

Model and Analysis of the Effect of China's Potential Domestic Emission Control Area with 0.1% Sulphur Limit

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Abstract

Purpose – The purpose of this study is to analyze the effect of China's potential Domestic Emission Control Area (DECA) with 0.1% sulphur limit on sulphur emission reduction.

Design/methodology/approach – We calculate the fuel cost of a direct path within the DECA and a path that bypasses the DECA for ships that sail between two Chinese ports in view of the DECA. Ships adopt the path with the lower cost and the resulting sulphur dioxide (SO₂) emissions can be calculated. We then conduct sensitivity analysis of the SO₂ emissions with different values of the parameters related to sailing distance, fuel price, and ships.

Findings – The results show that ships tend to detour to bypass the DECA when the distance between the two ports is long, the ratio of the price of low sulphur fuel and that of high sulphur fuel is high, and the required time for fuel switching is long. If the time required for fuel switching is less than 12h or even 24h, it can be anticipated that a large number of ships will bypass the DECA, undermining the SO₂ reduction effect of the DECA.

Originality/value – This study points out the size and shape difference between the emission control areas in Europe and North America and China's DECA affects ships' path choice and SO₂ emissions.

Keywords: Emission control areas, Shipping air emissions, Domestic emission control area of China

Paper type: Research paper

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1. Introduction

Air pollution is a global challenge that has been linked to climate change and adverse health effects. Shipping is fundamental in sustaining economic growth; however, more than 95% of the world's shipping fleet are powered by diesel engines that use low-quality high-sulphur fossil fuels (Nikopoulou et al., 2013). The shipping industry produces 13% of the global anthropogenic SO₂ emissions (Smith et al., 2014) that annually result in at least 80,000 premature deaths worldwide (Carr and Corbett, 2015).

The significant amount of SO₂ emissions by ships results from the high sulphur content in marine fuel. The sulfur content in marine fuel used to be unregulated. In 2005, the International Maritime Organization (IMO) enforced a hard cap of 4.5% (m/m) sulfur maximum for any marine fuel to curb the SO₂ emissions from ships. This cap was reduced to 3.5% in 2012. In October 2016, the IMO decided to dramatically reduce the sulphur cap for marine fuel to 0.5%¹, effective from 1 January 2020. This landmark decision represents more than 80% cut from the current 3.5% global limit (Marine Environment Protection Committee, 2017) and demonstrates a clear commitment by IMO to the environmental obligations of shipping.

The adverse effects of SO₂ emissions, such as the formation of acid rain and the cause of respiratory diseases, mainly take place on a local or regional basis. In other words, the same amount of SO₂ emissions at port or near coastal areas is much more harmful than that in the open sea far away from the human habitats. Therefore, regulatory bodies are more concerned about at-berth emissions and emissions in coastal waters and therefore have introduced more stringent sulphur limits than the IMO limits for at-vessel vessels and vessels sailing in coastal waters. The European Union (EU) has mandated a 0.1% maximum sulphur requirement for fuels used by ships at berth in EU ports since 1 January 2010. Hong Kong introduced a regulation to mandate ocean-going vessels at berth to switch to fuel with sulphur content not exceeding 0.5% starting from 1 July 2015. This landmark policy decision made Hong Kong the first Asian port to mandate fuel switch at berth. Curbing SO₂ emissions in coastal waters is achieved by designating Emission Control Areas (ECAs), as elaborated below.

¹ All the sulfur limits in the paper refer to the limit of the content of sulfur in the marine fuel used by ships without exhaust gas cleaning system. Other than burning fuel with sulfur contents lower than the limits, ships can take equivalent or cleaner measures to comply with the sulfur limit rules.

The EU and the governments of the United States and Canada have, under the International Convention for the Prevention of Pollution from Ships (MARPOL) Annex VI of the IMO, designated four ECAs with strict control of sulphur emissions from vessels. The ECAs include the Baltic Sea (in effect from 19 May 2006), North Sea (in effect from 22 November 2007), and North American and the United States Caribbean Sea areas (in effect from 1 August 2012), as shown in Fig. 1. The sulphur limit on fuels used by sailing and at-berth vessels within the ECAs was reduced from 1.5% to 1.0% on 1 July 2010 and to 0.1% on 1 January 2015.

