sustainability

MDPI

Article

A Bi-Level Programming Model for China's Marine Domestic Emission Control Area Design

Xuecheng Tian [1], Ran Yan [1,*], Jingwen Qi [1], Dan Zhuge [2] and Hans Wang [3,4]

1 Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Hong Kong; simontxcheng@163.com (X.T.); jingwen.qi@connect.polyu.hk (J.Q.)
2 School of Management, Shanghai University, Shanghai 200444, China; annie-dan.zhuge@polyu.edu.hk
3 Faculty of Business, The Hong Kong Polytechnic University, Hong Kong; shuaian_wang@163.com
4 Shenzhen Research Institute, The Hong Kong Polytechnic University, Shenzhen 518057, China
* Correspondence: angel-ran.yan@connect.polyu.hk

Abstract: Due to the adverse impact of seaborne sulfur emissions on coastal areas, the Ministry of Transport of the People's Republic of China is planning to implement a 0.1% sulfur cap on bunker fuel in the domestic emission control area (DECA) on 1 January 2025. As the current DECA width is only 12 NM, ships can bypass the DECA to reduce the use of high-priced ultra-low sulfur fuel oil (ULSFO) and thus save on fuel costs. The purpose of this study is first to assess the effect of China's 12-NM-wide DECA policy and then to assist the government in determining the optimal DECA width. We develop a bi-level programming model to capture the relationship between the government policy and ship operators' operations. In the lower-level programming model, we capture ship operators' decisions regarding their ships' sailing routes and speeds while considering the time required for fuel switching, which aims to minimize the total fuel costs over a given voyage. The optimal solution to the lower-level programming model is then embedded in the upper-level programming model to determine the optimal DECA width for the government, with the aim of minimizing the impact of seaborne sulfur emissions on the coastal area environment. The final results, obtained from computational experiments, validate the idea that ships tend to bypass the 12-NM-wide DECA and reduce their sailing speeds inside the DECA to decrease their use of ULSFO. Therefore, we recommend that the government increase the current DECA width to at least 112 NM to prevent ships from bypassing it and to achieve the desired sulfur reduction target.

Keywords: emission control area (ECA); domestic emission control area (DECA) of China; shipping air emissions; bi-level programming

Citation: Tian, X.; Yan, R.; Qi, J.; Zhuge, D.; Wang, H. A Bi-Level Programming Model for China's Marine Domestic Emission Control Area Design. *Sustainability* **2022**, *14*, 3562. https://doi.org/10.3390/su14063562

Academic Editor: Paolo Monti

Received: 19 January 2022
Accepted: 15 March 2022
Published: 17 March 2022

1. Introduction

Shipping transport is the backbone of international trade, with international seaborne trade reaching 10.7 billion tons in 2020 [1]. However, as more than 95% of the world's shipping fleet is powered by diesel engines that use low-quality high-sulfur fossil fuels, the shipping industry produces 13% of global anthropogenic sulfur dioxide (SO_2) emissions, which result in at least 80,000 deaths worldwide each year [2]. Due to the significant amount of SO_2 emissions from ships caused by high-sulfur fuel oil, sulfur content in marine fuel has started to become regulated globally (see Figure 1). In 2005, the International Maritime Organization (IMO) began enforcing a hard cap of 4.5% sulfur maximum for any marine fuel to decrease sulfur emissions from ships. In 2012, the cap was cut to 3.5%. Then, in 2016, the IMO announced plans to cut the sulfur cap on marine fuel to 0.5%; this 0.5% cap has been in place since 1 January 2020. The same quantity of SO_2 emitted in a port or near coastal areas is significantly more harmful than that emitted in the open sea far away from human habitats. Therefore, emission control areas (ECAs) have been established in coastal seas to impose sulfur limits for at-berth ships and ships cruising in coastal waters, which are more stringent than those imposed by the IMO for all ocean-going vessels. The

ECAs include the Baltic Sea (in effect since 19 May 2006), the North Sea (in effect since 22 November 2007), and the North American and United States Caribbean Sea areas (in effect since 1 August 2012). The sulfur limit on fuels used by sailing and at-berth ships within the ECAs was reduced from 1.5% to 1.0% on 1 July 2010, and to 0.1% on 1 January 2015. Hong Kong is the first Asian port to require at-berth ships to switch to fuels with a sulfur content of less than 0.5% since 1 July 2015. For simplicity, we refer to fuel with sulfur content not exceeding 0.1% as ultra-low sulfur fuel oil (ULSFO) and fuel with sulfur content not exceeding 0.5% as very-low sulfur fuel oil (VLSFO).

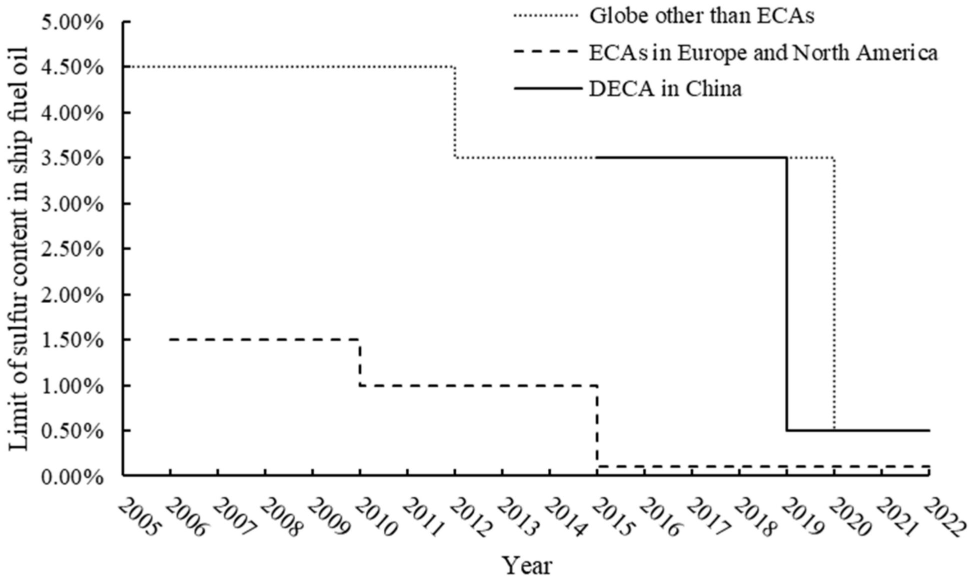

Figure 1. Upper limit of sulfur content in ship fuel oil.

Given China's vital role in global international shipping, the exhaust produced by a large number of ocean-going ships has exacerbated the environmental problem of port cities in China. To protect the marine environment, the Ministry of Transport of the People's Republic of China also took the lead in establishing a domestic emission control area (DECA) in 2015, which includes the Pearl River Delta, Yangtze River Delta, and Bohai Rim Waters [3]. Since 1 January 2019, ships within the DECA, whether sailing or berthing, have been required to use bunker fuel with a sulfur content no greater than 0.5%. In 2018, China further issued the "Marine Air Emission Control Areas Implementation Scheme", which designated the entirety of the continental territorial waters of the Chinese mainland as a DECA [4]. Additionally, in the scheme, the Ministry of Transport stated that it would evaluate the feasibility of the 0.1% sulfur cap on bunker fuel in the DECA to decide whether to implement it on 1 January 2025.

