, if an emitter has performed well at reducing its emissions, it can sell its leftover allowances. This potentially allows the participants of the system to find the most cost-effective ways of reducing emissions without significant government intervention.

To include an ETS mechanism in the model, we make the following modifications to the model presented in Section 2.2.2. Let H be the amount of CO₂ allowance (in tonnes) acquired by the shipping company from public authorities or auctions at price P^C per tonne (which may be zero or non-zero). Let P^S be the spot price of one tonne of CO₂ allowance trading in the secondary market, same for buying and selling. **Note that H and P^C are input to our model, since the tramp ship routing and scheduling problem we address in this chapter typically focuses on decisions on the operational/tactical level.** Also note that, the assumption regarding CO₂ allowance trading price P^S in the spot market is based on the viewpoint of a single tramp shipping company, therefore such spot price is assumed to be exogenous and constant during our planning horizon.

As in Section 3.1, we use $F_v(s, l)$ and FUEL to represent the amount of fuel consumed for every unit of distance sailed by ship v at speed s with load l , and the total fuel

consumption, respectively. There is a linear relationship between fuel burned and CO₂ produced, with the proportionality constant being known as the emissions factor. The third IMO GHG study (Smith et al., 2015) indicates that such factor is **between 3.11 and 3.21** (tonnes of CO₂ per tonne of fuel) independent of fuel type (for most common fuel types; emissions factor for marine LNG is 2.75). Therefore, the total amount of CO₂ emitted can be expressed by $3.2 \times \text{FUEL}$, using 3.2 as the emissions factor.

The objective function (19) is then changed to:

$$\begin{aligned} \max \quad & \sum_{i \in N^C} R_i Q_i + \sum_{i \in N^O} R_i Q_i y_i - \sum_{v \in V} \sum_{(i,j) \in A_v} D_{ij} C_v(s_{ijv}, l_{iv}) x_{ijv} - \sum_{i \in N^C} C_i^S z_i \\ & - \left[P^C H + P^S (3.2 \times \text{FUEL} - H) \right] \end{aligned} \quad (25)$$

where the expression in the brackets $[\cdot]$ represents the total costs for CO₂ emissions, including the costs of acquiring the initial CO₂ allowances H and the costs of buying additional allowances from the spot market (or the revenue of selling leftover allowances if the actual amount emitted is lower than H). The constraints remain unchanged compared with the model presented in Section 2.2.2.

Notice that by separating out terms that are constant values, we may rewrite the expression for total emission costs, i.e., the expression inside $[\cdot]$ in Eq. (25), into

$$P^S \times 3.2 \times \text{FUEL} + (P^C - P^S)H \quad (26)$$

in which the first term is the amount of total CO₂ emissions multiplied by the spot CO₂ allowance price P^S , and the second term is a constant value independent of any decision variable in the model. Therefore, the maximization of objective function (25) is equivalent to solving

$$\begin{aligned} \max \quad & \sum_{i \in N^C} R_i Q_i + \sum_{i \in N^O} R_i Q_i y_i - \sum_{v \in V} \sum_{(i,j) \in A_v} D_{ij} C_v(s_{ijv}, l_{iv}) x_{ijv} - \sum_{i \in N^C} C_i^S z_i \\ & - P^S \times 3.2 \times \text{FUEL} . \end{aligned} \quad (27)$$

Therefore, compared with objective function (19) in the original model, incorporating an ETS implicates adding an *extra charge* $P^S \times 3.2$ on *every tonne of fuel consumed* independent of the amount and price of the CO₂ allowances initially received (provided that the amount and price of the initial allowance are both input), and such charge depends on the trading price of CO₂ allowance in a spot market. Also note that this objective function is analogous to objective function (24) in the bunker levy case.

It is important to emphasize again the caveats of this conclusion, and that the underlying assumptions be comprehended. **First, as mentioned earlier the amount of allocated CO₂ allowances H and the average unit cost of acquiring these allowances P^C are input**

to our model due to the scope of a typical tramp shipping problem. These initial costs are therefore “sunk” and will not affect the ship routing, scheduling or optional cargo selection decisions. In reality, H may also be a decision variable when the initial allowances held by the shipping company are acquired in part (or all) from auctions. In EU ETS, for example, over 50% of the total amount of allowances over the period 2013–2020 will be auctioned in the primary market (on average over all sectors covered by EU ETS; in the aviation industry the proportion of auctioned allowances is 15%), while the remaining allowances are granted free and allocated to companies based on their historical emissions (European Commission, 2015). Therefore, for those companies with expected allowance demand higher than their allocated amount, H is also a decision to be made as the company may buy allowances through auctioning (at prices usually comparable to the spot price at the time of auctioning) to avoid having to fulfill its obligations from a secondary market later where the spot price may fluctuate widely.

