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Speed optimization over a path with heterogeneous arc costs

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ABSTRACT

The speed optimization problem over a path aims to find a set of speeds over each arc of the given path to minimize the total cost, while respecting the time-window constraint at each node and speed limits over each arc. In maritime transportation, the cost represents fuel cost or air pollutant emissions, so study of this problem has significant economic and environmental impacts. To accommodate different fuel and emission models, we allow the dependence of the cost on the speed to be a general continuously differentiable and strictly convex function, and different across the arcs. We develop an efficient algorithm that is able to solve instances of 1000 nodes in less than a second. The algorithm is 20 to 100 times faster than a general convex optimization solver on test instances and requires much less memory. The solutions found at intermediate steps of our algorithm also provide some insights to ship planners on how to balance the operating cost and service quality.

1. Introduction

Maritime transportation plays an important role in international trade. The volume of seaborne shipments surpasses 10 billion in 2015, accounting for more than four fifths of total world merchandise trade (United Nations Conference on Trade and Development, 2016). In maritime transportation, vessel sailing speed has a significant impact on bunker consumption, emissions, and transit time, and therefore is a critical operational decision (Psaraftis and Kontovas, 2014). It has been shown that reducing sailing speed can lead to substantial savings in bunker consumption (Wang et al., 2013; Psaraftis and Kontovas, 2014; 2015), which constitutes a significant portion of the operating cost for a shipping company (Notteboom, 2006). Meanwhile, the greenhouse gas emissions are positively correlated to the bunker consumption, so reducing sailing speed also effectively reduces emissions and the negative impact on the environment (Fagerholt et al., 2015). On the other hand, lower sailing speed means longer transit and delivery time, which affects the service quality and other operational decisions (Norstad et al., 2011; Wang and Meng, 2012b; Meng et al., 2013; Psaraftis and Kontovas, 2014; Xia et al., 2015). Therefore, speed optimization is a basic problem in maritime transportation for understanding the trade-off among operating cost, environmental impact, and service quality.

In this paper, we study a low-level operational problem regarding the vessel speed decisions. To be more specific, we would like to answer the following research question.

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> Speed Optimization over a Path (SOP): Given a sequence of nodes over a path, what is the optimal speed between each pair of consecutive nodes such that the total cost over the path is minimized and each customer is served within a prescribed time window?

This question was initially studied by Fagerholt et al. (2010) in the context of tramp shipping. In Fagerholt et al. (2010), a tramp trip is scheduled to visit a sequence of ports over a route, and the goal is to find the sailing speed over each leg of the route to minimize the fuel consumptions. The fuel consumption rate is assumed to be the same over all legs of the route.

In this paper, we assume that the costs per unit distance traveled are *different across the arcs*. We consider heterogeneous arc costs due to the following practical concerns: (1) the fuel consumption as well the emissions depend on many factors other than the speed, and some factors, such as vessel load and weather conditions, change over the route (for example, the daily bunker consumptions for a ship with full load and in ballast can differ by up to 30% of the total bunker consumption at the same speed (Psaraftis and Kontovas, 2014)); (2) the fuel price varies across ports, so the fuel cost per mile changes even with the same fuel consumption rate; (3) some ships use different types of fuels when sailing inside and outside emission control areas to follow the environmental regulations (Cullinane and Bergqvist, 2014; Fagerholt and Psaraftis, 2015). Therefore, heterogeneous cost functions in the speed optimization model provide a more accurate assessment of the bunker consumption and emissions.

The SOP is a nonlinear programming problem, so it is difficult to find a global optimal solution in general. In this paper, we assume the cost is a continuously differentiable and strictly convex function of the speed. Many fuel consumption and emission models used in practice satisfy this assumption (Psaraftis and Kontovas, 2013), for example the cubic function frequently used to estimate the daily bunker consumption (Ronen, 1982). Under this assumption, the SOP can be formulated as a convex optimization problem, and solved by a general convex optimization solver. However, the general solver offers little managerial insight to the ship planner other than the optimal speeds, and does not explore the special structure of the cost functions. Moreover, the SOP often appears as a subproblem in many more complex models involving other tactical and operational decisions, such as tramp ship routing and scheduling (Norstad et al., 2011), liner service network design (Meng and Wang, 2011; Wang and Meng, 2012a), fleet management (Alvarez, 2009; Gelareh and Meng, 2010), and the pollution-routing problem (Bektaş and Laporte, 2011). Thus a customized fast algorithm that can be easily embedded as a subroutine into other exact and heuristic methods is needed for the SOP.

In this paper, we develop a simple and efficient algorithm for the SOP. The algorithm is able to solve instances of 1000 nodes in less than one second. The Matlab implementation of the algorithm requires less than 100 lines of code. Another observation, that may be of independent interest, is that our algorithm requires much less memory than a general convex optimization solver; it is able to solve instances of 1,000,000 nodes in several hundred seconds while the general solver runs out of memory for instances of 10,000 nodes. We now summarize the contribution of our paper as follows.

- We study a speed optimization problem over a path to minimize the fuel consumption and emissions. The problem features heterogeneous convex costs and heterogeneous speed limits across arcs and service time-windows constraints.
- We develop a simple and efficient algorithm when the cost over each arc is a continuously differentiable and strictly convex function of the speed. Our algorithm is 20 to 100 times faster than a general convex optimization solver on test instances and requires much less memory.
- The solutions found at intermediate steps of our algorithm provide some insights to ship planners on how to balance operating cost and service quality.

The rest of the paper is organized as follows. Section 2 reviews the speed optimization models and algorithms in the literature and how they are integrated into other planning and operational models. Section 3 gives the mathematical description of the problem we study. Section 4 describes our algorithm and Section 5 elaborates one critical subroutine of the algorithm. Section 6 illustrates our algorithm with a practical example. Section 7 presents computational results on test instances with our algorithm. We conclude in Section 8.

2. Literature review

The bunker consumption as well as emissions of a ship depend on many factors including sailing speed, engine technology, and vessel and fuel types. Many functions have been proposed in the literature to quantify the relationship between the daily bunker consumption and sailing speed. The cubic function is frequently used in the literature for the estimation (Ronen, 1982; Notteboom and Vernimmen, 2009; Ronen, 2011). In Wang and Meng (2012b), the function is assumed to be a power function of the sailing speed, and the power is calculated to be between 2.7 and 3.3 with empirical data, providing some support for the cubic approximation. A quartic function is suggested by Kontovas and Psaraftis (2011) when the vessel speed is greater than 20 knots. Power functions that are dependent on vessel types are used in Du et al. (2011), with degree 3.5 for feeder containerships, degree 4 for medium-sized containerships, and degree 4.5 for jumbo containerships. Another important factor that affect the bunker consumption rate is the vessel load. It is shown in Psaraftis and Kontovas (2014) that the difference between bunker consumption for a ship at full load or in ballast at the same speed can be as much as 25% to 30% of the total bunker consumption, for the type of Very Large Crude Carrier. Load-dependent bunker consumption functions have also been considered in Psaraftis and Kontovas (2013); Xia et al. (2015). For a comprehensive