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DELINEATING A CHINESE EMISSION CONTROL AREA

THE POTENTIAL IMPACT OF SHIP REROUTING ON EMISSIONS

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

When making travel plans, a traveler's first choice is usually the quickest available trip from origin to destination. If the shortest route contains a toll, the traveler might consider a slight detour to avoid the additional charge. Ship operators make similar decisions while at sea. Because regional environmental regulations designed to reduce emissions from ships can increase operating costs, ship operators may choose a different route, avoiding the additional costs but also reducing the efficacy of the regulations themselves.

As China tackles its air quality issues, government regulators have turned their focus to shipping, an industry that burns thousands of tons of highly polluting heavy fuel oil (HFO) near densely populated coastlines every day. Historically, one way to reduce air pollution from ships is by establishing an Emission Control Area (ECA), a geographic region designated by the International Maritime Organization (IMO) where more stringent emission standards apply. China has already implemented domestic emission control areas in three port clusters along China's coastline, although they are smaller and currently have less stringent standards than an IMO ECA.

As a next step, China could think about applying to IMO to designate an international ECA covering its entire offshore coastal region. China must first decide on the delineation of the ECA itself—should it be only the size of its territorial sea (12 nautical miles, nm), or as wide as its exclusive economic zone (up to 200 nm), or something in between? A delineation closer to shore is politically easier to achieve because China can unilaterally regulate ships in its territorial waters. However, a narrow ECA delineation may actually increase emissions if ship operators divert around the ECA to save on fuel costs, as ECA-compliant fuel is more expensive than traditional marine fuel. Therefore, China should consider how to delineate an ECA to prevent rerouting and ensure maximum emission reductions and public health benefits.

In this paper, we quantify the emissions reduction potential of four ECA delineation scenarios, taking into account the potential for ships to route around the ECA. The scenarios are as follows:

1. ECA extending 12 nm from the coast, which is the boundary of China's territorial sea.
2. ECA extending 24 nm from the coast, which is the boundary of China's contiguous zone.[1]
3. ECA extending 50 nm from the coast.
4. ECA extending 100 nm from the coast.

Starting with our 2015 ship emissions inventory, which is based on actual ship traffic near China, we estimated the amount of ship-related air pollution emissions that could be covered by an ECA if no ships rerouted (baseline) and compared it to emissions that would be covered ships did reroute (rerouting). This assumes that ship operators are economically rational and would try to minimize fuel costs by rerouting outside the ECA.

1 A contiguous zone, defined by the United Nations Convention on the Law of the Sea, is "a zone contiguous to its territorial sea, described as the contiguous zone," and "may not extend beyond 24 nautical miles from the baselines from which the breadth of the territorial sea is measured." See http://www.un.org/depts/los/convention_agreements/texts/unclos/part2.htm.

We did this for each of the four scenarios. Chinese policymakers can use this information as they decide how wide the proposed ECA should be.

Key findings include:

» An ECA needs to be at least 100 nm from the coast to be most effective. Under a narrow ECA, ship operators may reroute some of their heavily frequented coastal voyages around the ECA to save money on fuel. When the ECA is 12 nm, 24, nm, and 50 nm, some ships reroute in an effort to reduce fuel costs. The closer the ECA boundary is to the coast, the more ships will reroute. Therefore, narrower boundaries undermine the effectiveness of the ECA. In contrast, an ECA of 100 nm would discourage ships from rerouting and would safeguard health and environmental benefits.

» An ECA boundary that is too close to shore can undermine the emissions reduction benefits of an ECA. When ships bypass the ECA zone, they avoid environmental regulations, redistributing rather than reducing emissions. Worse, rerouting results in a modest (up to 2%) increase in fuel consumption compared to shorter, more direct voyages because rerouted voyages cover longer distances and, in some cases, require ships to speed up (and burn more fuel) to stay on schedule.

» The more expensive ECA-compliant fuel is compared to globally compliant fuel, the more ships will reroute. Indeed, the decision to reroute is sensitive to bunker fuel prices. If the price differential between ECA-compliant fuel and post-2020 compliant fuel is large, ships are motivated to reroute. The larger that price differential, the wider the ECA boundary needs to be from shore to discourage rerouting.

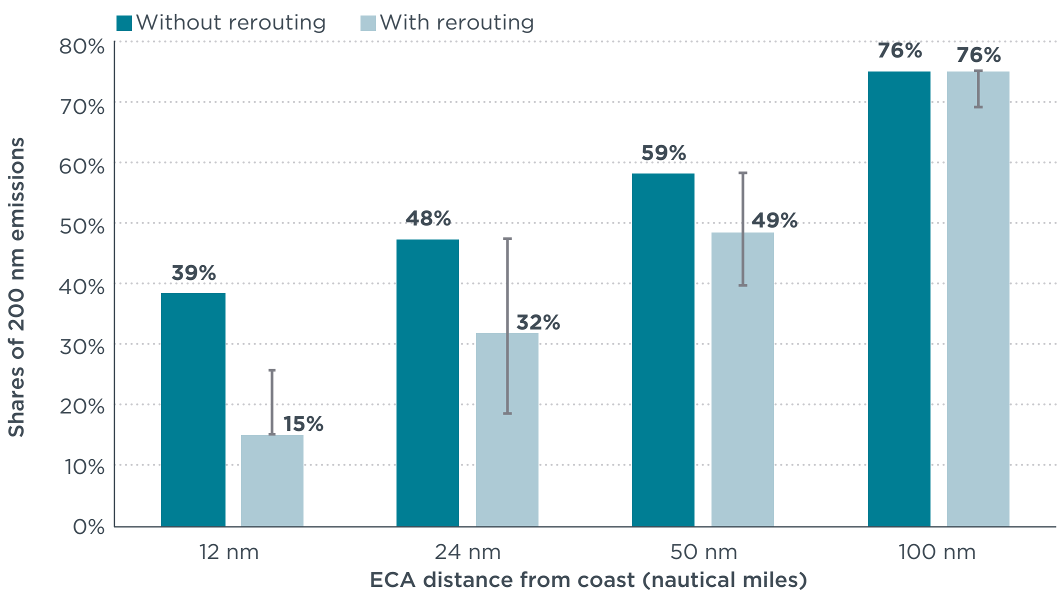

Figure-ES 1. The share of sulfur oxides that ships emit within 200 nautical miles covered by an Emission Control Area.

1. INTRODUCTION

1.1 BACKGROUND

Worldwide, the International Maritime Organization (IMO) has designated four Emission Control Areas (ECAs) to date (Figure 1). All ships traveling within these zones must abide by more stringent fuel quality standards to reduce emissions of sulfur oxides (SO_X) and particulate matter (PM), with separate engine standards for newbuild ships to control nitrogen oxide (NO_X) emissions (IMO, 2018). Member states may apply to the IMO for ECA designation and indicate the geographic reach of these areas. The North American ECA, for example, designates an area extending 200 nautical miles (nm) from the United States and Canada's territorial sea baselines,[2] an area within which significant adverse effects on human health and the environment were identified.[3] The North Sea and Baltic Sea ECAs, on the other hand, have nonuniform configurations (see Figure 1). While the total geographic area included is much smaller than that of the North American ECA, these ECAs are configured to cover the majority of ship traffic in each region. There are ongoing efforts to expand ECAs to other regions, including the Mediterranean Sea.

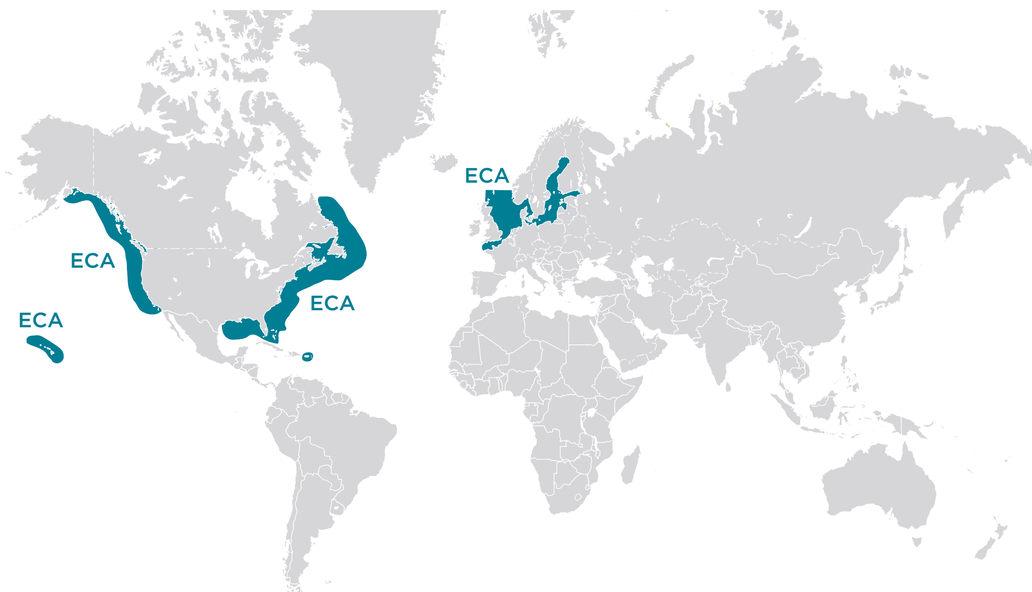

Figure 1. Existing Emission Control Areas around the world. Source: DNV GL 2015, updated by ICCT.