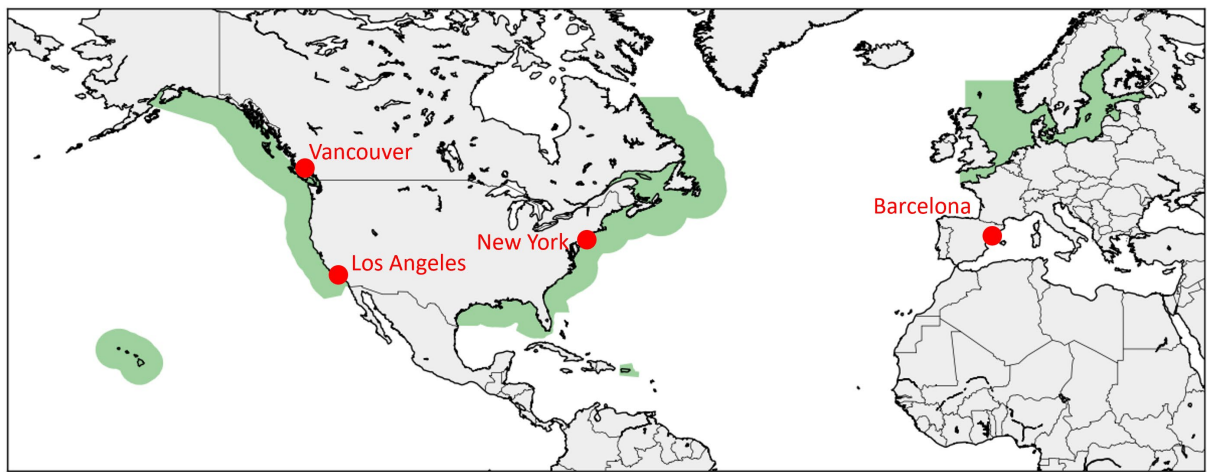


Fig. 1 Emission control areas in Europe and North America

After the establishment of the ECAs in Europe and North America, it has been conjectured that new ECAs will be established in coastal waters of Norway, Australia, Japan, Singapore, Mexico, and the Mediterranean Sea (Wilhelmsen, 2014), as these waters are close to developed economies. Nevertheless, before any of the above proposed ECAs had been established, on 4 December 2015, the Ministry of Transport (MoT) of the People’s Republic of China issued “Marine Air Emission Control Areas Implementation Scheme for the Pearl River Delta, Yangtze River Delta, and Bohai-rim Waters” (Ministry of Transport, 2015), which designated three domestic emission control areas (DECAs) in the Pearl River Delta, Yangtze River Delta, and Bohai-rim Waters. It is required that, starting from 1 January 2019, vessels within the DECAs, both sailing and at berth, must use fuel with sulphur content not exceeding 0.5%. On 30 November 2018, China’s MoT issued “Marine Air Emission Control Areas Implementation Scheme,” referred to as “the Scheme” for short hereafter, which designates the whole territorial waters of the Chinese Mainland as DECA, as shown in

Fig. 2, and mandates that starting from 1 January 2019, all vessels within the DECAs must use fuel with sulphur content not exceeding 0.5% (Ministry of Transport, 2018). In other words, China started to implement the 0.5% sulphur cap in its DECA one year earlier than the IMO's implementation of the global 0.5% sulphur cap. China's leading role in Asia is applauded and in the Scheme, MoT pointed that it will "evaluate the feasibility of a 0.1% sulphur cap for the DECA to decide whether to implement the 0.1% sulphur cap from 1 January 2025."

