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On two speed optimization problems for ships that sail in and out of emission control areas

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ABSTRACT

This paper deals with two speed optimization problems for ships that sail in and out of Emission Control Areas (ECAs) with strict limits on sulfur emissions. For ships crossing in and out of ECAs, such as deep-sea vessels, one of the common options for complying with these limits is to burn heavy fuel oil (HFO) outside the ECA and switch to low-sulfur fuel such as marine gas oil (MGO) inside the ECA. As the prices of these two fuels are generally very different, so may be the speeds that the ship will sail at outside and inside the ECA. The first optimization problem examined by the paper considers an extension of the model of Ronen (1982) in which ship speeds both inside and outside the ECA are optimized. The second problem is called the ECA refraction problem, due to its conceptual similarity with the refraction problem when light travels across two different media, and also involves optimizing the point at which the ship crosses the ECA boundary. In both cases the objective of the problem is to maximize daily profit. In addition to mathematical formulations, examples and sensitivity analyses are presented for both problems.

Introduction

Ocean-going vessels carry more than 90% of global trade (IMO, 2014), and shipping is considered an environment-friendly mode of transport. However, there are still significant emissions associated with shipping operations. Emissions from the shipping industry are closely correlated to its consumption of fuel, which has been estimated to be between 279 and 400 million tons (Cullinane and Bergqvist, 2014). The so-called Third IMO GHG study 2014 (Smith et al., 2014) provided updated estimates of carbon dioxide (CO_2) emissions from international shipping from 2007 to 2012. The 2012 figure was 796 million tonnes, down from 885 million in 2007, or 2.2% of global CO_2 emissions. CO_2 from all shipping was estimated at 940 million tonnes, down from 1100 tonnes in 2007. The reduction was mainly attributed to slow steaming.

As early as in 1997 in Kyoto, the United Nations Framework Conference on Climate Change (UNFCCC) designated the International Maritime Organization (IMO), the United Nations specialized agency with responsibility for the safety and security of shipping and the prevention of marine pollution by ships, as the body responsible for regulating maritime air emissions. In 2008, the Marine Environment Protection Committee (MEPC) of the IMO adopted amendments to the MARPOL Annex VI regulations that deal with SO_x and NO_x emissions. These amendments set the global limit on the sulfur

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content of a ship's fuel to 3.50% (from 2012) followed by a reduction to 0.50% from 2020 (though subject to a review to be completed by 2018 which may conclude to prolong this stricter requirement to 2025).

Four Emission Control Areas (ECAs) have also been defined by MARPOL, as shown in Fig. 1. These are the Baltic Sea, the North Sea and English Channel, and the North American and the US Caribbean coasts. The North American ECA applies to all ships sailing within 200 nautical miles of the North American coastline, including Canada, while for the other ones they are as illustrated in Fig. 1. Within these ECAs there is even more stringent control of the sulfur emissions with a limit of 0.1% sulfur content in the ship's fuel from January 1, 2015. The North American and US Caribbean ECAs also regulate NO_x emissions. In addition, the EU has adopted legislation transposing the IMO regulations into EU law, the latest version of which is Directive 2012/33/EU (also known as the sulfur directive). The sulfur directive is more stringent than MARPOL Annex VI, as irrespective of the outcome of the proposed IMO review in 2018, a reduction to a cap of 0.50% sulfur content will be unilaterally implemented in the EU on 1 January 2020 and also all passenger ships in the EU's non-ECA waters will have a maximum 1.5% sulfur content until that time.

There are mainly three ways shipping companies can achieve compliance with the ECA sulfur regulations, i.e. fuel switching, installing a scrubber and using liquefied natural gas (LNG) as fuel. For ships that operate both within and outside ECAs, such as deep-sea vessels, fuel switching is a straightforward compliance alternative. This means that the ships burns marine gas oil (MGO) within ECAs, while the more commonly used and cheaper fuel type, heavy fuel oil (HFO), is used outside. The ability to switch fuels is a necessity for deep-sea vessels that cross in and out of ECAs, so these ships need to keep two sets of segregated fuel tanks, one for HFO and another for MGO. Modifications should also be made in the fuel pump system and would also involve installing a fuel switch and a cooler, as HFO is preheated whereas MGO should be injected cold. The corresponding investment costs are ship dependent but in any event are about an order of magnitude lower as compared to the other two compliance options (see below).

The second option is to install a scrubber, which is a filtering/cleaning system to remove the sulfur from the exhaust. This permits the ship to use HFO in ECAs. The scrubber solutions are usually not considered cost effective for deep-sea vessels as the portion of time they spend in ECAs is low.

The third alternative involves using liquefied natural gas (LNG) as fuel. This virtually eliminates emissions of sulfur and potentially many other substances such as nitrogen oxides. This involves high investments for retrofitting the ship so that it can store and burn LNG, and also making sure there are adequate shoreside LNG supply facilities at the ports in which the ship will refuel.

Compliance with ECA regulations has received significant attention lately, both from shipping companies and from the research community. A recent special issue in Transportation Research Part D (Cullinane and Bergqvist, 2014) included several papers examining the ECA issue from various angles. These included Jiang et al. (2014) who performed an economic analysis to compare scrubbers and fuel switching, and Panagakos et al. (2014) who examined the possible designation of the Mediterranean as a Sulfur ECA. Brynolf et al. (2014) and Balland et al. (2012, 2013) also analyzed SO_x compliance in combination with NO_x abatement.

Fagerholt et al. (2015) developed an optimization model to be applied by ship operators for determining optimal routing and sailing speeds for a ship along a given sequence of ports, where some of the sailing is within ECAs. The objective was to minimize fuel costs. The paper considered fuel switch as a compliance means. A computational study was performed on a number of realistic shipping routes in order to evaluate possible impacts on fuel consumption and costs from the speed and routing decisions resulting from the ECA regulations. In contrast to what we do in this paper, Fagerholt et al. (2015) minimized costs and assumed there were time windows at the ports along the route.

In this paper we consider two new speed optimization problems that arise for ships that use fuel switch and sail in and out of ECAs, such as for instance deep-sea vessels. The first problem, studied in Section 'Extension of Ronen's approach to ECAs', is similar as the one introduced by Ronen (1982) in his pioneering paper on speed optimization, though extended to the situation with ECAs. The second problem we consider, presented in Section 'The ECA refraction speed optimization problem', is the so-called ECA-refraction problem. This problem also considers determining the sailing path between a port within the ECA and one outside the ECA, including the crossover point through the ECA boundary. In both cases the objective of the problem is to maximize daily profit. It should be emphasized that when maximizing daily profit, there is a tradeoff between the revenue and the fuel costs. A higher speed increases the revenue per time unit as the ship will be able to perform more voyages, but this also increases fuel consumption and fuel cost. For each of these two speed optimization problems with ECAs we propose a mathematical formulation and provide some test examples including sensitivity analysis.

Extension of Ronen's approach to ECAs

Ronen (1982) considered determining the optimal speed for three different types of voyages, where his Model 1 for an income generating leg probably has the most practical applicability. Therefore, we consider this type of voyage and extend Ronen's model to the case where the sailing leg is partially within the ECA and partially outside. This means there is a given distance within the ECA where the ship must use the more expensive fuel (e.g. MGO) and a given distance outside where the ship can consume normal fuel (HFO). Because of the differences of fuel prices and the convex non-decreasing fuel consumption as a function of speed, it will generally be optimal to sail with different speeds within and outside the ECA.

The problem therefore consists of determining the optimal speeds on the sailing leg within and outside the ECA.