As China addresses its air quality problems, government regulators have turned their focus to shipping, a sector that burns thousands of tons of the dirtiest fuel near densely populated coastlines every day. China already has implemented domestic emission control areas in three port clusters along China's coastline on the Bo Sea, Yangtze River Delta, and Pearl River Delta (International Council on Clean Transportation [ICCT], 2016). As a next step, China might consider the feasibility of applying to IMO to designate an international ECA covering its entire coastal region.

2 With some exceptions. For details, see U.S. Environmental Protection Agency (EPA, 2009).

3 Ibid.

Delineating a future Chinese ECA would be more complex than existing ECAs for several reasons. First, China has both an extensive Pacific coast and a large internal sea, the Bo Sea. This suggests an ECA shape that combines aspects of the North American coastal approach and Baltic Sea approach. Second, China cannot extend an ECA out to 200 nm without entering the territories of neighboring countries and regions or disputed areas.[4] But a narrow ECA would exclude a large portion of the ship traffic and the associated emissions. A regional approach, for example through a joint ECA application with Korea and Japan, could provide expanded coverage and air quality benefits but with added political complexity. This paper focuses only on a Chinese ECA.

An emissions inventory derived from current ship traffic can help policymakers make an informed decision about ECA delineation but ignores a critical point: ship operators might change their navigational behaviors once an ECA is established. Because ECAs will increase operational costs for ships by requiring a switch to cleaner and more expensive marine fuels or the use of exhaust aftertreatment, ship operators may choose to reroute to avoid operating within ECAs, even though it results in consuming marginally more fuel, because it saves on total fuel costs for the voyage. This reduces the quantity of emissions that are covered by the ECA and, therefore, reduces the ECA's effectiveness.

Evidence from other ECAs suggests that a narrow, belt-shaped ECA along the coastline could be susceptible to rerouting. Ship location data provided by Automatic Identification System (AIS) transmitters[5] along the California coast indicate that rerouting around maritime fuel quality regulations does occur. AIS devices, which are onboard most commercial ships, broadcast the instantaneous position, speed, heading, and identification information of ships to satellites and land-based stations. Maps showing ship traffic density along the California coastline show different traffic patterns between 2014 and 2015 (Figure 2) which correlate with a change in fuel quality requirements.

In 2014, state regulations required ships traveling within 24 nm of the California coastline to use cleaner but more expensive distillate fuels. That year, ships operating outside of the 24 nm zone could still use cheaper, but more polluting, heavy fuel oil (HFO). As a result, many ships operated just outside the 24 nm zone (left panel) to reduce fuel costs. In 2015, however, more stringent fuel quality standards began to apply to ships operating within the North American ECA. This meant that ships hat to use more expensive low-sulfur fuels or SO_x aftertreatment anywhere within the ECA, including an area extending 200 nm from the California coast. Some ships moved closer to shore, and therefore took a more direct route between ports, because there was no longer a benefit to operating just outside the 24 nm boundary line (right panel).

4 The Chinese exclusive economic zone (EEZ) is in some places narrower than 200 nm from the coastal baseline. So, a 200 nm ECA zone would inevitably enter into neighboring countries' EEZs which means a joint application by all the countries involved to IMO would be needed (National People's Congress of the People's Republic of China, 1998).

5 These data are commercially available. The AIS data vendor for this analysis was exactEarth Ltd.

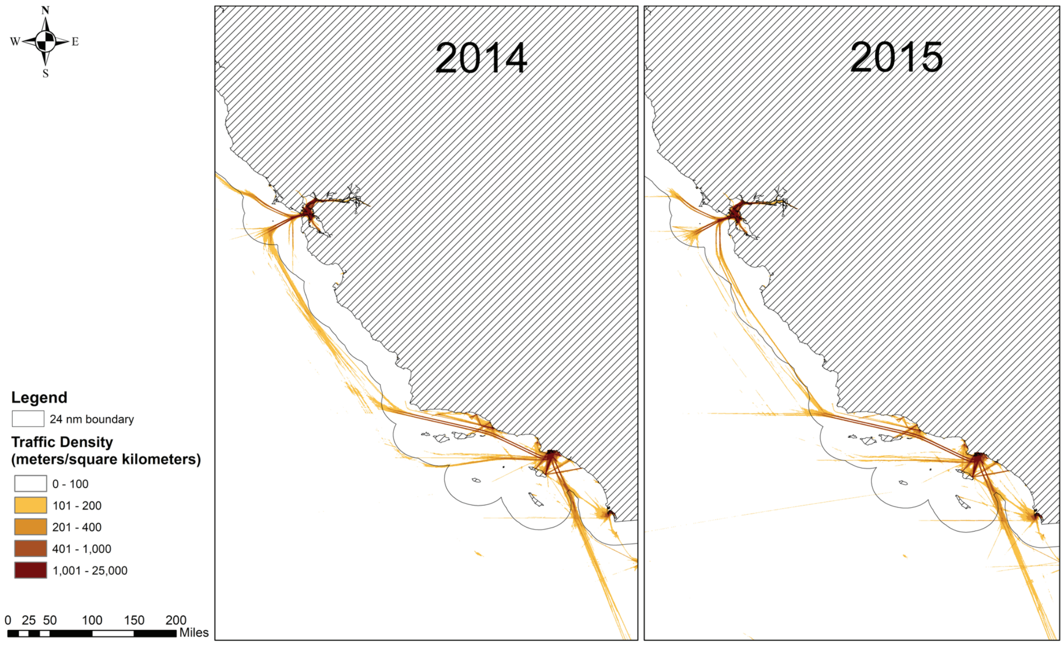

Figure 2. Line density of oceangoing vessel traffic in 2014 and 2015 along the California coastline

Ships reroute to avoid environmental regulations, but the incentives change with the way these zones are delineated and with the differential in operating costs inside and outside the zones. The time and fuel costs of routing outside a 200 nm wide ECA almost always outweigh the cost of travelling through the ECA. For narrower ECAs, rerouting may become more attractive. When preparing the North American ECA application, U.S. regulators believed that the cost-effectiveness of narrower (e.g., 24 nm) ECAs might be overestimated if ships could reduce operational costs by operating just outside of the ECA boundary (B. Wood-Thomas, personal communication, March 22, 2018.)

1.2 EXISTING WORK ON REROUTING UNDER ECAS

Ship routing and scheduling greatly affect voyage fuel consumption and operational costs. Therefore, there is a wealth of literature discussing ship routing and scheduling tactics in general. Given the recent introduction of ECAs, however, there are few studies directly addressing the question of how ships may reroute to reduce the amount of time spent in ECAs, but there are some.

Gausel (2014) systematically examined ship speed and routing considering ECA regulations with associated environmental consequences. Gausel analyzed four potential impacts on shipping operations brought by ECA regulations:

- » new sailing legs[6] and rerouting, especially with a small control area;
- » speed reductions within ECAs compensated by higher speed outside of them;
- » modal shift to land-based transport alternatives; and
- » market development due to higher freight rates, including cancelling of certain ship routes and potential uptake of LNG and scrubbers.

6 A leg refers to a section of a route connecting two sequential port stops.

European researchers (Jonson, Jalkanen, Johansson, Gauss, & van der Gon, 2014; Notteboom, Delhaye, & Vanherle, 2010) investigated the risk of modal shift due to freight rate increases induced by ECA regulations for the Baltic and North Sea ECAs, who concluded an expected volume loss of as high as 60% for certain routes given high freight rate differentials . That work warns that the potential modal shift to trucks could bring negative environmental impact to this region. For this paper, we focus on the potential impact of rerouting because it is closely related to ECA delineation and could provide supplementary information to more traditional ECA analysis based upon static traffic patterns. When rerouting, ships redistribute rather than reduce emissions, diluting the health benefits expected for people living in coastal areas.