Second, the additional costs resulted from an emission reduction scheme may have large effects on many tactical/strategic decisions. For example, if the amount of free allowances received from public authorities is little, and the expected costs to fulfill its obligations through either allowance auctioning or the secondary market are significant, the shipping company might cut back on long-term contracts or reduce the size of its fleet which are all incentives for modal shifts that take cargoes off seaways (e.g., from short sea shipping to land-based transportation, which may also be a source of “carbon leakage” into sectors with less stringent climate policy). These are outside the scope of a typical tramp ship routing and scheduling problem, but are significant issues that need further exploration.

Third, since the model is based on the viewpoint of one tramp shipping company, the trading price of CO₂ allowance in the spot market (P^S) is assumed to be exogenous and constant. In reality the spot market may exhibit an increasing marginal purchasing costs, i.e., the buying price of one unit of CO₂ allowance may increase when purchasing more, especially if the market is thin and if the shipping company is a major player in the business.

4 Computational Study

In this section we present a computational study to demonstrate the effects of implementing an emission reduction scheme in the form of a bunker levy. We only discuss the bunker levy scenario as in the previous section we have shown that the imposition of an ETS also implicates an extra charge on fuel use (from the viewpoint of a typical tramp operator).

We use 16 test instances taken from the benchmark instances for industrial and tramp routing and scheduling problems (Hemmati et al., 2014). The tests are performed based on the model with variable speeds presented in Section 2.2.2, where we *increase the input*

fuel price to imitate the implementation of a bunker levy. By doing so we can examine the impact of a bunker levy on the tramp operator’s operational decisions and its total fuel consumption (and hence emissions).

The problems are solved on the commercial ship routing decision support system TurboRouter (Fagerholt, 2004; Fagerholt and Lindstad, 2007) from SINTEF Ocean, using the multi-start local-search heuristic method presented in Brønmo et al. (2007) and Norstad et al. (2011). Note that the particular algorithm used for solving the fixed-route speed optimization problems (which are subproblems in the multi-start heuristic) is based on the discretization arrival times at each route node (Fagerholt et al., 2010); the alternative “recursive smoothing algorithm”, although shown to be more efficient in the case where fuel consumption depends only on speed, cannot be used here because of our inclusion of payload dependency (see discussions in Norstad et al., 2011).

4.1 Input data and test instances

To represent realistic situations faced in tramp shipping, the test instances we use have characteristics combining two geographical settings, short sea and deep sea shipping, and two cargo settings, full load and mixed load cargoes. In deep sea shipping, the cargoes are transported long distances and across at least one of the big oceans, for example from Liverpool to Yokohama. In short sea shipping, the cargo movements are within Europe, for example from Gdansk to Dunkirk. For full load instances, the cargo sizes are such that a cargo is a full shipload. And in mixed load cases, some of the cargoes are of smaller size and the ship capacity may accommodate several cargoes simultaneously.

We use four instances for each such combination of the above geographical and cargo settings, i.e., “Deep-Full”, “Deep-Mix”, “Short-Full” and “Short-Mix”, which amount to 16 instances in total. Each instance is referred to in the format *setting-Cx-Vy-z*, where *setting* is the combination of geographical and cargo settings, *x* is the number of cargoes, *y* is the number of ships and *z* is the *z*-th instance with the same setting and size. The complete list of instances is shown in Table 2, and these instances may be downloaded from: <http://home.himolde.no/hvattum/benchmarks/>.

Recall that in the model presented in Section 2.2.2, we use a non-linear function $C_v(s, l)$, defined on the speed interval $[\underline{S}_v, \bar{S}_v]$, to represent the variable transportation costs per unit of distance for ship *v* sailing at speed *s* with load *l* on board. To describe such a function well one must have a good approximation of the relationship between the ship’s fuel consumption rate and its speed and payload, since the fuel costs make up most of the variable transportation costs.