Concerning this scheme, Wang and Peng [2] pointed out the difference between China's DECA and the ECAs in Europe and North America. The difference lies in the width (the distance from the outer boundary to the coastline): the width of the DECA is only 12 NM, whereas that of the ECAs in Europe and North America is 200 NM. The narrow DECA width in China allows for ships to bypass the DECA to save on fuel costs. Taking the voyage from Shanghai to Shenzhen as an example, if ship operators want to save on fuel costs over this voyage, they may use the following detour strategy: first sailing the ship 12 NM from Shanghai to the boundary of the DECA using ULSFO, then sailing along the boundary using VLSFO at a lower price, and finally sailing 12 NM to Shenzhen using ULSFO. Although it is legal for ships to bypass the DECA while sailing from Shanghai to Shenzhen, doing so only moves sulfur emissions from the coastline to somewhere 12 NM away from the coastline. Furthermore, the total sulfur emissions increase greatly because of the much longer detour sailing route. Wang and Peng concluded that ships tend to bypass the DECA when the distance between two ports inside the DECA is long, the ratio of the price of ULSFO and that of VLSFO is high and the required fuel-switching time is long [2]. Although they have analyzed the factors affecting ships' detour behaviors, there exist some limitations. First, they only pointed out the possibility of ship detours and assessed the factors affecting ships' detours, but did not further put forward appropriate policy suggestions for the government. Second, when they evaluated ships' detour behaviors, they only roughly proposed an extremely simplified conceptual model, and did not use big data to reflect the detour behaviors of different types of ships. Consequently, our work is an extension of their work in these two aspects. Our focus is to propose the optimal DECA width design for the government. In order to derive the optimal DECA width, we take the detour behaviors of a great number of ships with real configuration information into consideration. As a result, we establish a bi-level programming model, where the upper-level programming model examines the optimal DECA policy for the government and the lower-level programming model examines ship operators' decisions regarding their ships' sailing routes and sailing speeds. Meanwhile, in our proposed model, we consider the fuel-switching period for ships that tend to bypass the DECA and use the activity-based method to assess ships' fuel consumption and sulfur emissions by using real big data.

The remainder of this paper is organized as follows. In Section 2, we review the related literature. In Section 3, the problem, mathematical model, and dataset are introduced. In Section 4, we conduct computational experiments with real-world data to uncover ship operators' decisions on the current DECA policy and formulate the optimal policy for policymakers. Finally, in Section 5, we discuss the main results and conclude the study.

2. Literature Review

The research topic of this study is to formulate an effective DECA policy by evaluating the decisions of different ship operators who own different types of ships. We focus on ships' option of fuel switching to comply with DECA policy, which is one of emission reduction technologies. Therefore, we critically review the literature in two streams: emission reduction technology adopted by the maritime industry and the effectiveness of ECAs.

Researchers have been investigating emission reduction technologies since the establishment of ECAs, including (1) installing scrubbers (i.e., ships install scrubber devices to filter the sulfur content of the exhaust); (2) using liquefied natural gas (LNG; i.e., the cleanest fossil energy on earth, with extremely low sulfur content); and (3) fuel switching (i.e., ships use low-sulfur oil in ECAs and high-sulfur oil outside ECAs). Regarding the first two options, Boscaratoa et al. [5] found that the scrubber system for filtering ship emissions was not developed enough to handle all of the contaminants generated by ship engines. Fung et al. [6] stated that using LNG instead of high-sulfur fuel oil could eliminate SO_2 emissions and reduce NOx and PM emissions by more than 80%. Then, Acciaro [7,8] and Chen et al. [9] studied the investment costs of LNG ships and indicated that there was a trade-off between low fuel prices and capital expenses for investment in LNG retrofit. Regarding the fuel-switching strategy that we study, Browning et al. [10] pointed out that using low-sulfur fuel oil in ECAs can dramatically reduce SO_2 and PM emissions, but ships' operational expenses would increase. Fagerholt et al. [11] and Chen et al. [12] studied fuel-switching strategies and concluded that ships may detour from ECAs to reduce their fuel costs by using less low-sulfur fuel oil. Zhen et al. [13] proposed a bi-objective mixed-integer linear programming model, aiming to optimize sailing routes and speeds within and outside the ECA while minimizing the total fuel cost and SO2 emissions for liner ships. In a recent study, Wang et al. [14] addressed a holistic liner shipping service planning problem that integrated fleet deployment, schedule design, and sailing path and speed optimization, considering the effect of ECAs, which could reduce the operational costs for ship operators by more than 2%. Zhuge et al. [15] also investigated a joint liner service planning problem considering three emission reduction measures, including sulfur emission regulations, carbon tax, and vessel speed reduction incentive programs, which showed great superiority in saving costs for ship operators. These studies mainly focus on ships' detour behaviors due to the establishment of ECAs. When establishing the lower-programming model of our work, we follow the proposed framework of these previous studies. However, in their models, none of them has considered the time required for fuel switching, which can affect ships' detour behaviors. In this study, we consider the fuel-switching period when analyzing ship operators' decisions. Furthermore, the existing studies mainly examined the detour route with a port inside the ECAs and the other port outside the ECAs in Europe and North America. In contrast, we focus on different sailings between two ports inside the DECA. For this reason, we need to establish slightly different models which are tailored according to the studied detour sailings.

The ECA policy has been studied by both academia and the maritime industry as an essential emission control strategy. Doudnikoff et al. [16] found decreasing the sailing speed inside ECAs and increasing the sailing speed outside ECAs to be beneficial for cost reduction, but this method increased total CO_2 emissions. Adland et al. [17] discovered that a tougher fuel sulfur content limit in the North Sea region did not affect ships' sailing speeds. Furthermore, once ECAs were introduced, a ship might no longer sail along the shortest route, as there might be another route that was longer but had a smaller proportion within the ECAs, leading to lower total costs. This phenomenon was referred to as "ECA refraction" by Fagerholt and Psaraftis [18], who considered a discrete set of candidate sailing routes and proposed a mixed-integer programming model to determine the sailing route and speed required for a ship to minimize its fuel costs. Svindland [19] compared SO_2 emissions before and after the adoption of the ECA policy and concluded that SO_2 emissions decreased after the policy was implemented. The majority of studies on the ECA policy has focused on the optimization of ships' sailing routes and speeds and on the policy's effects on the environment. We note that China's DECA is different from ECAs in Europe and North America, whereas the current DECA width in China provides great opportunities for ships to detour. Therefore, the current DECA policy cannot achieve the sulfur reduction target, which has been investigated by Wang and Peng [2]. Based on their work, we aim to design the optimal DECA policy in China's coastal areas (i.e., optimizing the width from the boundary of the DECA to the coastline) while considering ship operators' decisions regarding their ships' sailing routes and speeds between two ports inside the DECA.

3. Method

In this section, we first describe the problem to be studied in detail. We then develop a bi-level programming model that simultaneously captures and optimizes ship operators' decisions regarding their ships' sailing routes and speeds and helps policy makers formulate the optimal policy. Finally, we use automatic identification system (AIS) data to calculate ships' fuel oil consumption and sulfur emissions per hour under different discrete speeds using the activity-based method.