1.3 DEFINING THE PROBLEM

Suppose ship A travels regularly between the Port of Long Beach and the Port of Shenzhen. Along the way, it makes a stop at the Port of Shanghai to unload some cargo before proceeding to its final destination. Currently, ship A navigates its original route (green line in Figure 3) from Shanghai to Shenzhen as it represents the shortest route between the two ports. However, if a Chinese ECA 50 nm wide is in place, how might Ship A change its route? Ship A could continue to navigate its original route, paying for the additional cost of cleaner fuel but taking the shortest route. Alternatively, Ship A could choose to reroute (red line in Figure 3), a longer route but it allows Ship A to operate predominately outside of the ECA, which enables the ship to operate on cheaper fuel for most of the route.[7]

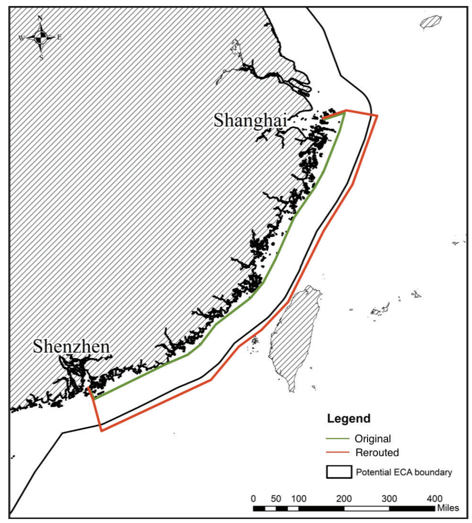

Figure 3. Example of rerouting around a 50 nm Chinese ECA between Shenzhen and Shanghai.

In this study, we examine potential rerouting behaviors and their impacts on an ECA's effectiveness at reducing overall emissions given various ECA boundaries.

Fuel consumption represents more than 50% of operational costs in the shipping sector (Lindstad et al., 2012). Already, operators optimize their fuel consumption around a variety of factors such as weather, ocean currents, and most efficient sailing speeds. Therefore, it is reasonable to assume that whether or not a ship chooses to reroute around an ECA will depend mostly on the difference in fuel costs between the original route and the ECA avoidance route. If a reroute results in higher fuel costs than switching to cleaner fuel due to longer distances and/or higher speeds, the ship will likely keep the original route. However, if rerouting proves less expensive, the ship will likely reroute.

These reroutes may be less expensive overall, but the result is greater fuel consumption and therefore more air pollution. Although these additional emissions would be moved

7 In the case of post-2020, the cheaper fuel should be compliant with IMO's 0.5% m/m sulfur cap, which we refer to as post-2020 compliant fuel.

further from the shore and the most affected populations, if the ECA is relatively narrow the distance that air pollution is shifted out to sea may be small. Depending on prevailing winds, these pollutants still can be transported inland, impacting public health.

We analyze four ECA delineation scenarios[8] in this paper:

1. ECA extending 12 nm from the coast, which is the boundary of China's territorial sea.
2. ECA extending 24 nm from the coast, which is the boundary for China's contiguous zone.
3. ECA extending 50 nm from the coast.
4. ECA extending 100 nm from the coast.

Although the North American ECA extends 200 nm from the territorial sea baseline (essentially the coastline), it is unlikely that China would be able to implement a 200 nm ECA because it would encroach on the marine territories of neighboring countries and regions. A regional approach, e.g. a Northeast Asia ECA which is beyond the scope of this work, may help maximize the benefits of the ECA.

To simplify our study, we assume domestic Chinese river and coastal vessels operate close to shore and therefore do not reroute under any delineation scenario. Thus, we focus our analysis on the emissions from oceangoing vessels (OGVs) only. OGVs are also more likely than river or coastal vessels to use lower-quality fuels that exceed an ECA's fuel sulfur limits and the engines on river and coastal vessels are more likely to fall under domestic environmental regulations to control other pollutants such as NO_x and PM. Additionally, given the time it takes to apply for an ECA in IMO, we assume a Chinese ECA takes effect in 2025 and therefore use 2025 as the evaluation year for our analysis. Because ECA NO_x regulations only will apply to newbuilds starting from the year of implementation, and the cost increment for NO_x aftertreatment is expected to be modest compared to the costs of fuel switching, we focus solely on the potential rerouting impact of SO_x requirements.

8 Note that the proposed widths are theoretical simplifications. In reality, an ECA doesn't have to be congruous throughout the coastline, especially where there are offshore islands or when territorial disagreement comes into play.

2. METHODOLOGY

We estimate the share of overall shipping air pollution covered under ECAs of various widths with and without consideration of ship rerouting. The baseline emissions are what ships emit within 200 nm of the coast. Baseline emissions were estimated using ICCT's Systematic Assessment of Vessel Emissions (SAVE) model using 2015 AIS data. We then estimated the proportion of baseline emissions that would be covered under different ECA widths (12 nm, 24 nm, 50 nm, and 100 nm) under two scenarios: no rerouting and rerouting. Specifically, we:

1. Estimated ship emissions within 12 nm, 24 nm, 50 nm, 100 nm, and 200 nm from China's coast without rerouting, which we refer to as the baseline emissions.
2. Identified typical ship routes (legs) within the 200 nm area.
3. Characterized the ships navigating these legs, including their ship type, engine power, and other characteristics that allowed us to estimate emissions from these ships.
4. Identified original and alternative legs corresponding to each ECA delineation scenario.
5. Estimated the distance traveled and cruise speeds for each original and rerouted leg under each ECA delineation scenario.
6. Estimated emissions and fuel costs for all legs based on a range of 2025 projected fuel prices.
7. Developed a rerouting decision matrix for each sample ship, leg, and fuel price scenario as a function of ECA width.
8. Estimated the proportion of emissions that remained within each ECA boundary (the emission retention rate) after rerouting.
9. Calculated the adjusted ECA emissions coverage by multiplying the proportion of baseline emissions within the ECA boundary without rerouting by the emission retention rate.

Each step in this methodology is described below. Step 1 is described in Section 2.1. Steps 2 through 4 are described in Section 2.2. Steps 5 and 6 are described in Section 2.3. Section 2.4 describes steps 7 through 9.

2.1 ASSESSING BASELINE ECA EMISSIONS COVERAGE WITHOUT REROUTING

We calculated SO_x emissions from all oceangoing vessels operating within 200 nm from the Chinese coast using AIS data and ICCT's SAVE model, as described in Mao et al (2017). The relevant equation for estimating these emissions is Equation 1:

$$E_i = \sum_{t=0}^{t=n}((P_{ME_i} \times \left(\frac{SOG_{i,t}}{V_{max}}\right)^3 \times EF_{ME_i} + P_{AE_i} \times EF_{AE_i} + P_{BO_i} \times EF_{BO_i}) \times 1 \text{ hour}) \qquad (1)$$

Where:

E_i = the emissions for ship *i*, in grams
t = timestamp, each AIS point is associated with an hourly timestamp
P_{ME_i} = main engine maximum power for ship *i*, in kW
$SOG_{i,t}$ = speed over ground for ship *i* at timestamp *t*, in knots
V_{max} = maximum speed for ship *i*, in knots
EF_{ME} = SO_x emission factor for the specific main engine type for ship *i*, in g/kWh
P_{AEi} = auxiliary engine power output for ship *i*, in kW
EF_{AE} = SO_x emission factor for the auxiliary engine for ship *i*, in g/kWh
P_{BO_i} = boiler power output for ship *i*, in kW
EF_{BO_i} = SO_x emission factor for the boiler for ship *i*, in g/kWh

Applying Equation 1 provided a geospatially allocated 2015 ship emissions inventory for ships operating within 200 nm of the Chinese coast. This result was used to understand how much SO_x emissions ECAs of different widths would cover assuming no ship rerouting. We calculated the fleetwide emissions within 200 nm from China's coastline first and then geo-fenced the emissions using different ECA delineation shapefiles. This gave us total SO_x emissions within 12 nm, 24 nm, 50 nm, and 100 nm.

A simple metric of baseline ECA emissions coverage (BEC) was defined as a ratio of SO_x emissions within a distance *j* from the coast divided by the SO_x emissions within 200 nm of the Chinese coast, as shown in Equation 2:

$$BEC_j = \frac{SO_x\ emissions_j}{SO_x\ emissions_{200\ nm}} \qquad (2)$$

2.2 IDENTIFYING REPRESENTATIVE TRAFFIC PLUS REROUTED LEGS

The leg of a voyage is a section of a longer route connecting two consecutive port stops. For example, a ship may visit the Ports of Shenzhen, Shanghai, and Tianjin in one route, with the journey between Shenzhen and Shanghai considered one leg while the journey between Shanghai and Tianjin another. Considering the magnitude of shipping trade in China and its neighboring countries, it is impractical to identify all possible legs. However, we can map ship traffic density in order to identify some representative legs that capture most ship traffic in this region.

Figure 4 maps ship traffic patterns for June 2015 in China's coastal waters using AIS data.