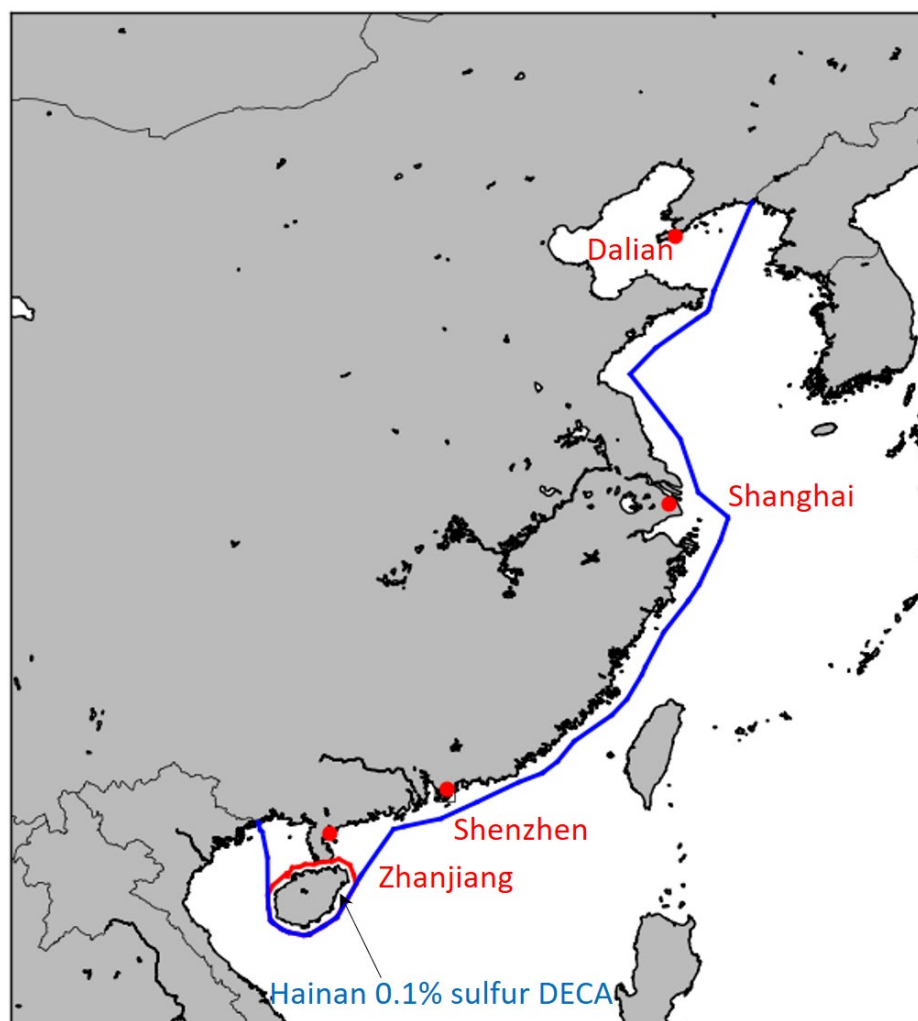


Fig. 2 Domestic emission control area of China
(Note: A 0.1% sulphur limit will be imposed in the waters surrounding Hainan Province of China starting from 1 Jan 2022.)

We study the environmental effects of China's Potential DECA with 0.1% sulphur limit. We underscore that China's DECA is different from the ECAs in Europe and North America. The difference is that China's existing DECAs, as well as the potential 0.1% sulphur DECA, are designed by China's domestic law and hence their boundaries are only 12 nm away from the coastline (Ministry of Transport, 2018). By contrast, the

ECAs in Europe and North America are approved by the IMO and much larger; for example, the boundaries of the North American ECAs are 200 nm away from the coastline (International Maritime Organization, 2019). Since low sulphur fuel is much more expensive than high sulphur fuel, ships will try to bypass ECAs if it is economical to do so. The location and shape of the European ECAs imply that ships visiting ports in the European ECAs can hardly bypass them. Since the North American ECAs are 200 nm wide, it hardly makes sense for a ship that sails from e.g. the Port of Los Angeles to e.g. the Port of Vancouver to first sail 200 nm out of the ECA (burning low sulphur fuel), then sail along the boundaries of the ECA (burning high sulphur fuel), and finally sail 200 nm in the ECA to Vancouver (burning low sulphur fuel). However, a ship that sails from the Port of Shanghai to the Port of Shenzhen is likely to sail from Shanghai for 12 nm out of the 0.1% sulphur DECA, then sail along the boundary of the DECA, and finally sail 12 nm in the DECA to arrive at Shenzhen. If this occurs, then the main environmental effect of the DECA is to push the SO₂ emissions along the coastline 12 nm to the sea and to lead to more carbon dioxide (CO₂) emissions because more fuel (the total amount of low sulphur fuel and high sulphur fuel) will be consumed to bypass the DECA; the economic effect is that shipping lines have to pay a higher fuel bill.