For every specific ship, the fuel consumption rate FC is in tonnes (t) per traveled nautical mile (M) which is a function of speed *s* (knots) and payload ρ (% of total capacity). We use the following empirical function, $FC = (As^2 + Bs + C) \times (0.8 + 0.2\rho)$, where *s* is within

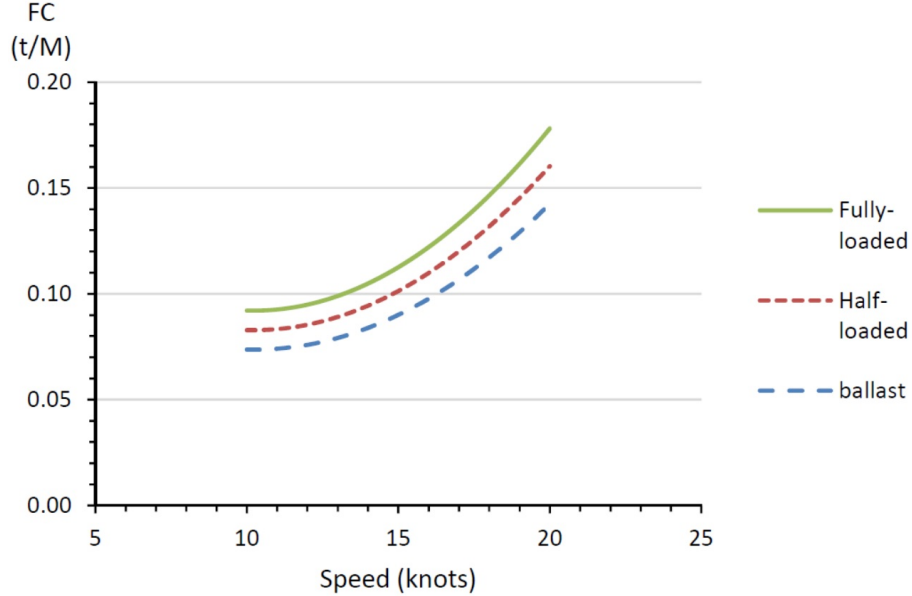


Figure 1: Fuel consumption characteristics for a Handymax bulk carrier.

the ship’s feasible speed range and ρ takes its value between 0% (ballast) and 100% (fully loaded). The parameters A, B and C are ship specific and obtained based on empirical fuel consumption values for each ship. The function also implies a linear relationship between payload and fuel consumption at a given speed, instead of a more sophisticated non-linear version (see Section 2.2.2), but it gives an acceptable approximation of the fuel consumption between ballast and fully-loaded (laden) states based on real data of these ships. Figure 1 depicts the fuel consumption characteristics for one of the ships used in the test instances, a Handymax bulk carrier of 56800 deadweight tonnes (dwt) capacity. The fuel consumption function in this case is $FC = (0.0019s^2 - 0.045s + 0.3739) \times (0.8 + 0.2\rho)$, where the feasible speed range of s is between 10 and 20 knots. The fuel consumption curves for ballast, half-loaded, and fully-loaded are shown in Figure 1, which correspond to $\rho = 0\%$, 50% and 100%, respectively.

4.2 Computational results

We first use one instance, Deep-Full-C50-V20-1, as an illustrative example to demonstrate the impact of an increase in fuel price on the tramp operator’s operational decisions and its fuel consumption and CO₂ emissions. This instance considers 50 cargoes, 20 ships and has the characteristics of deep sea shipping and full load cargoes.

Table 1 shows the results for instance Deep-Full-C50-V20-1 when altering the fuel price from \$200 to \$600 per tonne. It is clearly visible that as the fuel price goes up, the profit of the company decreases. The number of cargoes served also decreases from 46, when fuel price is \$400 and below, to 43 and 37, when fuel price is as high as \$500 and \$600

Table 1: Comparison under different fuel prices for instance Deep-Full-C50-V20.

Fuel Price /tonne	\$200	\$300	\$400	\$500	\$600
# Total Cargoes	50	50	50	50	50
# Served Cargoes	46	46	46	43	37
Income (mill \$)	34.51	34.21	34.39	32.37	28.71
Profit (mill \$)	24.57	20.54	17.05	13.58	10.66
Total Days at Sea	1594	1591	1611	1489	1285
Total Mileage	425,947	423,724	425,950	381,135	314,651
Avg Speed (knots)	11.14	11.09	11.02	10.67	10.20
Fuel Consump.(t)	49,674	45,548	43,329	37,574	30,088
CO ₂ emissions (t)	158,957	145,754	138,653	120,236	96,281
Tonne-Miles (mill t-M)	13,073	13,073	13,068	12,129	10,370
CO ₂ /Tonne-Mile (10 ⁻³ t/t-M)	0.0122	0.0111	0.0106	0.0099	0.0093

respectively. This is because the operator is rejecting more optional cargoes when fuel is expensive, so as to reduce its fuel consumption, see the “Fuel Consump.(t)” row.