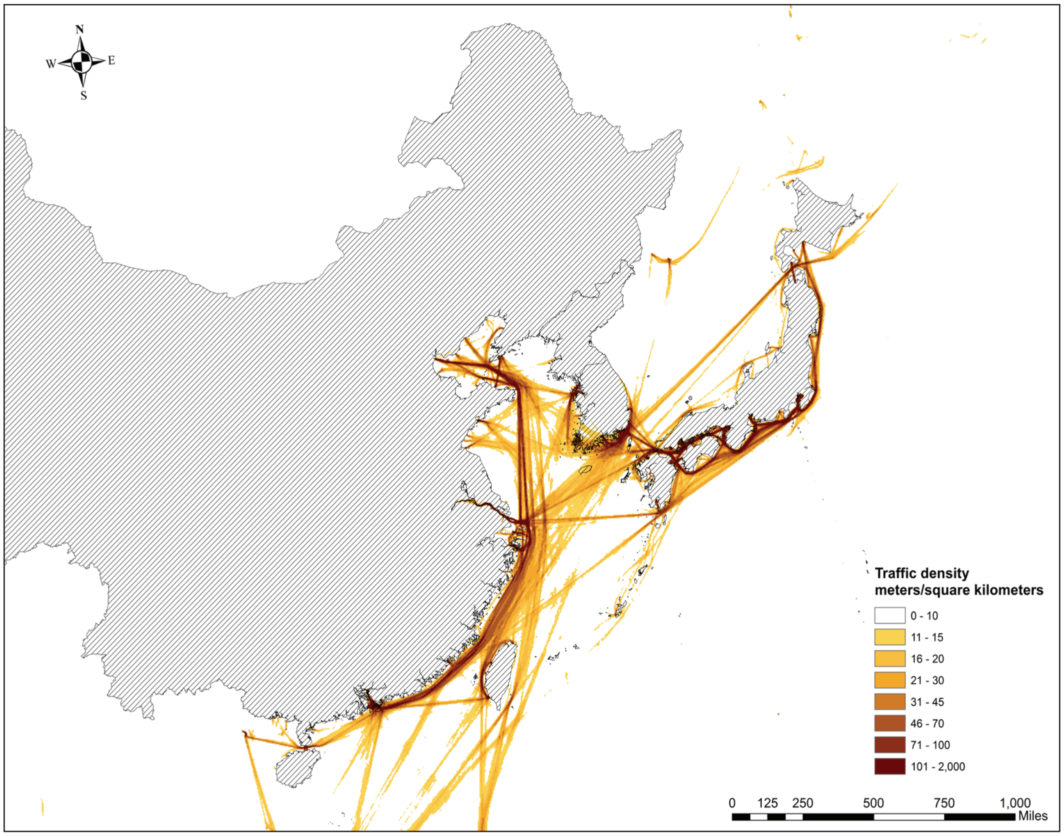

Figure 4. Line density of OGV ship traffic along China's coastline in June 2015.

These data can be used to identify representative, highly frequented shipping legs. The following general guidelines were applied to this task:

1. We chose legs covering the darkest, most frequented shipping lanes shown in Figure 4.
2. For those legs, we verified whether they are real shipping legs as represented by route-specific freight rates. Publicly available freight rates indicated a legitimate leg.
3. For overlapping legs, only the most prominent was chosen. For example, legs between Shanghai and Shenzhen and between Shanghai and Xiamen overlap. The Shanghai to Shenzhen lane is the more prominent one, and ships should behave similarly on both legs, so only that lane was selected for further analysis.

Using these data, we can identify five representative, highly frequented shipping legs: the legs between Tianjin and Shanghai, Shanghai and Shenzhen, Shanghai and Kaohsiung, Shenzhen and Busan, and between Xiamen and Yokohama (Figure 4).[9] Note that some part of the leg connecting Shanghai and Shenzhen coincides with the leg between Shenzhen and Busan, and thus was overlaid by color of the latter leg.

9 Although some legs, like those between Shanghai and Fukuoka, Shenzhen and Kaohsiung, and Shanghai and Busan seem like frequent legs (see Figure 4, with not the darkest color), we didn't include them because they are less important than those chosen.

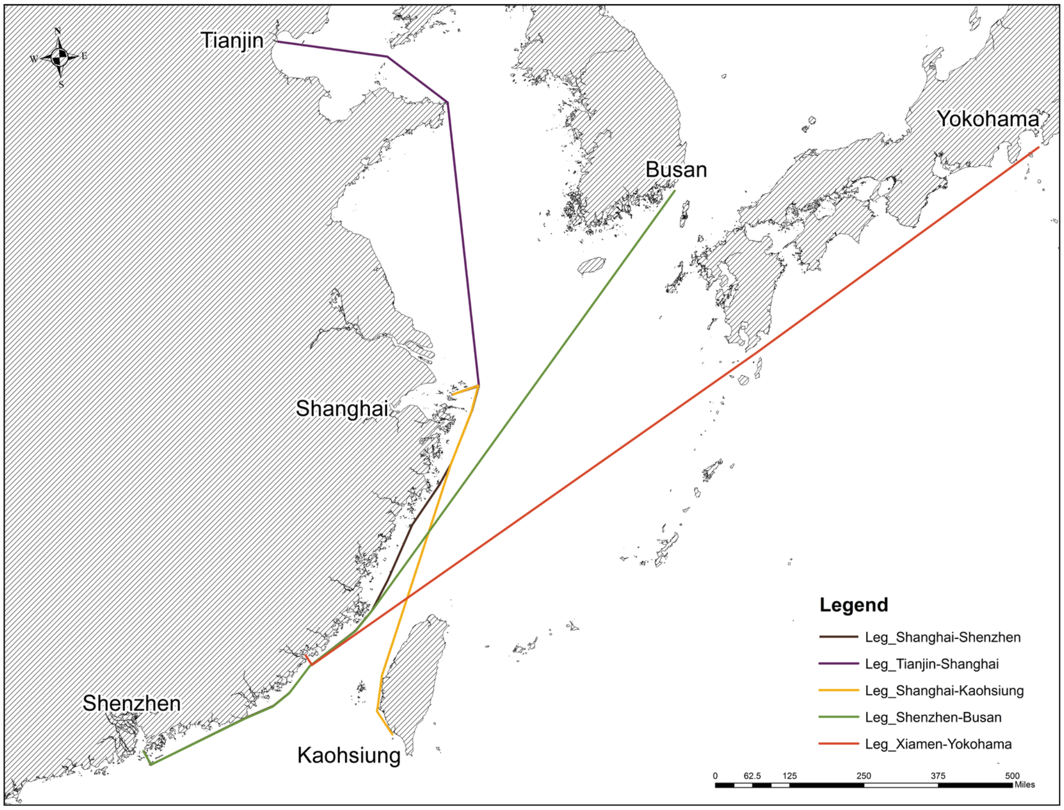

Figure 5. Representative shipping legs for analysis.

We then identified sample ships for each of these legs. We randomly selected a sample of ships representing major ship classes on these legs such that there were two ships for each leg and 10 ships in total. Table 1 details vessel characteristics data on the sample ships, which represent the major five ship classes (container, tanker, bulk carrier, general cargo, and LNG carriers) that were active in this region (Mao et al., 2017).

Table 1. Selected information for sample ships that transit each of the five legs

Ship ID	Leg	Ship class	Mean speed over ground (knots)	Design speed (knots)	Main engine power (megawatt)	Main engine specific fuel oil consumption (g/kWh)
1	Shanghai-Shenzhen	Container ship	12.8	24.8	40.0	171
2	Shanghai-Shenzhen	Bulk carrier	10.8	14.2	9.96	172
3	Tianjin-Shanghai	General cargo ship	11.3	14.5	8.95	170
4	Tianjin-Shanghai	Container ship	11.3	25.2	45.8	168
5	Shanghai-Kaohsiung	Oil tanker	9.6	14.7	12.2	172
6	Shanghai-Kaohsiung	Container ship	13.7	25.2	45.8	168
7	Shenzhen-Busan	Container ship	15.7	27.5	80.1	166
8	Shenzhen-Busan	LNG carrier	13.6	17.4	2.83	177
9	Xiamen-Yokohama	Container ship	14.5	24.2	36.5	174
10	Xiamen-Yokohama	Container ship	14.7	18.7	10.9	170

Source: IHS Fairplay ship database

After choosing the representative legs, we mapped the likely alternative legs corresponding to different ECA delineation scenarios. As an example, Figure 6 shows four alternative legs corresponding to the four ECA delineation scenarios for the Shenzhen-Busan leg. The alternative legs represent the shortest distances between the same two ports while minimizing the distance travelled within ECAs out to 12 nm (orange), 24 nm (red), 50 nm (blue), and 100 nm (purple), respectively.