3.1. Problem Statement

From the perspective of the government, bypassing the DECA is legal but deviates from the original intention of establishing the DECA to reduce the sulfur emissions near coastal areas. This study aims to assist the government in finding the optimal DECA width that can achieve the expected goals among a set of DECA width scenarios. In order to achieve this goal, we need to consider different ship operators' decisions regarding their ships' sailing routes and speeds under each scenario, as ships may differ in attributes that can affect their fuel consumption and sulfur emissions. To facilitate our presentation, following the modelling method of Fagerholt et al. [11], we assume that there are several given candidate shipping routes between two ports inside the DECA, including the shortest shipping route along the coastline (which only contains a DECA stretch) and several shipping routes containing both DECA stretches and non-DECA stretches. For a certain ship and a given shipping schedule, the corresponding ship operator determines the optimal sailing route and the optimal sailing speeds in different stretches on the route. For example, as shown in Figure 2, suppose that there are three shipping routes from port A to port B, namely routes 1, 2, and 3. If the ship chooses route 1, it will use ULSFO throughout the voyage. However, if the ship chooses route 2 or 3, which include two DECA stretches and one non-DECA stretch, it will need to switch fuel when leaving and re-entering the DECA. We note that switching fuels requires time, and the time required can vary from a few hours to 3 days, depending on the ship's condition, the type of fuel and fuel pipe system, and the experience of the operators [2]. During the period that a ship switches from VLSFO to ULSFO to re-enter the DECA, the ship is required to lower the main engine power by slow sailing. Therefore, switching fuels affects the detour behaviors and sailing speeds, and we consider this in our model. In contrast, we do not consider the fuel-switching period when the ship leaves the DECA. The time required to switch to VLSFO after leaving the DECA is much shorter and can thus be ignored [2].

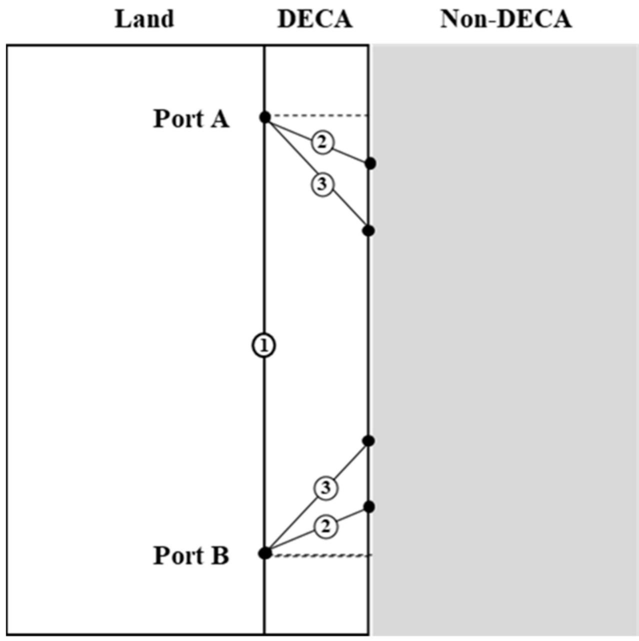

Figure 2. An example of multiple routes between two ports inside the DECA.

A bi-level programming model is therefore developed to address the above issue. The upper-level programming model captures the government's decision-making process, which is to determine the optimal DECA width among a given set of DECA width scenarios. The lower-level programming model reflects the sailing behaviors of different types of ships under each DECA width scenario. The width in different scenarios is set to 12 NM or above. Furthermore, the sulfur cap inside the DECA is set to 0.1% and the sulfur cap outside the DECA is set to 0.5%. In order to obtain the optimal DECA width design, we first need to solve the lower-level programming model, that is to analyze how ship operators decide their ships' sailing routes and speeds with the aim of minimizing the fuel costs of a given voyage under each scenario. Then, the optimal solutions of the lower-level programming model are substituted into the upper-level programming model to assess the total amount of sulfur emissions from ships in each scenario. Finally, the optimal policy of the DECA width with the minimum impact of seaborne sulfur emissions on the environment of coastal areas can be found.

3.2. Model Development

Before we present the bi-level programming model, the notation used is introduced in the nomenclature (see Table A1 in Appendix A).

First, the upper-level programming model is presented as follows:

$$\min_{y} \sum_{w\in W} y_w \sum_{r\in R} e^{-\rho l_{wr}} \sum_{s\in S} \sum_{v\in V_s} (P_{vs}^{ULSFO} T_{rvws}^{DECA} x_{rvws}^{DECA} + P_{vs}^{VLSFO} T_{rvws}^{NB} x_{rvws}^{NB} + P_{v_s s}^{VLSFO} T_{rs}^{NA} z_{rws}) \tag{1}$$

subject to

$$\sum_{w\in W} y_w = 1 \tag{2}$$

$$y_w \in \{0,1\}, \forall w \in W. \tag{3}$$

Objective function (1) in the upper-level programming model shows that the government will formulate the optimal DECA width so that the environmental impact of total seaborne sulfur emissions on coastal areas is minimized. Here, we use $e^{-\rho l_{wr}}$ to represent the environmental impact of sulfur emissions on coastal areas since the diffusion degree of emission at a certain point decays exponentially as the diffusion distance increases [20]. The setting of ρ is best determined by air quality models designed for the specific region. We separate the overall detour behavior of a ship into two main parts, with one part inside the DECA and the other part outside the DECA. Regarding the part inside the DECA, $P_{vs}^{ULSFO} T_{rvws}^{DECA} x_{rvws}^{DECA}$ represents the sulfur emissions of a ship using ULSFO. Regarding the part outside the DECA, we separate it into two segments in accordance with the fuel-switching period, where $P_{vs}^{VLSFO} T_{rvws}^{NB} x_{rvws}^{NB}$ represents the sulfur emissions using VLSFO before fuel switching and $P_{v_s s}^{VLSFO} T_{rs}^{NA} z_{rws}$ represents the sulfur emissions using VLSFO during fuel switching. x_{rvws}^{DECA}, x_{rvws}^{NB}, and z_{rws} denote the solutions of the lower-level programming model. Constraints (2) guarantee that the government can only choose one scenario for the DECA width. Constraints (3) define the binary requirements for the decision variables in the upper-level programming model.