The objective of the paper is to examine what factors affect whether ships will bypass the 0.1% sulphur DECA and thereby to provide policy suggestions on the establishment of the DECA. This study focuses on the option of fuel switching to comply with the DECA rules. In fact, ships can use scrubbers to clean their exhaust gases or use engines that burn liquefied natural gas (LNG). The new 0.1% sulfur ECA rule does not affect the operations of ships that are equipped with scrubbers or LNG engines. Moreover, we focus on ships that sail between two Chinese ports but did not consider ships that sail between a port in China and a non-Chinese port, e.g., a Japanese port. This is because ships that sail between two Chinese ports travel along the coastline of China and emit a significant amount of SO₂ near China's coastal cities, but ships that sail between a port in China and a non-Chinese port travel almost vertically to the coastline of China and emit a marginal amount of SO₂ near China's coastal cities.

2. Literature review

2.1 Shipping lines' operations under ECA rules

The ECA rules affect shipping lines' operations not only in fuel switching, but also in speed and path choice. Since the price of low sulphur fuel is higher than that of high sulphur fuel and the fuel consumption of a ship increases with its speed, a ship that sails between a port in an ECA (e.g., New York) and a port that is outside the ECAs (e.g., Barcelona) should sail at a lower speed when it is within the ECA and at a higher speed when it is outside the ECA to compensate the lost sailing time within the ECA. By speed differentiation, the ship will burn less low sulphur fuel and more high sulphur fuel and the total fuel cost can be lower than that when the ship sails at a fixed speed between the two ports. Doudnikoff and Lacoste (2014) optimized the sailing speeds of ships under ECA rules to minimize shipping lines' costs. Dulebenets (2016) optimized the speeds under ECA rules to minimize costs while considering the constraint that the total amount of emissions cannot exceed a threshold. Sheng et al. (2019) developed a mixed-integer nonlinear optimization model that optimizes the fleet size and sailing speed for an industrial shipping company operating for ports within and outside ECAs.

A ship may no longer sail along the shortest path once there are ECAs because there may exist another path that is longer but has a shorter proportion within the ECAs. Fagerholt and Psaraftis (2015) call this phenomenon "ECA refraction." Chen et al. (2018) developed a route choice model for Asia–Europe shipping to analyze the effect of setting up an ECA for the Mediterranean Sea. It is found that an ECA for the Mediterranean Sea may not necessarily reduce ship emissions as ships may sail along the Cape of Good Hope path. Fagerholt et al. (2015) considered a discrete set of candidate paths for ships to sail and developed a mixed-integer programming model to decide the path and speeds to minimize the fuel costs. Fagerholt and Psaraftis (2015) examined the optimization of ECA refraction point (equivalently, the sailing path) and speed; in other words, they have considered an infinite number of candidate paths. Gu and Wallace (2017) optimized both the speeds of ships and the sailing paths and found that ships that frequently visit ports within ECAs should be retrofitted with exhaust gas clean systems, which allow them to burn high-sulfur fuel within ECAs. Zhen et al. (2018) developed a mixed-integer programming model for path and speed optimization for a cruise ship.

Most of the above studies have focused on speed and path optimization for sailing between a port in an ECA and a port that is outside the ECAs. As mentioned in the introduction section, the areas of the European and North American ECAs are large and ships that sail between two ports in the same ECA generally sail along the shortest

path within the ECA. In contrast, the width of China's DECA is only 12 nm and ships that sail between two ports in the DECA are likely to take a path that bypasses the DECA. Hence, we focus on sailings between two ports in the DECA.

2.2 Cost-benefit analysis of ECAs

In 2009, the governments of the United States and Canada conducted a cost-benefit analysis of designating the North American ECAs and submitted the analysis to the IMO for approval of the North American ECAs. In the analysis, the possible speed and path optimization by shipping lines under the ECA rules is not considered (US Environmental Protection Agency, 2009). The European Commission funded a study on the cost-benefit analysis of designating the Mediterranean Sea as a 0.1% sulphur ECA, and the analysis does not consider speed and path optimization, either (Cofala et al., 2018). It should be stressed again that whereas the effect of speed and path optimization on the cost-benefit analysis of the existing ECAs as well as the potential one of the Mediterranean Sea is limited, ignoring shipping lines' speed and path optimization in the cost-benefit analysis of China's potential 0.1% sulphur DECA can considerably affect the conclusion.