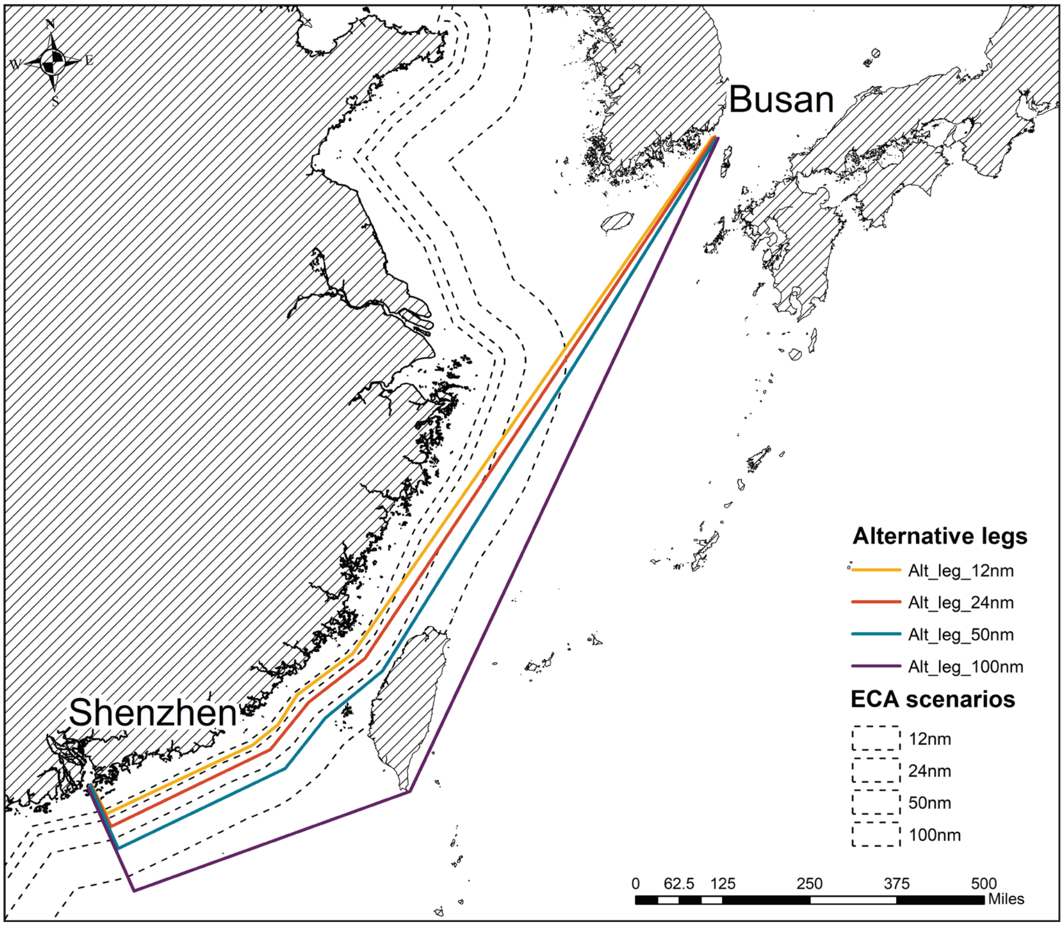

Figure 6. Alternative legs between Shenzhen, China, and Busan, Korea.

From these legs, individual stretches were defined. A stretch is a section of a leg falling completely inside or outside of an ECA. Most original legs transiting Chinese ports would have only one stretch falling completely within prospective ECAs. Rerouted legs would have two or three stretches: one or more short ones near the origin and destination ports within the ECA, and another longer one outside. For original legs routing deep out to sea, for example between Shenzhen and Busan, the largest stretch would fall within the prospective ECA with a second, generally shorter leg, outside of the ECA.

2.3 ESTIMATING FUEL CONSUMPTION AND FUEL COSTS FOR ORIGINAL AND ALTERNATIVE LEGS

We estimated the fuel consumption of representative ships on original and alternative legs by summing fuel consumption along all stretches of each leg using the following equation:

$$FC_{i,s} = SFOC_i \times P_{ME_i} \times \left(\frac{SOG_i}{V_{max_i}}\right)^3 \times \sum \frac{l_{s,i}}{SOG_i} \qquad (3)$$

Where:

$FC_{i,s}$ = fuel consumption of ship *i* on stretch *s*, in grams

$SFOC_i$ = main engine specific fuel oil consumption for ship *i*, in grams of fuel/kWh

P_{ME_i} = main engine maximum power for ship *i*, in kW

$L_{s,i}$ = length of stretch *s* traveled by ship *i*, in nautical miles

SOG_i = speed over ground for ship *i*, in knots

V_{max} = maximum speed for ship *i*, in knots

We assume that ships travel at a constant cruising speed during both their original and alternative legs. We do not include fuel use while in port, as it is equivalent for both the original and alternative legs. We also exclude the fuel consumption of boilers, because boilers usually are shut off during cruising, and the fuel consumption of auxiliary engines, which is usually small compared to that of the main engine. Thus, the fuel consumption in Equation 3 is for the main engine only.

Speed is an important determinant of fuel use and emissions, and the average cruising speed may change if the alternative route is much longer than the original route. Ships engaged in liner services, like container ships and general cargo ships, are more likely to increase cruising speeds during a rerouting, as they tend to have tight timetables. Ships mostly engaged in tramp service (e.g., tankers, bulk carriers), on the other hand, have schedules that are more flexible and are therefore less likely to increase speeds during a reroute.

Sailing speeds of the original leg were derived directly from AIS data, which reports the hourly average sailing speeds for individual ships. We estimate the sailing speed of the alternative leg using the leg's distance and sailing time bounded by a delay allowance which we determined using expert judgment. Three considerations were taken into account: a baseline level of flexibility is provided for all ship types because on average there is at least half a day anchorage before berthing at port; all things being equal, longer voyages should have extended time allowances because their schedules are more likely to be padded to account for delays due to bad weather, etc.; and the time allowance for container ships should be lower than for other ship types because of their high average cruising speed and quick port turnaround times. If the alternative leg distance, operated at the original speed, would delay arrival at the destination port longer than the delayed allowance, modeled speeds were increased accordingly. This would increase fuel consumption and costs and therefore act as a disincentive for rerouting.

The delay allowance reflects the scheduling flexibility and is different for different ship types. Because there is variability in the original travel time between different ships, we set a high and low range for the delay allowance by distance, presented in Table 2. When the leg length is greater than 1,000 nm, we used the higher delay allowance. Otherwise, the lower delay allowance was used.

Table 2. Assumptions on delay time allowance for each ship class

Ship class	Delay allowance by leg length (hrs)	
	1,000 nm and below	>1,000 nm
Container ship	4	6
Bulk carrier	8	15
General cargo ship	8	15
Oil tanker	8	15
LNG carrier	8	15

Fuel costs are a function of the type of fuel used, its price, and the amount consumed, as shown in Equation 4.

$$Fuel\ cost_{i,l} = \sum FC_{i,s} \times FP_{k,s} \qquad (4)$$

Where:

$Fuel\ cost_{i,l}$ = fuel cost of ship *i* navigating leg *l*, in dollars

$FC_{i,s}$ = fuel consumption of ship *i* on stretch *s*, in tonnes

$FP_{k,s}$ = Price of fuel type *k* used on stretch *s*, in dollars/tonne

Fuel prices are very volatile, making future prices difficult to predict. Furthermore, it is unclear exactly which fuels will be used to comply with future fuel quality requirements, both within ECAs and globally. At present, ships have two main choices to comply with SO_x ECA requirements: switch to distillate fuel or install and operate an exhaust gas cleaning system (i.e., a "scrubber"). This may change in 2020, when various types of bunker fuel will be produced to meet the new global sulfur cap at 0.5% m/m, although several companies are retrofitting their fleets with scrubbers and ordering new ships with scrubbers already installed. Both baseline and ECA-compliant fuels may be a pure distillate, a blend of distillate and residual fuels, desulfurized residual fuel, or something else.

Despite volatility, marine fuel prices should generally track crude oil prices (Roy & Comer, 2017). Consistent with Roy and Comer (2017), for the main analysis we assume a single 2025 distillate fuel price based upon the World Bank (2017) predicted crude oil prices. We assume that China implements an ECA in 2025. To account for the uncertainties associated with the future global fuel type and price, we identified high, medium, and low fuel price differentials between the ECA-compliant fuel (distillate) and the post-2020 compliant fuel (0.5% sulfur fuel, or low-sulfur HFO [LSHFO]) as shown in Table 3.

The high price differential is taken from IMO's fuel oil availability study (Faber et al., 2016), which predicts post-2020 compliant fuel to be priced at about 96% of distillate fuel in 2020. In the longer term, IMarEST (2018) projects that post-2020 compliant fuel could fall to 20% lower than distillates after 2030. We adopt this value as the high price differential. The medium price scenario was taken as 12% lower than distillates, which is simply an average of the high and low differentials. Scrubbers are not evaluated as a compliance mechanism because as of 31 May 2018, they are installed on only 938 ships (1% of oceangoing vessels globally).[10]

Table 3. Fuel price scenarios, in 2015 U.S. dollars

Stretch	Fuel type	Scenarios	2025 fuel price ($/tonne)[a]
Within ECA	Distillate	—	547
Outside ECA	Post-2020 compliant fuel	High differential	438
		Medium differential	482
		Low differential	525

2.4 ESTIMATING SHIP REROUTING AND EMISSIONS DISPLACEMENT UNDER AN ECA

Using the estimated fuel consumption and fuel cost, we determined whether the original or alternative leg is the most economical for a ship operator for each of the different ECA scenarios. We assumed the ship operator opts for the least expensive routing option.