After the government decides the DECA width, ship operators adjust their ships' sailing routes and speeds in accordance with the specific policy to minimize their fuel costs. Next, we move on to the lower-level programming model presented as follows, which describes how ship operators make decisions under each scenario.

$$\min_{x,z} \sum_{w\in W} \sum_{r\in R} \sum_{s\in S} \sum_{v\in V_s} [\alpha_1 F_{vs} T_{rvws}^{DECA} x_{rvws}^{DECA} + \alpha_2 (F_{vs} T_{rvws}^{NB} x_{rvws}^{NB} + F_{v_s s} T_{rs}^{NA} z_{rws})] \tag{4}$$

subject to

$$T_s \geq \sum_{r\in R} \sum_{v\in V_s} (T_{rvws}^{DECA} x_{rvws}^{DECA} + T_{rvws}^{NB} x_{rvws}^{NB} + T_{rs}^{NA} z_{rws}), \forall s \in S, w \in W \tag{5}$$

$$\sum_{v\in V_s} x_{rvws}^{DECA} = z_{rws}, \forall r \in R, s \in S, w \in W \tag{6}$$

$$\sum_{v\in V_s} x_{rvws}^{NB} = z_{rws}, \forall r \in R, s \in S, w \in W \tag{7}$$

$$\sum_{r\in R} z_{rws} = 1, \forall s \in S, w \in W \tag{8}$$

$$z_{rws} \in \{0,1\}, \forall r \in R, s \in S, w \in W \tag{9}$$

$$x_{rvws}^{DECA} \geq 0, \forall r \in R, v \in V_s, s \in S, w \in W \tag{10}$$

$$x_{rvws}^{NB} \geq 0, \forall r \in R, v \in V_s, s \in S, w \in W. \tag{11}$$

Objective function (4) minimizes the sum of all ships' fuel costs in the sample under all width scenarios. In accordance with the introduction of the environmental impact in the upper-level programming model, $\alpha_1 F_{vs} T_{rvws}^{DECA} x_{rvws}^{DECA}$ represents the fuel costs of using ULSFO inside the DECA, $\alpha_2 F_{vs} T_{rvws}^{NB} x_{rvws}^{NB}$ represents the fuel costs of using VLSFO outside the DECA before the ship switches fuel, and $\alpha_2 F_{v_s s} T_{rs}^{NA} z_{rws}$ represents the fuel costs of using VLSFO outside the DECA during the fuel-switching period. Constraints (5) require that the sailing time of each ship is less than the specified sailing time limit.

Constraints (6) and (7) define the relationship between speed variables and routing variables by stating that the sum of the speed weight variables for each route should equal the binary variable indicating whether this route is selected. Constraints (8) indicate that under each scenario, for each ship, only one route can be selected. Constraints (9), (10), and (11) define the binary requirements and non-negativity of the decision variables for the lower-level programming model.

3.3. Dataset Description

In this study, we apply the activity-based emission evaluation methods for marine traffic proposed by Qi et al. [21] to calculate fuel consumption and sulfur emissions of ships using AIS data. Based on the location and time information extracted from AIS and ship configuration data obtained from the World Register of Ships (WRS) database, the mass of SO_2 emitted by ships can be positioned with high spatial resolution. In our dataset, to fully characterize the decisions of different ship operators, we obtain AIS data and configuration data from 541 ships, which constitute the sample of ships to be examined. The ships of concern cover four main types (i.e., bulk ship, container ship, multi-purpose ship, and tanker) with varying sizes and attributes. The AIS data used in the numerical experiments are from the Pearl River Delta on 1 January 2017. The selected ships' sailing speeds range from slow docking to full-speed sailing, allowing for the calculation of each ship's fuel consumption and sulfur emissions per hour at different speeds. The descriptive statistics of those ships in the sample are shown in Table 1. By applying the activity-based method to the obtained data, we calculate the average SO_2 emission inventory list, as shown in Table 2.

Table 1. Descriptive statistics of various types of ships in the sample.

Ship Type	Number of Ships	Deadweight (ton)			Installed Main Engine Power (kw)			Design Speed (knot)		
		Min	Max	Mean	Min	Max	Mean	Min	Max	Mean
Bulk ship	280	2846	208,389	79,526	972	18,660	9536	11.0	15.9	14.2
Container ship	86	5956	229,039	75,967	3354	80,080	33,430	13.6	26.6	21.3
Multi-purpose ship	110	950	72,863	14,322	374	14,042	3943	7.9	19.2	12.9
Tanker	65	2277	413,842	78,987	1290	33,098	9744	10.8	16.3	14.0

Table 2. Average SO_2 emission inventory list (kg/h).

Ship Type	Deadweight (ton) /Capacity (TEU)	Speed Range (knot)			
		<1	1–8	8–12	>12
Bulk ship	≤40,000	0.074	0.326	0.706	1.606
	40,000–80,000	0.088	0.467	1.109	1.987
	80,000–120,000	0.088	0.476	1.341	2.532
	120,000+	0.088	0.675	1.888	3.659
Container ship	≤5000	0.433	1.178	1.396	2.773
	5000–10,000	0.475	1.290	2.064	5.050
	10,000–15,000	0.503	1.221	2.390	5.993
	15,000+	0.435	1.190	3.175	12.140
Multi-purpose ship	≤20,000	0.196	0.724	0.688	1.342
	20,000–40,000	0.196	0.743	0.957	1.608
	40,000–60,000	0.196	0.746	1.004	2.899
	60,000+	0.196	0.803	1.258	2.285
Tanker	≤50,000	0.300	0.394	0.940	1.649
	50,000–120,000	0.218	0.516	1.378	2.173
	120,000+	0.260	0.669	2.511	4.682

TEU: twenty-feet equivalent unit.

We assume that the DECA width in different scenarios increases from 12 NM to 300 NM with 1 NM as an interval. Therefore, we can obtain $|W| = 289$ scenarios. We take the voyage from the Port of Shanghai to the Port of Shenzhen (851 NM) as an example. Assume that there are seven candidate shipping routes to choose from for this voyage, $|R| = 7$. Among them, one route sails within the DECA for the entire voyage, and the remaining six routes include both DECA stretches and a non-DECA stretch. The time required for fuel switching from VLSFO to ULSFO is also considered. Since we cannot obtain the parameters of the time required for fuel switching T_{rs}^{NA}, the fixed sailing speed during fuel switching v_s, and the specified sailing time limit T_s, we find ship configuration information on deadweight dwt_s and the design speed v_{ds} from the WRS database, so as to derive T_{rs}^{NA}, v_s, and T_s based on the following equations:

$$T_s = \frac{851}{v_{ds} \times 0.85}, \forall s \quad (12)$$

$$v_s = v_{ds} \times 0.7, \forall s \quad (13)$$

$$T_{rs}^{NA} = \frac{dwt_s - \min[dwt]}{\max[dwt] - \min[dwt]} \times 10 + 1, \forall s. \quad (14)$$

Equation (12) represents the specified sailing time for a ship derived from the sailing distance divided by the sailing speed, at which the ship travels roughly 80% to 90% of its design speed [21]. Since a ship's sailing speed must be slowed during fuel switching, Equation (13) assumes that its fixed sailing speed during fuel switching is only 70% of its design speed. Equation (14) assumes that the required fuel-switching time for a ship is proportional to its own deadweight. As a ship's deadweight and capacity increase, the more fuel it consumes and the longer the fuel-switching time it requires [2]. Consequently, in our case study, the shortest fuel-switching time is set to 1 h and the longest fuel-switching time is 11 h.

As the vertical distance of the detour route from the coastline increases, the environmental impact of sulfur emissions generated along the route on coastal areas will decrease. By referring to the Multi-scale Atmospheric Transport and Chemistry (MATCH) potency data for Mediterranean Sea and Celtic Sea obtained by Concawe [22], we approximately set $\rho = 0.038$. Figure 3 depicts the environmental impact of sulfur emissions generated along a route on the coastal areas when $\rho = 0.038$.