3. Model and sensitivity analysis

3.1 Model

We focus on ships that sail between two Chinese ports. To facilitate the analysis, we assume that China's coastline is a straight line and its DECA is a rectangle with width W , as shown in Fig. 3. Port A and port B are located on China's coastline and their distance is L . A ship needs to sail from port A to port B in time T . Suppose that the fuel consumption per unit distance for the ship is a power function of its speed, av^b , where a and b are parameters, $a > 0$, $b > 1$, and v is the speed. The ship can sail along the coastline, burning low sulphur fuel whose price is α_2 . The fuel cost will be

$$C_1 = \alpha_2 a (L/T)^b L = \alpha_2 a L^{b+1} T^{-b} \quad (1)$$

where L/T is the sailing speed.

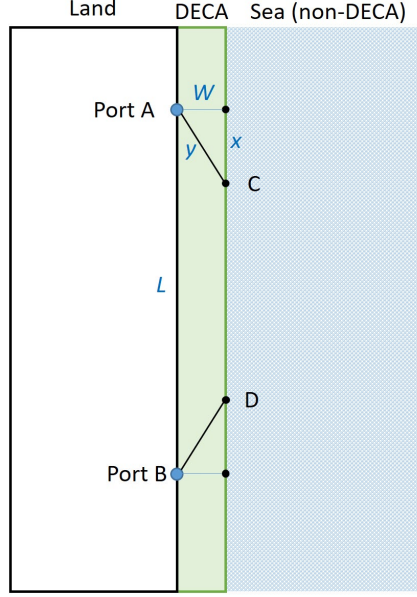


Fig. 3 Model setup

The ship can also first sail to a point (denoted as point C) on the DECA boundary, burning low sulphur fuel, then sail along the boundary just outside the DECA to another point (denoted as point D), burning high sulphur fuel whose price is α_1 ($\alpha_1 < \alpha_2$), and finally sail to port B. We assume for the moment that it takes no time to switch between high sulphur fuel and low sulphur fuel and will discuss the effect of fuel switching time in Section 3.2.3. We need to determine (i) the optimal location of C (equivalently, the optimal value of x or y) and its symmetric location D and to decide (ii) the optimal sailing speed when the ship sails on AC and BD, denoted by v_2 , and (iii) the optimal speed on CD, denoted by v_1 . The minimum fuel cost for the path ACDB can be formulated as an optimization model:

$$[M] \quad C_2 = \min_{0 \leq x \leq L/2, y > 0, v_1 > 0, v_2 > 0} \alpha_1 a(v_1)^b (L - 2x) + \alpha_2 a(v_2)^b 2y \quad (2)$$

subject to

$$x^2 + W^2 = y^2 \quad (3)$$

$$\frac{L - 2x}{v_1} + \frac{2y}{v_2} = T. \quad (4)$$

We defined a conversion coefficient $\gamma := (\alpha_2 / \alpha_1)^{1/(b+1)}$. According to Fagerholt and Psaraftis (2015)², the locations of C and D satisfy

² The preconditions for this result, as well as for the result on the optimal speeds within and outside the DECA, are (i) the fuel consumption per unit distance for the ship is a power function of its

$$(x^*, y^*) \in \arg \min_{0 \leq x \leq L/2, y = \sqrt{x^2 + W^2}} [(L - 2x) + \gamma 2y]. \quad (5)$$

Solving model (5), we can obtain the optimal values of x and y :

$$x^* = \frac{W}{\sqrt{\gamma^2 - 1}} \quad (6)$$

$$y^* = \frac{\gamma W}{\sqrt{\gamma^2 - 1}}. \quad (7)$$

The first-order optimality conditions imply that the optimal sailing speed outside the DECA is γ times the speed within the DECA. Hence, the optimal sailing speeds v_1^* and v_2^* satisfy

$$v_1^* = \gamma v_2^* \quad (8)$$

$$\frac{L - 2x^*}{v_1^*} + \frac{2y^*}{v_2^*} = T. \quad (9)$$

Therefore,

$$v_1^* = \frac{(L - 2x^*) + \gamma 2y^*}{T} \quad (10)$$

$$v_2^* = \frac{(L - 2x^*) + \gamma 2y^*}{\gamma T}. \quad (11)$$

Consequently, the minimum total fuel cost when the ship sails along the boundary of the DECA is