Rerouting around an ECA has two main negative consequences: (1) some of the emissions are simply moved outside the ECA boundary rather than controlled, and (2) overall emissions increase because ships burn more fuel, and therefore release more air pollution. In order to evaluate the efficacy of different ECA delineation scenarios, we must compare the emissions within an ECA from a scenario without rerouting (termed “voyage emissions”) to the emissions remaining in an ECA after a rerouted scenario (termed “rerouted emissions”).

Figure 7 characterizes the different emissions quantified in the study using the Shenzhen to Busan leg as an example. For this ship, voyage emissions come from fuel consumed on the green line within the perspective ECA. Under rerouting, the ship travels the red line first perpendicular to the ECA, and then the blue line to its destination. This approach minimizes the amount of time operating in the ECA on the more expensive fuel. Fuel consumed on the red line determines the rerouted emissions that would be covered by an ECA 50 nm from the coast. Air pollutants emitted when navigating the yellow and blue lines are unregulated by the dashed ECA zone. Fuel consumed on all stretches is considered when estimating total fuel costs and the fuel consumption multiplier, as described below.

10 Exhaust gas cleaning system associations, “Scrubber orders full ahead”. Retrieved from: http://www.egcsa.com/scrubber-orders-full-ahead/.

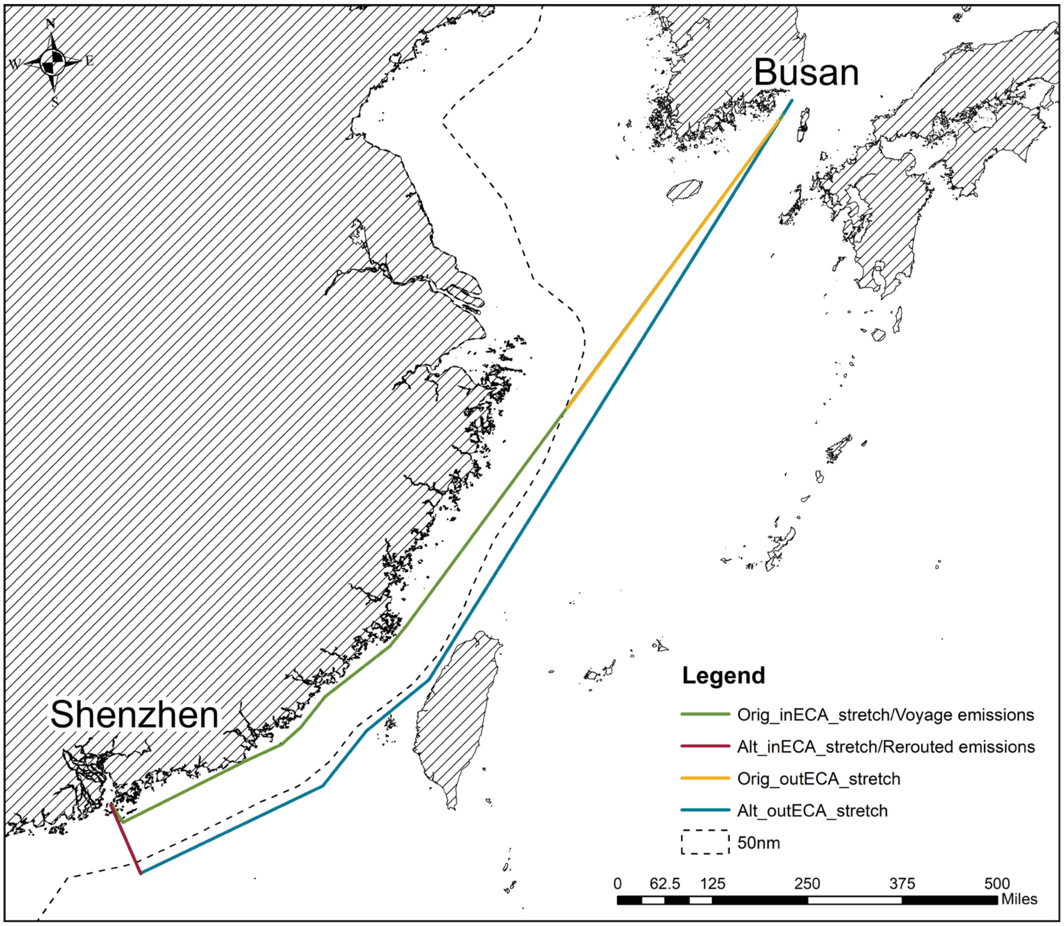

Figure 7. Voyage and rerouted emissions by leg.

The main metric relating ship rerouting and the emissions distribution is an emission retention rate. In order to quantify the portion of emissions covered by an ECA after being impacted by ship rerouting, we quantified an emission retention rate for each ECA scenario. The retention rate is a simple average of the ratio of rerouted to voyage emissions for the 10 sample ships for the different ECA delineation scenarios.[11] Equations 5 and 6 show how we calculated the impact of ship rerouting on ECA coverage for each ECA scenario.

$$ERR_j = \frac{1}{N} \times \sum \frac{RFC_{i,j}}{VFC_{i,j}} \qquad (5)$$

Where:

ERR_j = percentage of emissions retained within the boundary of an ECA j nautical miles from the Chinese coast after rerouting, which is directly proportionate to the percentage of fuel consumption retained within the boundary of the ECA

$RFC_{i,j}$ = fuel consumed by ship i within the ECA boundary that extends j nautical miles from the Chinese coast when rerouting

11 A methodology to weight the individual legs, which were chosen qualitatively as described above, is beyond the scope of this document. A sample calculation of this simple average approach, represented by Equation 5, is provided in Appendix C.

$VFC_{i,j}$ = fuel consumed by ship *i* within the ECA boundary that extends *j* nautical miles from the Chinese coast without rerouting, which we call voyage fuel consumption

N = the total number of sample ships

We multiplied *ERR* by *BEC* (Equation 1) for each ECA scenario to estimate to amount of SO_x emissions (in tonnes) that would remain within the ECA boundary if ships reroute.

Finally, for each ECA scenario, because some ships would opt to reroute, the absolute amount of emissions to move from one port to another would increase because of the longer travel distance, driving an increase in total ship emissions in the coastal waters. Here, we calculated the total increase in fuel consumption for individual sample ships, both inside and outside of the ECA, as a proxy for how ship rerouting would impact overall emissions in the coastal waters.

$$\Delta FC_{i,j} = \left(\left(\frac{AFC_{i,j} - OFC_{i,j}}{OFC_{i,j}}\right)\text{-}1\right) \times 100 \qquad (7)$$

Where:

$\Delta FC_{i,j}$ = percent increase in fuel consumption for ship *i* due to rerouting when the ECA is *j* nautical miles from the Chinese coast

$AFC_{i,j}$ = the fuel consumption along the alternative leg (i.e., during rerouting) for ship *i* when the ECA is *j* nautical miles from the Chinese coast

$OFC_{i,j}$ = the fuel consumption along the original leg (i.e., without rerouting) for ship *i* when the ECA is *j* nautical miles from the Chinese coast

3. RESULTS AND DISCUSSION

3.1 BASELINE ECA EMISSIONS COVERAGE WITHOUT REROUTING

We estimate that oceangoing vessels emitted 956,000 tonnes of SO_X within 200 nm of China's coastline in 2015. Each ECA delineation scenario would cover a subset of those emissions without rerouting, with the share increasing as the ECAs get wider (Figure 8).

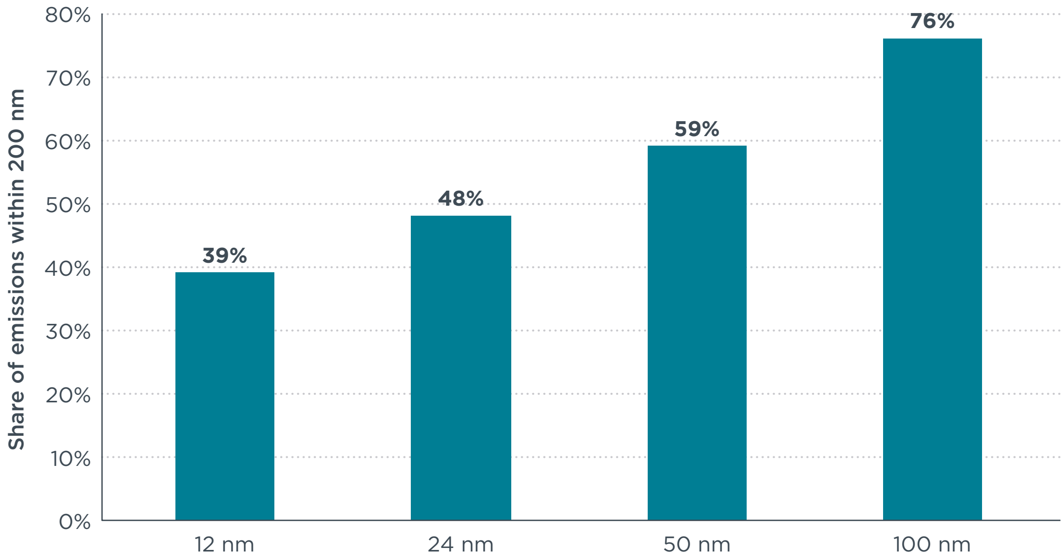

Figure 8. Percentage of SO_X emissions within 12 nm, 24 nm, 50 nm, and 100 nm of the Chinese coast without rerouting.