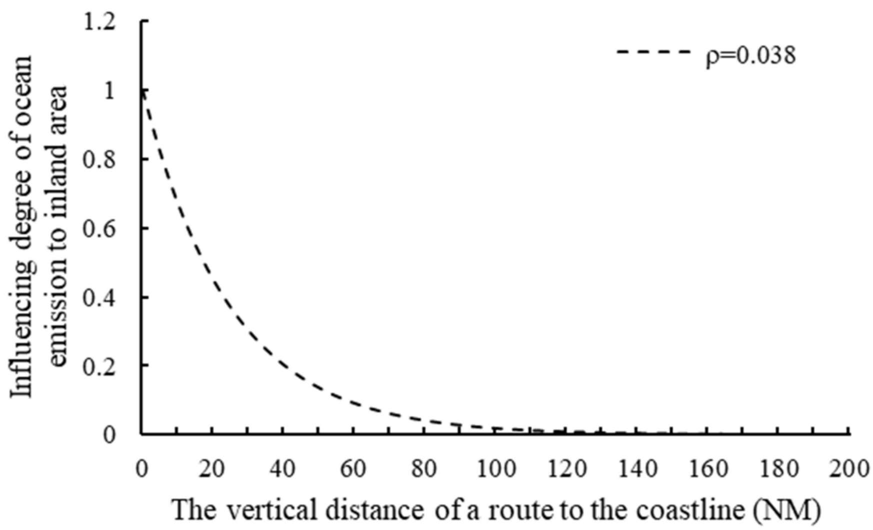

Figure 3. The environmental impact of sulfur emissions on coastal areas.

4. Results

In this section, based on ships' fuel oil consumption and sulfur emissions per hour under different discrete speeds calculated by AIS data using the activity-based method, we use an individual ship to show the impact of the DECA policy on a shipping operator's decisions. Finally, by solving the bi-level programming model [23–27], we can assist the government in determining the optimal DECA width. Uncertainties are not considered in the study [28–35].

4.1. Optimal Decisions of a Single Ship

In this subsection, we use a real ship to verify that ships tend to bypass the DECA and switch fuels to save on fuel costs when the width of the DECA is too small. We use a DECA width of 12 NM, in accordance with China's current policy. Suppose that a container ship named VANCOUVER plans to depart from the Port of Shanghai to the Port of Shenzhen. Part of its configuration information is shown in Table 3. Given the above information, its fuel-switching time is assumed to be 3 h and the sailing speed during fuel switching is set to 15 knots. We use VANCOUVER's AIS data (204 records) to assess its fuel consumption per hour at different speeds, as shown in Figure 4.

Table 3. Technical information about ship VANCOUVER.

Ship Name	Design Speed (knot)	Capacity (TEU)	Installed Main Engine Power (kw)
VANCOUVER	23.3	4253	36,559

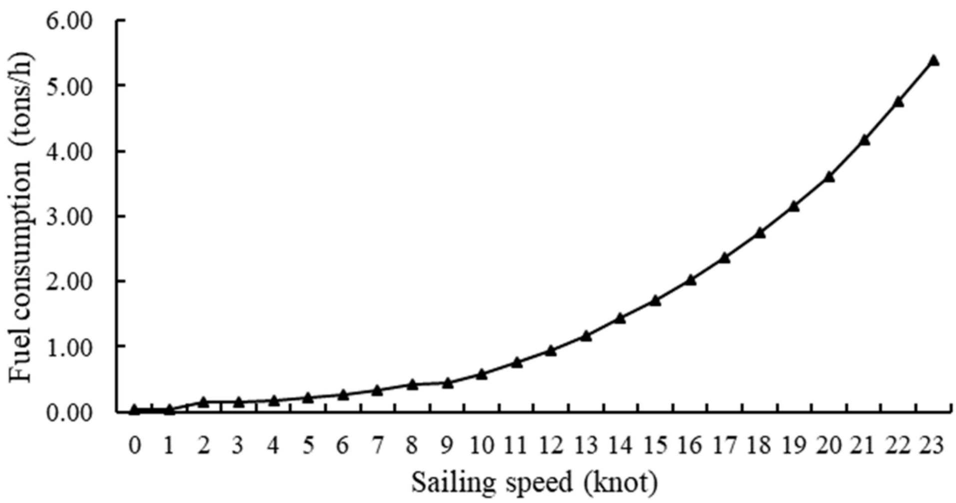

Figure 4. Fuel consumption under each sailing speed for ship VANCOUVER.

The fuel price settings in the benchmark model are searched online that the ULSFO price is $\alpha_1 = 480.5$USD/ton and the VLSFO price is $\alpha_2 = 480.5$ USD/ton [36], and we assume the specified sailing time of $T_{VANCOUVER} = 42$ h. In addition to the benchmark case, by following Fagerholt et al. [11], we adjust the ULSFO price α_1 to 790, 850, and 960 USD/ton, and perform experiments by solving the lower-programming model with the solver Gurobi called by language Python. Ship operators may take different decisions based on different fuel price combinations. The final results are shown in Table 4. The ratio column indicates by how much the average sailing speed outside the DECA increases compared with that inside the DECA. In addition, we obtain the results without considering the fuel-switching period, which are shown in Table 5.

Table 4. The optimal average speed and total costs of ship VANCOUVER for each ULSFO price considering the fuel-switching period.

α_1 (USD/ton)	Average Speed (knot)			Optimal Total Costs (USD)
	Inside the DECA	Outside the DECA	Ratio (%)	
480.5	20.27	20.27	0.00	75,751.80
790	19.00	20.96	10.4%	81,465.81
850	18.00	21.05	16.9%	81,881.05
960	17.00	21.13	24.3%	82,524.12

Table 5. The optimal average speed and total costs of ship VANCOUVER for each ULSFO price without considering the fuel-switching period.

α_1 (USD/ton)	Average Speed (knot)			Optimal Total Costs (USD)
	Inside the DECA	Outside the DECA	Ratio (%)	
480.5	20.27	20.27	0.00	75,751.80
790	19.00	20.52	8.0%	80,094.98
850	18.00	20.61	14.5%	80,501.31
960	17.00	20.67	21.6%	81,131.22

Several conclusions can be drawn from the above results shown in Tables 4 and 5. First, regardless of whether the fuel-switching period is considered, when the width of the DECA is only 12 NM, VANCOUVER will bypass the DECA to save on fuel costs. Furthermore, the average sailing speeds outside the DECA will be greater than those inside the DECA. Decreasing the sailing speed inside the DECA can reduce ULSFO consumption, thus reducing total fuel costs. As shown in Table 4, when considering the fuel-switching period, when the price of ULSFO is higher, the sailing speed inside the DECA is much lower. In this way, decreasing the sailing speed inside the DECA can reduce ULSFO consumption and fuel costs to a greater extent. In contrast, outside the DECA, the ship will increase its sailing speed to arrive at the destination port within the specified sailing time limit. Additionally, as the price gap between ULSFO and VLSFO increases, the difference between the speed inside and outside the DECA will increase.

The comparison between Tables 4 and 5 shows that the fuel-switching process increases the average sailing speeds outside the DECA. The ship is required to reduce its sailing speed to satisfy the low main engine power during the fuel-switching period. To avoid delay, the ship then needs to increase its sailing speed outside the DECA to compensate for the slow sailing during the fuel-switching period. Furthermore, the total fuel costs of considering the fuel-switching period are higher than those when the fuel-switching period is ignored. Specifically, the first method results in higher fuel costs because of the increased sailing speed outside the DECA before the fuel-switching period.