$$C_2 = \alpha_1 a(v_1^*)^b (L - 2x^*) + \alpha_2 a(v_2^*)^b 2y^*. \quad (12)$$

If $C_1 < C_2$, then the shipping line will choose to sail along the coastline, burning low sulphur fuel and emitting less SO₂, and this is exactly what the government intends to achieve. If $C_1 > C_2$ ³, then the ship will bypass the DECA, and this is not desirable for the government and the public because (i) the main environmental effect of the DECA will be to push the SO₂ emissions along the coastline 12nm to the sea and the SO₂ emissions reduction within the DECA and on its boundary will be very limited,

speed αv^b for any speed greater than 0 and (ii) the maximum physical speed of the ship is large enough. In our paper, we assume that the two preconditions hold because the width of China's DECA is only 12nm and the sailing speed of a ship on the path that bypasses the DECA will not change much from that on the shortest path.

³ The case of $C_1 = C_2$ hardly occurs in reality and hence we do not discuss it.

if any; (ii) more fuel (the total amount of low sulphur fuel and high sulphur fuel) will be consumed to bypass the DECA as the distance of AC+CD+DB is longer than that of AB, and more CO₂ will be emit because burning one ton of low sulphur fuel and burning one ton of high sulphur fuel emit virtually the same amount of CO₂⁴; (iii) shipping lines have to pay a much higher fuel bill than the case of no DECA.

3.2 Sensitivity analysis

We conduct numerical tests to see whether ships will bypass the DECA under different scenarios (combinations of the values of the parameters). The baseline scenario is as follows. The DECA width $W = 12$ nm (Ministry of Transport, 2018). The distance between port A and port B is $L = 851$ nm (distance between Shanghai and Shenzhen). The total sailing time T does not affect the choice between the two paths. In the fuel consumption function, the value of the parameter a does not affect the choice between the two paths, and we set $b = 2$ (daily fuel consumption is proportional to the speed cubed). The price of high sulphur fuel is $\alpha_1 = 366$ USD/ton (Jallal, 2019) and the price of low sulphur fuel is $\alpha_2 = 619$ USD/ton (Ship & Bunker, 2019). We will calculate the cost ratios C_2 / C_1 under a number of scenarios. If the ratio is less than 1, then the ship will bypass the DECA. In the baseline scenario, $C_1 = \$16,404$ and $C_2 = \$10,241$. Therefore, the ship will bypass the DECA by sailing along A→C→D→B with $x^* = 18.5$ n mile and $y^* = 22.1$ n mile.

3.2.1 Sensitivity with the distance of ports

We first analyze the sensitivity of the cost ratio C_2 / C_1 with the distance L between the two ports and plot the results in Fig. 4. It can be seen that bypassing the DECA is preferable for larger values of L . Moreover, the ratio first decreases quickly with L and then decreases slowly. Theoretically, when L is infinity, the ratio C_2 / C_1 will be equal to $\alpha_1 / \alpha_2 \approx 0.59$. We define the *critical distance* as the value of L such that $C_2 / C_1 = 1$. The critical distance in this example is only 80nm, which means ships

⁴ If both the high sulphur fuel and low sulphur fuel are heavy fuel oil, then burning one ton of fuel emits 3.114 ton of CO₂ (Marine Environment Protection Committee, 2014). If the high sulphur fuel is heavy fuel oil and the low sulphur fuel is distillate, then their consumption rates and the CO₂ emissions per ton of fuel are slightly different (less than 2% difference) (Environmental Protection Department of Hong Kong, 2013).

will bypass the DECA whenever the distance between the two ports is greater than 80 nm. In other words, nearly all ships will bypass China's DECA.

For the North American ECA with a width of $W = 200$ nm, the critical distance is $L \approx 1350$ nm. This distance is longer than the distances of most port pairs, for example, the distance between the port of Los Angeles and the port of Vancouver is 1221nm.