One may notice that the number of cargoes served remains 46 for the first three columns, while fuel consumption in the low fuel price case is significantly higher. This is because when the fuel price is low, the operator sails the ships at faster speed to chase cargoes with higher income. Take \$200 fuel price for example, compared to the \$300 case, only one cargo is different while the other 45 cargoes are identical. When fuel is \$200 per tonne, the ship operator takes the cargo with higher income, but also needs to operate a ship at a much higher speed to be able to serve this cargo within its stipulated time windows. The fuel consumption increases accordingly, but the ship operator can afford it because of low fuel price in this case. In fact, we see this trend across Table 1 when the fuel price increases from \$200 to \$600, namely the ship operator gradually gives up those optional cargoes that are “harder” to service, so that ships can sail at lower speed and save more on fuel. This can be seen from the decreasing speed values from the “Avg Speed (knots)” row, which shows the average sailing speed of all ships in the fleet.

We also show the amounts of CO₂ emissions in Table 1, calculated from multiplying the fuel consumption by the emissions factor 3.2 (tonnes of CO₂ per tonne fuel). We then compute the total tonne-miles of all cargoes in each case. It can be seen that when the fuel price goes up, the amount of CO₂ emissions per tonne-mile of cargo transported decreases, meaning the ships are operated in a more “CO₂ efficient” way. However, this is achieved by giving up the “hard” optional cargoes, such as the ones with demanding time windows

or at difficult locations that require long ballast sailings.

Table 2 shows the comparison under two fuel prices, \$300 and \$600 per tonne, for all 16 instances. Increasing the fuel price from \$300 to \$600 per tonne implies a bunker levy of 100%, which is not realistic in the near future. In addition, higher fuel prices due to taxation probably would also result in increased freight rates (and thus higher revenues from the same cargoes, since shipping companies cannot bear all the increased costs), while the rates in our study are assumed constant. Therefore, the results are intended, only for illustrative purposes, to show the effects of a bunker levy on a tramp operator’s economic and environmental performances.

In Table 2 we summarize, for each instance and under two fuel prices, five important attributes, including the number of cargoes served, profit, average speed of the fleet, total amount of CO₂ emissions and the amount of CO₂ emitted per tonne-mile. The “%Δ” columns indicate the relative changes when increasing the fuel price from \$300 to \$600. We observe that these changes are in general consistent with the trend found based on Table 1: when the fuel becomes expensive because of a levy, the tramp operator accepts fewer cargoes to transport, especially those that need ships sailing faster to meet their time windows. There are a few exceptions, e.g., for instance Short-Full-C25-V7-2 the average fleet speed is increased by 4.5% in spite of expensive fuel. In this instance, the single cargo being dropped by the \$600 solution (compared to its \$300 counterpart) is relatively poorly paid and has a long transporting distance. In addition this cargo has an “easy” time window that allows the ship servicing it to sail a slow voyage which brings the average speed of the fleet down. When fuel becomes expensive, this slow and long voyage is dropped due to the low income of the corresponding cargo, leading to an overall increase in the fleet’s average speed.

On average across all 16 instances, we observe in Table 2 that as a consequence of the high levy on fuel, the tramp operator accepts around 10% fewer cargoes, and sails its fleet 3.5% slower. In addition, the ship operator’s total profits are 38.5% lower, whereas its fuel consumption and hence CO₂ emissions are reduced by 17.8%. Moreover, the average “CO₂/Tonne-Mile” measure decreases by 6.3% when fuel is expensive, indicating that the ships are operated more efficiently in terms of CO₂ emitted for every tonne-mile of cargo transported. As was discussed earlier, such efficiency is achieved by dropping the “hard” optional cargoes, such as the ones with difficult time windows (e.g., loading needed rather soon, or requiring fast transport) that demand high sailing speed or at difficult locations that require long ballast sailings. These potentially “inefficient” cargoes (from the single tramp operator’s perspective) are accepted when fuel price is low, but when fuel becomes too expensive with added levy, the “hard” optional cargoes no longer make worthwhile contribution to the total profits. At a broader level, these cargoes may still find their way to their respective destinations in any case, perhaps by other shipping companies.

Table 2: Comparison of results for all instances under two fuel prices, \$300 and \$600 per tonne.