4.2. Optimal Decision about DECA Width

In the previous section, we use a specific container ship, VANCOUVER, to verify that it chooses to bypass the 12-NM-wide DECA. To determine the optimal policy from the government's perspective, we comprehensively consider the response actions of the 541 sample ships under multiple candidate width scenarios. As stated in Section 4.1, we assume that there are 289 width scenarios, ranging from 12 NM to 300 NM. The first step is to solve the lower-level programming model to find the optimal solutions that capture the responses of the 541 ships with respect to their sailing routes and speeds under each width scenario. The second step is to embed the optimal solution of each ship under each width scenario into the upper-level programming model in order to find the optimal width scenario with the minimum environmental impact on the coastal areas of total seaborne sulfur emissions. Since ship operators' decisions are highly affected by the fluctuating oil prices, more accurately, by the ratio between ULSFO and VLSFO prices, the lower-level decisions would in turn affect the optimal DECA width for the government. For this reason, we first conduct 10 sets of experiments, which are set according to different ratios of α_1/α_2 ranging from 1.1 to 2 with 0.1 as an interval. We set the VLSFO price α_2 to 480.5 USD/ton, and the final results are shown in Figure 5.

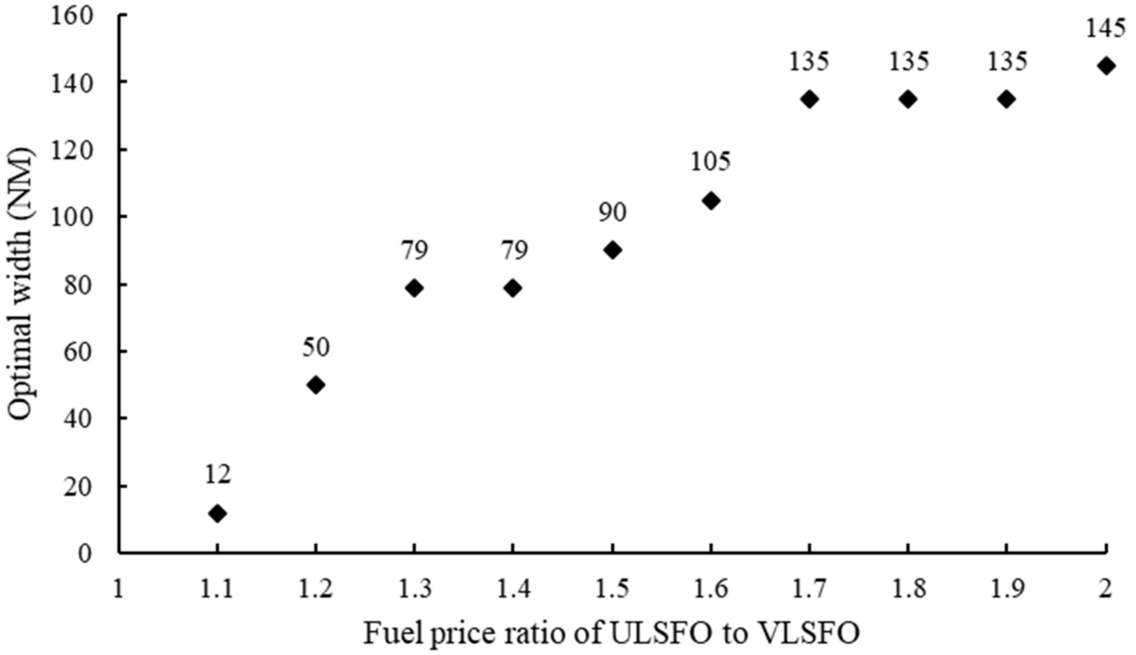

Figure 5. The optimal width for the DECA under each fuel price combination.

First, the results show that China's current DECA width can only achieve the expected emission reduction target when the fuel price ratio of ULSFO to VLSFO is less than 1.1. When the price ratio is bigger than 1.1, the optimal DECA width would be larger than the current DECA width because ships tend to bypass the DECA to reduce their ULSFO consumption and therefore their total fuel costs. As such, sulfur emissions beyond 12 NM will still have adverse impacts on the coastal environment. Therefore, increasing the DECA width is the only way to prevent ships from bypassing the DECA. Second, from Figure 5, we observe that the optimal DECA width will generally increase with the increase in the fuel price ratio, but the proportion of increase will gradually decrease. This is probably because that a higher fuel price ratio will cause more ships to bypass the DECA, so that the optimal DECA width should be increased accordingly. However, since the environmental impact of sulfur emissions on coastal areas decreases exponentially with an increased vertical distance from the detour route to the coastline (as shown in Figure 4), the emission reduction contribution brought by increasing the DECA width can be relatively limited.

In order to find a more accurate policy recommendation for the Chinese government, we searched corresponding monthly average prices of ULSFO and VLSFO from 1 November 2019, to 1 November 2021, of 20 ports around the world [36], which are shown in Figure 6. We then obtained the average price ratio of ULSFO to VLSFO during this period at about 1.24. The optimal DECA width under this price ratio is 112 NM, which does not fall into the range of 50–79 NM when the price ratio falls into the 1.2–1.3 interval. This result implies that the relationship between the optimal DECA width and the fuel price ratio is not strictly monotonic. This is because our proposed bi-level programming model considers various types of ships and many practical constraints, which can make their relationship intricate. However, we can still suggest that the Chinese government increase the current

DECA width to at least 112 NM, which is obtained by using the average value of historical fuel prices.

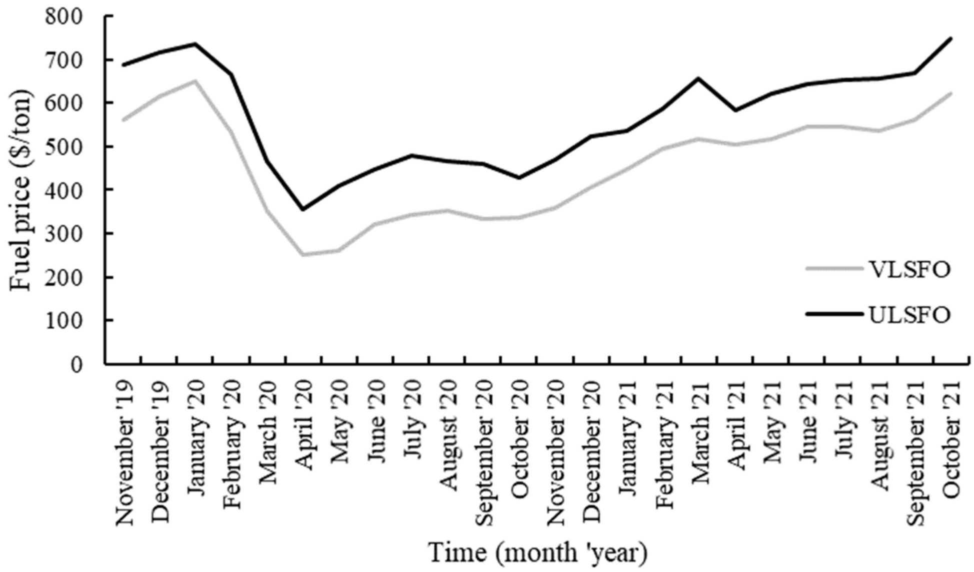

Figure 6. Historical monthly average prices of VLSFO and ULSFO.