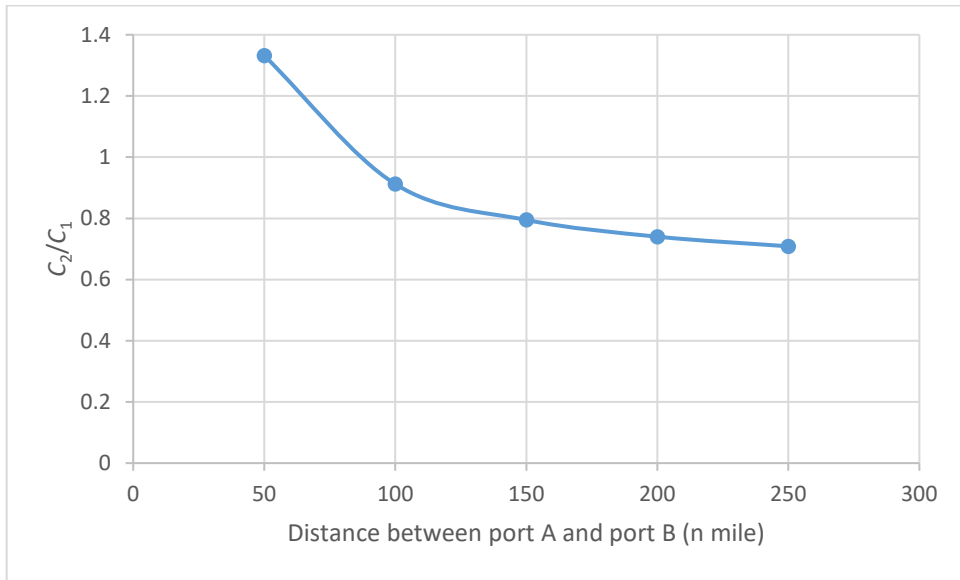


Fig. 4 Sensitivity of the ratio of the costs of the two paths with port distance

3.2.2 Sensitivity with the fuel prices

The critical distance of the two ports is also related to the ratio of the price of low sulphur fuel and that of high sulphur fuel, α_2 / α_1 . We set the price ratio at values in $\{1.2, 1.3, 1.4, 1.5, 1.6, 1.7\}$, that is, the price of low sulphur fuel is 20%, 30%, 40%, 50%, 60%, and 70% higher than that of high sulphur fuel, and calculate the critical distance. The results are shown in Fig. 5. The critical distance decreases with the price ratio. That means, ships are more likely to bypass the DECA when low sulphur fuel is much more expensive than high sulphur fuel. However, the curve is fairly flat and even if low sulphur fuel is only 20% more expensive than high sulphur fuel, ships will bypass the DECA if the port distance is greater than 135 nm.

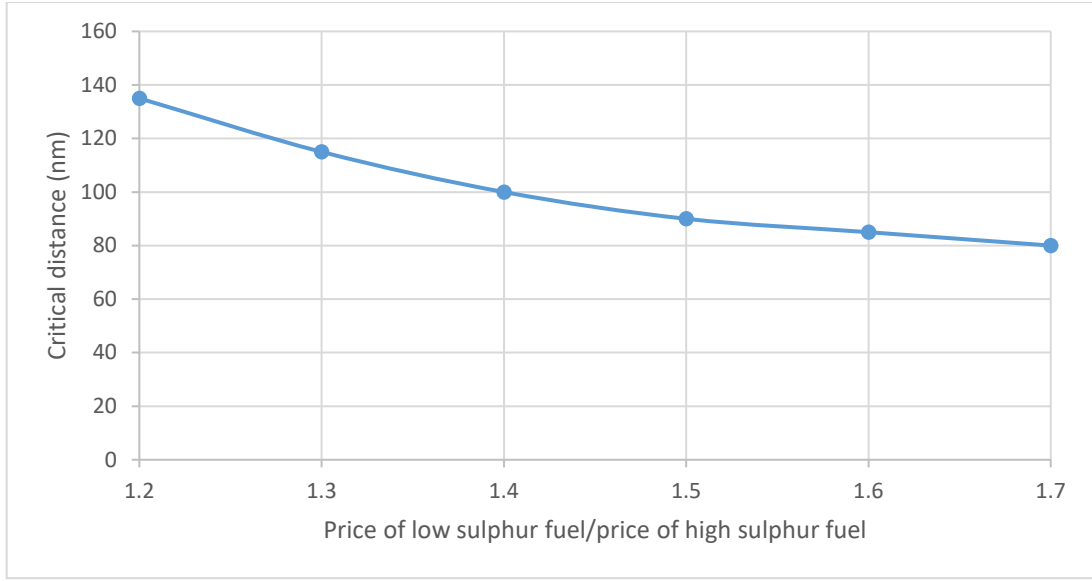


Fig. 5 Sensitivity of the critical distance with the ratio of the prices of the two types of fuel