Instance	# Cargoes Served		Profits (mill \$)		Avg Speed (knots)		CO ₂ emissions (t)		CO ₂ /Tonne-Mile (10 ⁻³ t/t-M)						
	\$300	\$600	%Δ	\$300	\$600	%Δ	\$300	\$600	%Δ	\$300	\$600	%Δ			
Deep-Full-C25-V7-1	23	14	-39.1	9.57	3.47	-63.7	12.4	11.6	-6.5	70,438	38,345	-45.6	0.0106	0.0094	-11.5
Deep-Full-C25-V7-2	25	20	-20.0	12.17	5.88	-51.7	12.0	11.0	-8.3	76,003	55,251	-27.3	0.0095	0.0084	-11.4
Deep-Full-C50-V20-1	46	37	-19.6	20.54	10.66	-48.1	11.1	10.2	-8.1	145,754	96,281	-33.9	0.0111	0.0093	-16.2
Deep-Full-C50-V20-2	49	39	-20.4	22.31	11.45	-48.7	10.9	10.4	-4.6	128,294	92,563	-27.9	0.0088	0.0078	-11.4
Deep-Mix-C30-V6-1	20	17	-15.0	10.26	5.92	-42.3	10.9	10.1	-7.3	45,667	36,541	-20.0	0.0138	0.0130	-5.8
Deep-Mix-C30-V6-2	21	20	-4.8	11.07	7.92	-28.5	12.0	11.1	-7.5	48,240	33,805	-29.9	0.0164	0.0127	-22.6
Deep-Mix-C35-V7-1	35	31	-11.4	41.50	22.03	-46.9	14.4	14.2	-1.5	227,949	174,845	-23.3	0.0059	0.0059	0.0
Deep-Mix-C35-V7-2	35	33	-5.7	50.85	34.78	-31.6	14.2	14.3	0.4	176,144	162,297	-7.9	0.0057	0.0055	-3.5
Short-Full-C25-V7-1	24	23	-4.2	2.07	1.21	-41.5	11.6	11.5	-0.9	9,277	8,630	-7.0	0.0206	0.0201	-2.4
Short-Full-C25-V7-2	25	24	-4.0	2.11	1.17	-44.5	11.1	11.6	4.5	10,218	9,325	-8.7	0.0205	0.0198	-3.4
Short-Full-C50-V20-1	50	50	0.0	5.30	3.58	-32.5	12.5	12.4	-0.8	19,123	18,726	-2.1	0.0146	0.0143	-2.1
Short-Full-C50-V20-2	50	48	-4.0	4.73	3.01	-36.4	12.5	12.4	-0.7	19,260	17,469	-9.3	0.0155	0.0149	-3.9
Short-Mix-C30-V6-1	30	28	-6.7	4.14	3.04	-26.6	12.8	12.4	-3.3	12,102	9,856	-18.6	0.0251	0.0248	-1.2
Short-Mix-C30-V6-2	30	29	-3.3	3.76	2.75	-26.9	11.9	11.7	-1.7	10,842	9,898	-8.7	0.0260	0.0263	1.2
Short-Mix-C35-V7-1	35	34	-2.9	4.32	3.28	-24.1	11.4	11.3	-1.3	12,732	11,245	-11.7	0.0235	0.0218	-7.2
Short-Mix-C35-V7-2	35	34	-2.9	5.03	3.91	-22.3	12.0	11.0	-8.0	11,136	10,800	-3.0	0.0242	0.0243	0.4
Average Change			-10.2			-38.5			-3.5			-17.8			-6.3

However, the imposition of a levy may help the players in the market increase their CO₂ efficiency as a whole by redistributing the cargoes to their appropriate carriers.

5 Conclusion

This chapter has presented the typical tramp ship routing and scheduling model and discussed how market-based CO₂ reduction measures, including the bunker levy and ETS schemes, can be incorporated into the model. It has been shown that from the viewpoint of a tramp ship operator on the operational level, the implementation of an ETS implicates the addition of an extra charge on every tonne of fuel consumed, which is similar to a bunker levy. Such conclusion was obtained when assuming that the CO₂ allowances initially acquired are sunk costs. This assumption is consistent with the typical context of a tramp ship routing and scheduling problem, but the effects of an emission reduction scheme on a ship operator's tactical decisions need to be addressed and further studied. For example, the shipping company might cut back on long-term contracts or reduce the size of its fleet if the extra costs for CO₂ reduction are too expensive. These may lead to modal shifts from (short sea) shipping to land-based transportation modes and potential carbon leakage.

A computational study on 16 benchmark instances has been done to demonstrate the effects of implementing a bunker levy in the form of a tax based on fuel price. It has been shown that in response to a largely elevated fuel price, the ship operator will accept fewer optional cargoes, slow down the ships, and operate the fleet in a more "CO₂ efficient" way, i.e., emit less per tonne-mile of cargo transported.

Many perspectives remain open with respect to this study. First, we focused on decisions made by a tramp ship operator on a operational/tactical level. This scope can be expanded to include some important and directly relevant tactical/strategic decisions such as the composition of the fleet, i.e., to determine if the size and mix of the fleet need changing to adapt to new environmental regulations. Second, similar analysis from this work can also be done in other shipping sectors, such as container shipping.

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