5. Discussion

In this study, we develop a bi-level programming model to assist the government in determining China's optimal DECA width. In the lower-level programming model, we first capture ship operators' decisions regarding their ships' sailing routes and speeds while considering the time required for fuel switching, which aims to minimize the total fuel costs. We find that ships tend to bypass the DECA and reduce their sailing speeds inside the DECA to reduce the use of high-priced ULSFO. Since there is no previous study considering the fuel-switching time when simulating ships' detour behaviors, our study shows that the fuel-switching process affects ships' sailing speeds by increasing the average sailing speeds outside the DECA. The rationale is that ships need to increase their sailing speeds outside the DECA to compensate for the lowered sailing speed during the fuel-switching period. Furthermore, the total fuel costs would be increased when considering the fuel-switching period in the mathematical model, which is brought by the increased sailing speed outside the DECA before the fuel-switching period. The results indicate that our model is able to better reflect the ships' detour behaviors due to the establishment of ECAs or DECA in practice. By filling in the gaps which have not been addressed by previous related research, we lay a foundation and provide a reference for future studies that consider the fuel-switching period when investigating the policy of ECAs and DECA.

We then embed the optimal decisions of various ships in the upper-level programming model to determine the optimal DECA width, with the aim of minimizing the environmental impact of seaborne sulfur emissions on coastal areas. In the objective function of the upper-level programming model, we apply the MATCH potency data [22] to reflect the environmental impact of sulfur emissions on coastal areas. To the best of our knowledge, this study innovatively conducts the first quantitative analysis to determine the optimal DECA width, and thus to achieve the desired sulfur reduction target. Different from the relevant work of Wang and Peng [2], we not only consider ships' detour behaviors, but also focus more on the policymaking for the government. Based on the big data obtained and the established bi-level programming model, we perform extensive experiments with different price combinations of ULSFO and VLSFO. The optimal DECA widths under these combinations show that the current DECA width in China is insufficient to prevent ships from bypassing the DECA. By using the average fuel price ratio of historical data, we suggest that the Chinese government increase the current DECA width to at least 112 NM.

We finally point out two future research directions based on our study. First, since this study separates the decision-making process into two stages, where the government and ship operators make decisions sequentially, we may consider integrating their optimization objectives in a single model to achieve the maximum Pareto social benefit. This methodology is more insightful, and the challenge would be how to measure the trade-off between the government's environmental benefit and the shipping operators' economic benefit. Second, the optimal setting of parameter ρ for China can be investigated further by using the MATCH model [22], which may help to obtain much more precise results for the government. Third, the computational results show that the relationship between the optimal DECA width and the fuel price ratio is not strictly monotonic. Therefore, their relationship deserves an investigation to provide useful suggestions for ship operations and the government.

6. Conclusions

This paper conducts the first quantitative study to help the Chinese government to determine the optimal DECA width. Especially, a bi-level programming model is established to simulate the decision-making process of the government and ship operators. In the lower-level programming model, detour behaviors of different types of ships due to the establishment of the DECA are considered. Then, the optimal decisions of ship operators regarding their ships' sailing routes and sailing speeds are embedded into the upper-level programming model, which needs to be solved to find the optimal DECA width. Computational experiments show that the current DECA width in China is too narrow to prevent ships from bypassing the DECA to save on fuel costs. Therefore, by using the average fuel price ratios of historical data, we recommend that the government should increase the current DECA width to at least 112 NM.

Author Contributions: Conceptualization, methodology, software, formal analysis, writing—original draft preparation, and visualization: X.T.; methodology, writing—review and editing, and supervision: R.Y.; conceptualization and methodology: J.Q.; conceptualization and methodology: D.Z.; conceptualization, methodology, supervision, project administration, and funding acquisition: H.W. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by GuangDong Basic and Applied Basic Research Foundation: 2019A1515011297.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

List of Abbreviations (In Order of Appearance)

DECA	domestic emission control area
NM	nautical mile
ULSFO	ultra-low sulfur fuel oil
ECA	emission control area
IMO	International Maritime Organization
VLSFO	very-low sulfur fuel oil
LNG	liquefied natural gas
AIS	automatic identification system
WRS	World Register of Ships
TEU	twenty-feet equivalent unit

Appendix A

Table A1. Nomenclature.

Sets	
R	The set of route options
V_s	The set of discrete speed points for ship s
W	The set of DECA width scenarios
S	The set of ships (each ship owned by a ship operator)
Parameters	
l_{wr}(nm)	Farthest vertical distance from route r to the coastline under scenario w
ρ	Preset adjustable constant to reflect the impact potency of marine emissions
$e^{-\rho l_{wr}}$	Coefficient for environmental impact of sulfur emissions on coastal areas, with e representing the natural number
v_s(knot)	Fixed speed during the fuel-switching period for ship s
α_1(USD/ton)	Fuel price of ULSFO
α_2(USD/ton)	Fuel price of VLSFO
T_s(h)	Sailing time limit of ship s over a given voyage
T_{rvws}^{DECA}(h)	Sailing time inside the DECA along route r with speed alternative v under scenario w for ship s
T_{rvws}^{NB}(h)	Sailing time outside the DECA along route r before fuel switching with speed alternative v under scenario w for ship s
T_{rs}^{NA}(h)	Fixed fuel-switching period outside the DECA for ship s on route r
F_{vs}(ton/h)	Fuel consumption per hour with speed alternative v for ship s
P_{vs}^{ULSFO}(kg/h)	Sulfur emissions per hour with speed alternative v for ship s using ULSFO
P_{vs}^{VLSFO}(kg/h)	Sulfur emissions per hour with speed alternative v for ship s using VLSFO
Decision variables	
z_{rws}	Binary variable that equals 1 if route r is chosen in scenario w by ship s and 0 otherwise
x_{rvws}^{DECA}	Weight of speed alternative v inside the DECA on route r in scenario w for ship s
x_{rvws}^{NB}	Weight of speed alternative v outside the DECA before fuel switching on route r in scenario w for ship s
y_w	Binary variable that equals 1 if scenario w is chosen by the government and 0 otherwise

References

1. UNCTAD. Review of Maritime Transport, United Nations Publications. 2021. Available online: https://unctad.org/system/files/official-document/rmt2021_en_0.pdf (accessed on 22 December 2021).
2. Wang, S.; Peng, C. Model and analysis of the effect of China's potential domestic emission control area with 0.1% sulphur limit. *Marit. Bus. Rev.* **2019**, *4*, 298–309. [CrossRef]
3. Ministry of Transport. Implementation Plan on Domestic Emission Control Areas in Waters of the Pearl River Delta, the Yangtze River Delta and Bohai Rim. 2015. Available online: http://zizhan.mot.gov.cn/zfxxgk/bzsdw/bhsj/201512/P020160215528398838765.pdf (accessed on 22 December 2021).
4. Ministry of Transport. Marine Air Emission Control Areas Implementation Scheme. 2018. Available online: http://xxgk.mot.gov.cn/jigou/haishi/201812/t20181220_3146515.html (accessed on 22 December 2021).
5. Boscaratoa, I.; Hickeya, N.; Kašpara, J.; Pratib, M.V.; Mariani, A. Green shipping: Marine engine pollution abatement using a combined catalyst/seawater scrubber system. 1. Effect of catalyst. *J. Catal.* **2015**, *328*, 248–257. [CrossRef]
6. Fung, F.; Zhu, Z.; Becque, R.; Finamore, B. *Prevention and Control of Shipping and Port Air Emissions in China*; Natural Resources Defense Council: New York, NY, USA, 2014.
7. Acciaro, M. Real option analysis for environmental compliance: LNG and emission control areas. *Transp. Res. Part D Transp. Environ.* **2014**, *28*, 41–50. [CrossRef]
8. Acciaro, M. A real option application to investment in low-sulphur maritime transport. *Int. J. Shipp. Transp. Logist.* **2014**, *6*, 189–212. [CrossRef]