As shown in the Figure 8, ECA coverage of OGV SO_X emissions increases from about 40% at 12 nm to as high as 76% at 100 nm compared to the amount of emissions that would fall under a 200 nm ECA. Because most traffic is concentrated near shore, doubling the width of the ECA, say from 24 to 50 nm, tends to increase emissions coverage of the ECA by about one-quarter. This suggests that a relatively narrow ECA could control most of the near-shore air pollution and provide sufficient protections for public health; however, this ignores the effects of ships rerouting around the ECA to save on fuel costs, which we explore further below.

Note that these baseline results should be interpreted with caution. Because we included emissions only from oceangoing vessels, the actual emission share of all vessel traffic regulated under each delineation scenario would be somewhat different if emissions from the Chinese domestic fleet were to be included. According to a study of the Pearl River Delta region (Li et al. 2016), China's domestic fleet emits about 30% of total ship emissions in a sea region extending about 24 nm from the coast. If we apply this number to our results, it would result in the emission share numbers in 12 nm, 24 nm, 50 nm, and 100 nm boundaries increasing to 47%,[12] 55%, 64% and 79% respectively. In the next two sections, we explore how these coverages change when rerouting is considered.

12 The actual emissions covered by the 12 nm boundary could be even higher considering that the Pearl River Delta region is dominated by international vessel traffic. The share of domestic fleet we referenced here is likely to be an underestimate of that at the national scale.

3.2 SHIP'S REROUTING DECISIONS WHEN FACING AN ECA

The rerouting decisions for each of the 10 sample ships under different ECA delineation and fuel price assumption are shown in Figure 9. We analyzed each ship's rerouting decision for each of the ECA delineation scenarios and for three fuel price scenarios: high, medium, and low. The red dots indicate individual ships and where they operate in relation to each given ECA delineation scenarios (green band). Those bands ranges from the coast only (far left) out to 100 nm (near right). Ships tend to stick to the left as much as possible because these would be the naturally shortest shipping routes and therefore offering the shortest travel time and lowest fuel cost. When ships reroute, they move outside of the green bands but try to stay closely outside (the right side) of them.

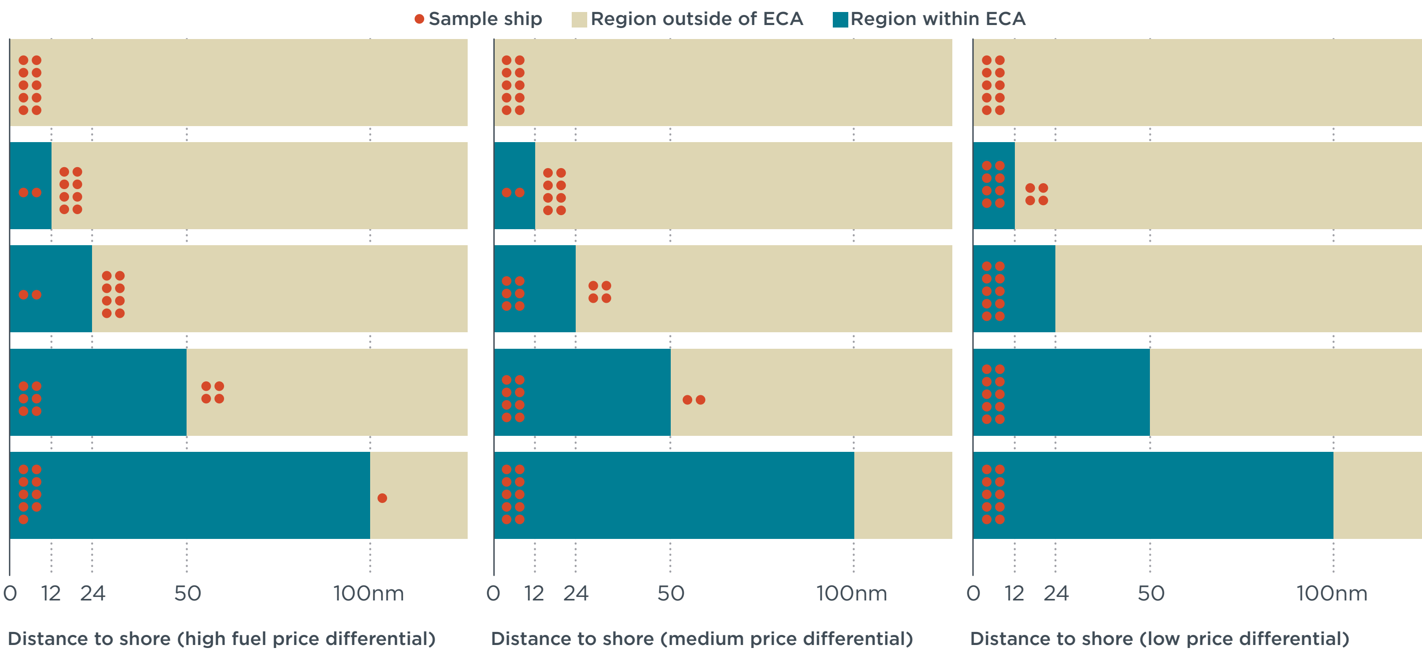

Figure 9. Rerouting decision matrix for 10 sample ships under three fuel price scenarios.

Three observations can be drawn from Figure 9. First, ships are less likely to reroute with wider ECAs. For example, in the medium fuel price differential case, eight out of 10 ships opt to reroute in the 12 nm delineation, wherea s only four and two reroute in the 24 nm and 50 nm scenarios, respectively. In the 100 nm delineation, no rerouting was expected. Intuitively, this makes sense as it is more costly and less beneficial to bypass a wider ECA than a narrow one.

Second, fuel price differential plays a major role in determining whether or not a ship will reroute. If the future price of post-2020 compliant fuels is low, there will be a large price increase to use ECA-compliant fuels, increasing the incentive for ships to reroute. Even in a 100 nm ECA delineation scenario, some ships would still find it more economical to reroute in a high-price differential scenario. On the other hand, if future post-2020 compliant fuel costs are high, the cost difference of switching to ECA-compliant fuels is small, reducing the incentive for ships to reroute. In a low fuel price differential scenario, only four out of 10 ships might choose to reroute even at the narrowest ECA delineation.

A third observation can be made by comparing Figure 9 and Figure 5, namely, that some legs are more prone to rerouting than others. The leg between Tianjin and Shanghai is never rerouted for any ECA width or fuel scenario. This is due to the position of original leg, which combines a long in-ECA stretch with unavoidable travel in the Bo Sea with a long portion in the Yellow Sea that is outside of most ECA delineations (purple line in Figure 5). In contrast, ships on legs from Shanghai to Shenzhen or Shenzhen to Busan are most likely to route outside of ECAs to take advantage of the cheaper fuel. Even with a very small fuel price differential, some ships on these legs still opt to change course if a 12 nm ECA is in place.

3.3 IMPACT OF REROUTING ON EMISSION SHARES COVERED BY ECAS

These results—the baseline emissions of each ECA delineation, and the expected rerouting behavior—can be combined to provide a more detailed view of future coverage.

Table 4 summarizes the emission retention rate—an estimate of the share of initial emissions within each ECA delineation that remain in that zone (i.e., are not rerouted)—estimated for each ECA delineation scenario and fuel price assumption. These range from 100% (no rerouting) for wider ECAs and higher fuel price scenarios, to as low as 33% for the 12 nm ECA under the most likely and low fuel cost assumptions. Further detail about this calculation is provided in Appendix C.

Table 4. Emission retention rate by ECA width and fuel price assumption

Scenarios	Retention rate by ECA delineation scenario			
	12 nm	24 nm	50 nm	100 nm
High price differential	33%	34%	66%	91%
Medium price differential	33%	64%	82%	100%
Low price differential	64%	100%	100%	100%

These emission retention rates can then be combined with the baseline emissions coverage shown in Figure 8 to estimate the emissions coverage of different ECA widths after accounting for rerouting.

Comparing the coverage of original and retained emissions estimates the impact rerouting will have on the efficacy of different delineation scenarios. The comparison is shown in Figure 10, where each bar group represents an ECA delineation scenario. The left shaded bar is the original emission share (compared to emissions within 200 nm) without rerouting. The right hollow bar is the retained emission share with rerouting under the most likely fuel price scenario. The fuel price differential scenarios are presented as the error ticks on the hollow bars.

As shown in the figure, the retained emission share for a 12 nm ECA (15%) is about 60% lower than the original share with no rerouting under the medium fuel price differential scenario. Moving further away, under the 24 nm ECA scenario, retained emission share falls by one-third (48% versus 32%) under the medium fuel price differential scenario. At 100 nm, however, the original 76% emission share is retained under all but the low fuel price differential scenario, where it falls modestly to 70%.