3.2.3 Sensitivity with the time required for fuel switching

Switching between fuels takes time. Specifically, ship operators must allow sufficient time for the fuel system to be flushed of all high sulphur fuel before arriving at the DECA boundary. This process may take any time between a few hours and three days, depending on the ship conditions (new ships take shorter time), the types of fuel and fuel pipe system, and the familiarity of the operators (Safety4Sea, 2016). The time required to switch to high sulphur fuel after leaving the DECA is much shorter and we assume it to be zero. The switching time from high sulphur fuel to low sulphur fuel, denoted by Δ (hours), affects the critical distance. Supposing that the ship speed is 15 knots, the critical distance with fuel switching time Δ will be 15Δ nm longer than that with zero fuel switching time. The critical distances under different combinations of fuel price ratio α_2 / α_1 and fuel switching time Δ are shown in Fig. 6. We can see that the critical distance is very sensitive to the fuel switching time. If the fuel switching time is 72 h, then very few ships will bypass the DECA (the critical distance is about 1200nm, and the distance between the port of Dalian and the port of Zhanjiang in Fig. 2 is 1390 nm).

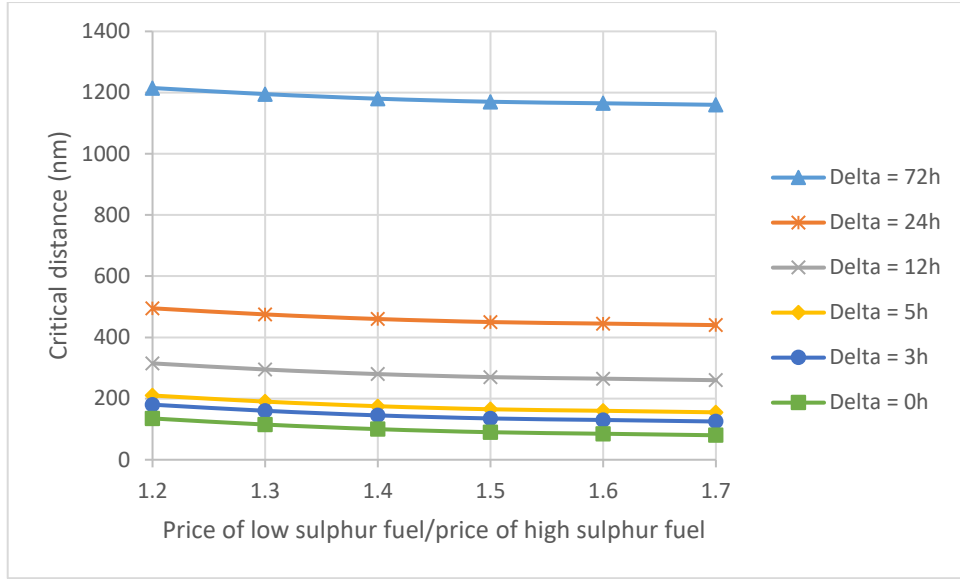


Fig. 6 Sensitivity of the critical distance with the fuel price ratio and fuel switching time (Δ)

4. Summary and discussions

We have analyzed the scenarios under which ships that sail between two Chinese ports will bypass the potential 0.1% sulphur DECA. Ships are more likely to bypass the DECA when the distance between the two ports is large. The critical distance decreases mildly with the ratio of the price of low sulphur fuel and that of high sulphur fuel and significantly with the required time for fuel switching. Notably, if the time required for fuel switching is less than 12h or even 24h, it can be anticipated that a large number of ships will bypass the DECA, undermining the SO₂ reduction effect of the DECA. We therefore suggest that on-site investigations of ship operators regarding their time for fuel switching must be conducted before the 0.1% sulphur DECA is established. The establishment of a 0.1% sulphur DECA should further take into account that new ships tend to have shorter fuel switching time.

As shown in Figure 2, 0.1% sulphur limit will be imposed in the waters surrounding Hainan Province of China starting from 1 Jan 2022. Since the water area of this DECA is very small, based on our analysis, it can be predicted that a large majority of ships will bypass the DECA. Ships that enter the DECA are mainly those destined for ports located inside it.

Finally, as many governments are interested in setting up emission control areas, the findings in our study are useful for them to assess the effects on ship operations before the emission control areas are established.

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