9. Chen, S.; Zheng, S.; Zhang, Q. An investment strategy under uncertainty on LNG-powered vessels for environmental compliance. In Proceedings of the 16th COTA International Conference of Transportation Professionals, Shanghai, China, 6–9 July 2016; pp. 1890–1950.
10. Browning, L.; Hartley, S.; Bandemehr, A.; Gathright, K.; Miller, W. Demonstration of fuel switching on oceangoing vessels in the Gulf of Mexico. *J. Air Waste Manag. Assoc.* **2012**, *62*, 1093–1101. [CrossRef]
11. Fagerholt, K.; Gausel, N.T.; Rakke, J.G.; Psaraftis, H.N. Maritime routing and speed optimization with emission control areas. *Transp. Res. Part C Emerg. Technol.* **2015**, *52*, 57–73. [CrossRef]
12. Chen, L.; Yip, T.L.; Mou, J. Provision of emission control area and the impact on shipping route choice and ship emissions. *Transp. Res. Part D Transp. Environ.* **2018**, *58*, 280–291. [CrossRef]
13. Zhen, L.; Hu, Z.; Yan, R.; Zhuge, D.; Wang, S. Route and speed optimization for liner ships under emission control polices. *Transp. Res. Part C* **2020**, *110*, 330–345. [CrossRef]
14. Wang, S.; Zhuge, D.; Zhen, L.; Lee, C. Liner Shipping Service Planning Under Sulfur Emission Regulations. *Transp. Sci.* **2021**, *55*, 491–509. [CrossRef]
15. Zhuge, D.; Wang, S.; Wang, D. A joint liner ship path, speed and deployment problem under emission reduction measures. *Transp. Res. Part B Methodol.* **2021**, *144*, 155–173. [CrossRef]
16. Doudnikoff, M.; Lacoste, R. Effect of a speed reduction of containerships in response to higher energy costs in sulphur emission control areas. *Transp. Res. Part D Transp. Environ.* **2014**, *28*, 51–61. [CrossRef]
17. Adland, R.; Fonnes, G.; Jia, H.; Lampe, O.D.; Strandenes, S.P. The impact of regional environmental regulations on empirical vessel speeds. *Transp. Res. Part D Transp. Environ.* **2017**, *53*, 37–49. [CrossRef]
18. Fagerholt, K.; Psaraftis, H. On two speed optimization problems for ships that sail in and out of emission control areas. *Transp. Res. Part D Transp. Environ.* **2015**, *39*, 56–64. [CrossRef]
19. Svindland, M. The environmental effects of emission control area regulations on short sea shipping in Northern Europe: The case of container feeder vessels. *Transp. Res. Part D Transp. Environ.* **2018**, *61*, 423–430. [CrossRef]
20. Llewelyn, R. An analytical model for the transport, dispersion and elimination of air pollutants emitted from a point source. *Atmos. Environ.* **1983**, *17*, 249–256. [CrossRef]
21. Qi, J.; Wang, S.; Qu, X. Emission Evaluation of Marine Traffic. *Smart Innov. Syst. Technol.* **2020**, *185*, 201–211.
22. Concawe. Environmental Impacts of Marine SO2 Emissions. 2018. Available online: https://www.concawe.eu/wp-content/uploads/2018/02/Rpt_18-1.pdf (accessed on 7 March 2022).
23. Qi, J.; Wang, S.; Psaraftis, H. Bi-level optimization model applications in managing air emissions from ships: A review. *Commun. Transp. Res.* **2021**, *1*, 100020. [CrossRef]
24. Wang, X.; Chen, G.; Xu, S. Bi-objective green supply chain network design under disruption risk through an extended NSGA-II algorithm. *Clean. Logist. Supply Chain* **2022**, *3*, 100025. [CrossRef]
25. Yi, W.; Wu, S.; Zhen, L.; Chawynski, G. Bi-level programming subsidy design for promoting sustainable prefabricated product logistics. *Clean. Logist. Supply Chain* **2021**, *1*, 100005. [CrossRef]
26. Yi, W.; Zhen, L.; Jin, Y. Stackelberg game analysis of government subsidy on sustainable off-site construction and low-carbon logistics. *Clean. Logist. Supply Chain* **2021**, *2*, 100013. [CrossRef]
27. Zhang, L.; Zeng, Z.; Gao, K. A bi-level optimization framework for charging station design problem considering heterogeneous charging modes. *J. Intell. Connect. Veh.* **2020**, *5*, 8–16. [CrossRef]
28. Guan, Y.; Li, S.E.; Duan, J.; Wang, W.; Cheng, B. Markov probabilistic decision making of self-driving cars in highway with random traffic flow: A simulation study. *J. Intell. Connect. Veh.* **2018**, *1*, 77–84. [CrossRef]
29. Jiang, Z.; Xu, Z.; Li, Y.; Min, H.; Zhou, J. Precise vehicle ego-localization using feature matching of pavement images. *J. Intell. Connect. Veh.* **2020**, *3*, 37–47. [CrossRef]
30. Liu, J.; Khattak, A.; Han, L.; Yuan, Q. How much information is lost when sampling driving behavior data? Indicators to quantify the extent of information loss. *J. Intell. Connect. Veh.* **2020**, *3*, 17–29. [CrossRef]
31. Xu, Q.; Wang, J.; Wang, B.; Yan, X. Modeling and simulation of intersection quasi-moving block speed guidance based on connected vehicles. *J. Intell. Connect. Veh.* **2020**, *3*, 67–78. [CrossRef]
32. Wang, W.; Wu, Y. Is uncertainty always bad for the performance of transportation systems? *Commun. Transp. Res.* **2021**, *1*, 100021. [CrossRef]
33. Yan, R.; Wang, S.; Zhen, L.; Laporte, G. Emerging approaches applied to maritime transport research: Past and future. *Commun. Transp. Res.* **2021**, *1*, 100011. [CrossRef]
34. Zhen, L.; Sun, Q.; Zhang, W.; Wang, K.; Yi, W. Column generation for low carbon berth allocation under uncertainty. *J. Oper. Res. Soc.* **2021**, *72*, 2225–2240. [CrossRef]
35. Zhen, L.; Wu, Y.; Wang, S.; Hu, Y.; Yi, W. Capacitated closed-loop supply chain network design under uncertainty. *Adv. Eng. Inform.* **2018**, *38*, 306–315. [CrossRef]
36. Ship and Bunker. Hong Kong Bunker Prices. 2021. Available online: https://shipandbunker.com/prices/apac/ea/cn-hok-hong-kong (accessed on 22 December 2021).