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Ship speed optimization: Concepts, models and combined speed-routing scenarios

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ABSTRACT

The purpose of this paper is to 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.

1. Introduction

In recent years, increasing fuel prices, depressed market conditions and environmental issues as regards air emissions from ships have brought a new perspective to ship speed. If this perspective had not received much emphasis in the past, this is not so today, and it will receive even more attention in the future. In addition to being efficient from an economic perspective, a ship also has to be environmentally friendly as regards air emissions. To that end, significant regulatory activity is already taking place within the International Maritime Organization (IMO) and other bodies. Such activity aims to cover the whole range from technical to operational to market-based measures and a wide spectrum of emissions, from greenhouse gases (GHGs) such as carbon dioxide (CO_2), to non-GHG gases such as sulfur oxides (SO_x), nitrogen oxides (NO_x), particulate matter (PM) and others.

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. It that sense, the impact of a change in ship speed on both ship operating costs and emissions can be quite dramatic. This can be manifested at two levels, the design level and the operational level.

At the design level, 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).

At the operational level, the practice of reducing speed as a response to depressed market conditions and/or high fuel prices is known as "slow steaming", and is being practised in almost every commercial ship sector these days, including tankers, bulk carriers and containerships. In its simplest form, slow steaming may involve just slowing down vis-à-vis a vessel's design speed. However, speeds cannot be reduced below a certain threshold, as the ship's main engine may stall. Higher

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

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speed reductions can be achieved in modern, electronically-controlled engines than in older, camshaft-controlled engines. In order that slower speeds can be attained, it may be necessary to ‘derate’ the engine, that is, reconfigure the engine so that a lower power output is achieved, Such a reconfiguration may involve dropping one or more cylinders from the main engine or other measures. Depending on engine technology, ‘slow steaming kits’ are provided by engine manufacturers so that ships can smoothly reduce speed at any desired level. In case speed is drastically reduced, the practice is known as “super slow steaming”.

In practice, super slow steaming has been pioneered by Maersk Line after it initiated trials involving 110 container vessels beginning in 2007. These trials showed that 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. Slow steaming is also being practiced in other shipping markets.

In addition to being important from an economics perspective, speed reduction can also have important environmental benefits, as emissions from ships are directly proportional to fuel burned. In that sense, speed reduction is one of the important operational or logistics-based measures to reduce emissions from ships.

The purpose of this paper is to clarify some important issues as regards ship speed optimization at the operational level and to develop models that optimize ship speed for a spectrum of ship routing scenarios and for several variants that concern the objective function to be optimized. Its main contribution vis-a-vis the state of the art is the incorporation of those fundamental parameters and other considerations that weigh the most in a ship owner’s or charterer’s speed decision at the operational level and also in his routing decision, wherever relevant. These are (a) the fuel price, (b) the state of the market (freight rate), (c) the inventory cost of the cargo, and (d) the dependency of fuel consumption on payload. To do so, the paper goes over various examples so as to illustrate the properties of the optimal solution and the various trade-offs that are involved.

The rest of this paper is organized as follows. In Section 2 we discuss modeling approaches for this class of problems, including assumptions, simplifications and possible misconceptions. In Section 3 we list the scenarios and problem variants examined in the paper. In Section 4 we discuss some properties of the optimal solution, including some that are counter-intuitive. Finally in Section 5 we present the paper’s conclusions. Appendix A describes the algorithm used for one of the examples in the paper.

2. Modeling approaches: Assumptions, simplifications and possible misconceptions

2.1. Treatment of speed in the literature

Before we deal with ship speed problems, we cite a parallel body of research in road transportation, in which vehicle speed is a decision variable that impacts various attributes including cost and emissions. See for instance Figliozzi (2010), Bektas and Laporte (2011), Erdoğan and Miller-Hooks (2011), Özceylan et al. (2011) and Kopfer and Kopfer (2013). In these papers, economic and environmental trade-offs among several objective functions are examined, in case vehicle speed is constant or variable. The main difference with a maritime setting is the form of fuel consumption function, which in the road setting is a function of road profile, driver behavior, and other factors that are not relevant in shipping. However from an optimization viewpoint it is clear that some of the techniques used can be very relevant (e.g., neighborhood search).

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

However, not including speed as a decision variable may render solutions subobtimal. This is so because generally there are important economic trade-offs between (a) the lower charter and cargo inventory costs associated with a higher speed and (b) the higher fuel costs associated with such higher speed. Assuming a fixed speed precludes the balancing of such trade-offs. A speed that is assumed fixed may also in some cases remove flexibility in the overall decision making process. For problems that include port capacity constraints, berth occupancy constraints, time window constraints or other constraints that preclude the simultaneous service of more than a given number of vessels, satisfying such constraints would conceivably be easier to meet were it not for the assumed constancy in ship speed.

Assuming fixed ship speeds is typically also the case for models that compute shipping emissions worldwide, even though typically these do not belong to the OR/MS literature. See for instance IMO (2009) and Psaraftis and Kontovas (2009), among others. In their calculations, these models typically take as input *design speeds* extracted from commercially available ship databases, such as those maintained by IHS Fairplay, among others.

Still, dealing with speed is not new in the maritime transportation literature and this body of knowledge is rapidly growing. In Psaraftis and Kontovas (2013) some 40 relevant papers were reviewed and a taxonomy of these papers according to various criteria was developed.

As in other areas, most OR/MS papers that deal with ship speed consist of two basic steps: (A) the formulation of an optimization model, followed by (B) the design and testing of an algorithm, exact or heuristic, that solves the optimization problem associated with the model. Both steps (A) and (B) are important. Much as it would not make sense to develop an