



# Bunker consumption optimization methods in shipping: A critical review and extensions



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## ABSTRACT

It is crucial nowadays for shipping companies to reduce bunker consumption while maintaining a certain level of shipping service in view of the high bunker price and concerned shipping emissions. After introducing the three bunker consumption optimization contexts: minimization of total operating cost, minimization of emission and collaborative mechanisms between port operators and shipping companies, this paper presents a critical and timely literature review on mathematical solution methods for bunker consumption optimization problems. Several novel bunker consumption optimization methods are subsequently proposed. The applicability, optimality, and efficiency of the existing and newly proposed methods are also analyzed. This paper provides technical guidelines and insights for researchers and practitioners dealing with the bunker consumption issues.

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## 1. Introduction

Maritime transportation is the backbone of world trade, and world seaborne trade was estimated at 8.4 billion tons in terms of the total goods loaded in 2011 (UNCTAD, 2011). In recent years, increased competition and global shipping downturn have been putting downward pressure on the revenues of shipping companies; at the same time, increased security regulations and fuel prices continued to increase their operating costs. The bunker cost constitutes a large proportion of the operating cost of a shipping company (Notteboom, 2006). For example, Ronen (2011) estimated that when bunker fuel price is around 500 USD per ton the bunker cost constitutes about three quarters of the operating cost of a large containership.

The amount of bunker consumed by ships also determines the amount of gas emission, including Green House Gas (GHG) such as carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), Non-Green House Gases such as sulfur oxides (SO<sub>x</sub>) and nitrogen oxides (NO<sub>x</sub>), and various other pollutants, such as particulate matter, volatile organic compounds, and black carbon (Psaraftis and Kontovas, 2013). The above gases have negative effect on global climate. For example, GHGs contribute to global warming, SO<sub>x</sub> causes acid rain and deforestation, and NO<sub>x</sub> causes undesirable health effects. According to the 2009 GHG study by the International Maritime Organization (IMO, 2009), international shipping contributes 2.7% of the CO<sub>2</sub> emitted globally. IMO is currently considering many measures to reduce GHGs (Psaraftis, 2012). For instance, the IMO Marpol 73/78 Annex VI regulations aim to reduce nitrogen oxide (NO<sub>x</sub>) emissions and prevent sulfur oxide (SO<sub>x</sub>) and particulate matter emissions from ships. In view of strict regulations on CO<sub>2</sub> emission, tradable CO<sub>2</sub> emission schemes have been developed and applied, and the current average contract price is about 8 Euros per ton of CO<sub>2</sub> emitted (ICE-ECX, 2012). To meet

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future regulation on emission, shipping companies must either reduce bunker consumption or use cleaner but more expensive bunker fuel, or purchase emission quota from other companies.

### 1.1. Impact of sailing speed on shipping capacity, inventory cost and bunker consumption

The bunker consumption of a ship on one hand depends on the design and structure of the ship, and it is on the other hand very sensitive to the sailing speed. This study focuses on the impact analysis of sailing speed on bunker consumption.

Fig. 1 plots the relations between sailing speed and bunker consumption for four types of ships: ships with a capacity of 3000 twenty-foot equivalent units (3000-TEU ships for short), 5000-TEU ships, 8000-TEU ships and 10000-TEU ships. Clearly, when the speed increases, the bunker consumption increases more than linearly. Ronen (1982) mentioned that daily bunker consumption is approximately proportional to the sailing speed cubed, and Wang and Meng (2012a) further calibrated the relation using historical operating data of containerships and found that the exponent is between 2.7 and 3.3, which supports the third power approximation. Du et al. (2011) used the exponent of 3.5 for feeder containerships, 4 for medium-sized containerships, and 4.5 for jumbo containerships according to suggestions of a ship engine manufacturing company. Kontovas and Psaraftis (2011) suggested using an exponent of four or greater when the speed is greater than 20 knots.

In general, a higher sailing speed has both advantages and disadvantages. The first advantage is that the amount of cargo that can be shipped annually is larger. For example, consider a ship with a capacity of 10,000 tons that sails between two ports (A and B) whose distance is 10,000 n miles, and suppose that the total time for discharging and then loading a full ship load is 3 days at each port, as shown in Fig. 2. If the ship sails at 15 knots, it needs  $3 + 10,000/(24 \times 15) \approx 30.8$  days to transport 10,000 tons of cargo from port A to port B (or from port B to port A). Therefore in 1 year it can transport  $365/30.8 \times 10,000 = 1.19 \times 10^6$  tons of cargo. If the ship sails at 20 knots, it needs only 23.8 days to ship cargo from A to B and hence would be able to transport  $1.53 \times 10^6$  tons of cargo annually. The second advantage is that the inventory cost associated with shipping is lower. In the above example, the cargo needs a total of 30.8 days for maritime transportation and handling if the ship sails at 15 knots, and needs only 23.8 days at the speed of 20 knots. The inventory cost of containerized cargos is high because of the high value of the cargos. For instance, Notteboom (2006) estimated that one day delay of a 4000-TEU ship implies a total cost of 57,000 Euros associated with the cargos in the containers; Bakshi and Gans (2010) estimated the inventory cost of containerized cargo at 0.5% the value of a container per day.

The disadvantage of a higher sailing speed is that the amount of bunker burned is much higher. Suppose that the daily bunker consumption is proportional to the sailing speed cubed. As a result, the bunker consumption for accomplishing a trip from port A to port B in Fig. 2 is proportional to the sailing speed squared (the daily bunker consumption is proportional to the sailing speed cubed, but the number of days required is inversely proportional to the sailing speed). Therefore, the amount of bunker consumed annually at the speed of 20 knots (proportional to  $20^2 \times (365/23.8) \approx 6134$ ) is 130% higher than that at the speed of 15 knots (proportional to  $15^2 \times (365/30.8) \approx 2666$ ), and the amount of cargo carried is only  $(1.53-1.19)/1.19 \approx 29\%$  higher. Consequently, the optimal sailing speed is desirable to balance the tradeoffs between cargo shipping capability, inventory cost, and bunker cost.

### 1.2. Contexts of bunker consumption optimization

In literature, bunker consumption optimization is cast into three application contexts. The first one is minimizing the operating cost of a shipping company by optimizing the sailing speed. For example, in shipping network design (Alvarez,

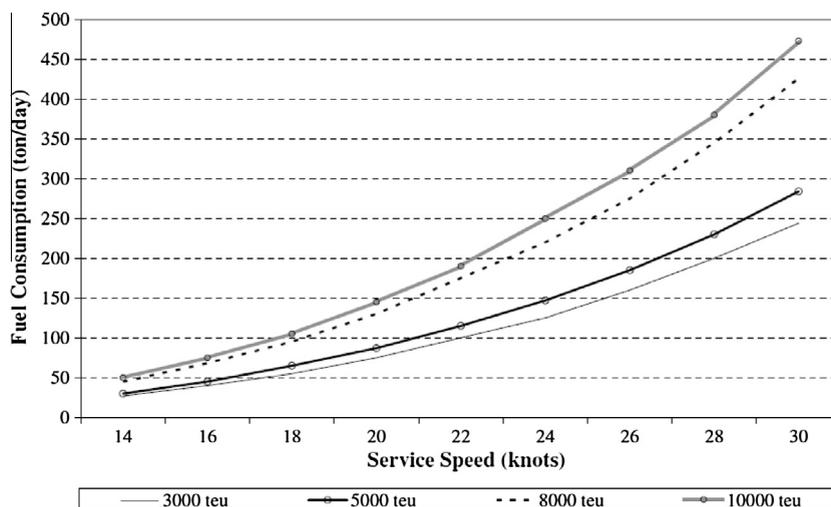


Fig. 1. Sensitivity of bunker consumption with regard to speed (Notteboom, 2006).

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