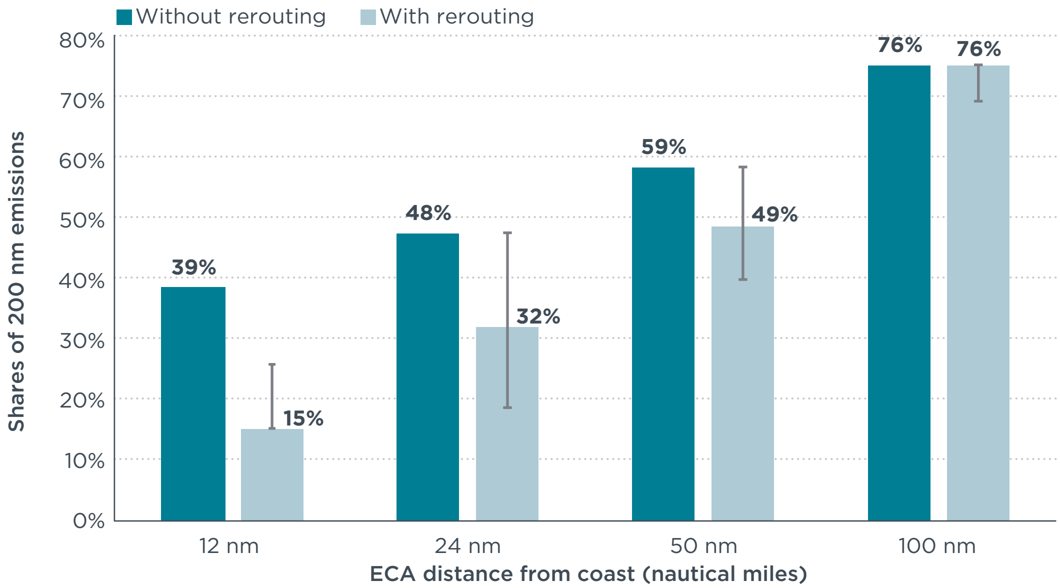

Figure 10. The share of sulfur oxides that ships emit within 200 nautical miles covered by an Emission Control Area.

What was calculated but not shown in Figure 10 was the increase in fuel consumption under each delineation scenario. This indicates how rerouting would increase ship emissions for sample ships under different delineation scenarios traveling full leg lengths. If no rerouting takes place, no increase in rate would be expected (0%). As expected, total fuel consumption on analyzed legs increases with rerouting due to longer journeys and sometimes-higher cruise speeds. As the ECA zone expands, total fuel consumption increases by a modest amount (2%) after considering rerouting. Under the low fuel price scenario, the increase would first expand from 2% to 6% at 50 nm, after which time it falls again to about 1%. Taking into account other legs that are less frequented and less prone to rerouting, the overall increases in fuel consumption in China's coastal waters remains modest. This means that rerouting acts mostly to shift rather than absolutely increase emissions and fuel use.

Overall, setting the ECA boundary 100 nm from the Chinese coast avoids rerouting altogheter, except when the fuel price differential between ECA-compliant and post-2020 compliant fuels is high. In all cases, the 100 nm boundary results in the largest emissions coverage and does not increase overall fuel consumption near the coast.

4. CONCLUSIONS

In order to quantify the impact of rerouting on the future emissions regulated by different ECA delineations, we carried out a case study of 10 ships on five representative routes along China's coastline. This provides an estimate of the magnitude of emissions that could be controlled in the proposed ECA zones. Combined with emission inventories compiled from AIS data, the emissions that would be regulated by an ECA with and without rerouting under each delineation scenario were quantified.

Assuming that ships do not reroute around ECAs no matter their distance from the coast, one might conclude that a narrower ECA would suffice in controlling the majority of ship traffic emissions near China. Moreover, a narrower ECA may be attractive to policy makers given the complications of enforcing ECA requirements on the open sea. Additionally, because the Chinese government has complete authority over ships traveling within 12 nm of its coast (its territorial sea), it could be easier for the government to enforce ECA regulations within its territorial sea.

This conclusion completely changes if one considers that ships can, and would, reroute around a narrow ECA to save on fuel costs. We found that the amount of emissions that would be controlled by an ECA would be overestimated if rerouting behavior is not considered. Based on our case study, between four and eight out of 10 sample ships could reroute around the 12 nm boundary depending on fuel prices, displacing rather than controlling emissions through the use of lower sulfur fuels. These unregulated emissions would likely be repositioned right outside the ECA boundary, as seen along the Californian coast in 2014, rather than being reduced.

A fundamental goal in delineating a future ECA is to maximize its health and environmental benefits while reducing enforcement complexity. A wider ECA zone would cover a greater fraction of ship emissions, but with some additional enforcement complexity should governments pursue enforcement technologies like aerial or satellite-based surveillance. However, once the ECA goes beyond the territorial sea, the incremental challenge of enforcement becomes minor, as the majority of the challenge would come from technology investment in monitoring devices and personnel training. Although a narrower ECA would make it easier to monitor and regulate, it might induce gaming by providing an incentive for ship operators to route around the ECA to use a cheaper, dirtier fuels, even though it means the ship will travel a longer distance and consume more fuel. A wide ECA boundary, on the other hand, discourages such behaviors because of diminishing and, eventually, zero fuel cost savings potential.

We found that an ECA needs to be at least 100 nm from the coast to be most effective. An ECA boundary that is too close to shore can undermine the emissions reduction benefits of an ECA. When ships bypass the ECA zone, they avoid environmental regulations, redistributing rather than reducing emissions. Worse, rerouting results in a modest (up to 2%) increase in fuel consumption compared to shorter, more direct voyages because rerouted voyages cover longer distances and, in some cases, require ships to speed up (and burn more fuel) to stay on schedule. Under a narrow ECA, ship operators may reroute some of their heavily frequented coastal voyages around the ECA to save money on fuel.

The more expensive ECA-compliant fuel is compared to globally complaint fuel, the more ships will reroute. Indeed, the decision to reroute is sensitive to bunker fuel prices.

If the price differential between ECA-compliant fuel and post-2020 compliant fuel is large, ships are motivated reroute. The larger that price differential, the wider the ECA boundary needs to be from shore to discourage rerouting.

When the ECA is 12 nm, 24, nm, and 50 nm, some ships reroute in an effort to reduce fuel costs. The closer the ECA boundary is to the coast, the more ships will reroute. Therefore, narrower boundaries undermine the effectiveness of the ECA. In contrast, an ECA of 100 nm would discourage ships from rerouting and would safeguard health and environmental benefits.

Further analysis, supplemented with fate and transport modeling, is needed for a more complete understanding of how rerouting would actually affect China's coastal air quality. Furthermore, delineation scenarios beyond 100 nm were not considered given territorial disputes with neighbors. A joint ECA application by China, South Korea, and Japan in the East Asia region, similar to that seen in the North and Baltic Seas, might further reduce rerouting and provide the most robust air quality benefits.

We made many assumptions in order to analyze potential ship rerouting. Tens of thousands of ships navigate the hundreds of routes and legs along China's coastline, with different routing decisions likely under a given set of environmental regulations. For simplicity, this study focused on case studies of 10 representative ships on five representative routes/legs. It is reasonable to believe the high-level results—that the wider the ECA boundary, the smaller the incentives to reroute—would hold true. Additional analysis of more ship types, legs, and fuel price scenarios could help confirm this finding. In future studies, a selection of representative legs weighted by actual traffic volume and a larger pool of ship samples could be used to validate these current results.

The absolute share of emissions retained under different ECA delineation scenarios should be interpreted with caution because we included emissions from the main engines of oceangoing vessels in this study. Although we are most interested in the "delta" value resulting from whether ships' rerouting behavior is or is not considered, future analysis with a comprehensive ship emission inventory covering OGVs plus river and coastal vessels could offer a refined estimate of ECA emissions coverage. In reality, the emission retention rate will also depend on how strictly the ECA is enforced. Robust enforcement will be needed if the full benefits of an ECA are to be enjoyed.

REFERENCES

DNV GL (2015). IMO NOx Tier III requirements to take effect on January 1st 2016. Retrieved from https://www.dnvgl.com/news/imo-nox-tier-iii-requirements-to-take-effect-on-january-1st-2016-51970

Faber, J., Ahdour, S., 't Hoen, M., Nelissen, D., Singh, A., Steiner, P., … Hanayama, S. (2016). *Assessment of fuel oil availability*. Retrieved from the CE Delft website: https://www.cedelft.eu/publicatie/assessment_of_fuel_oil_availability/1858.

Gausel, N. T. (2014). *Optimal ship speed and routing when considering ECA regulations* (Master's thesis). Retrieved from http://hdl.handle.net/11250/2400615

International Maritime Organization. *Sulphur oxides (SO_x) and Particulate Matter (PM) – Regulation*. Retrieved from http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Pages/Sulphur-oxides-(SOx)-%E2%80%93-Regulation-14.aspx.

IMarEST. (2018). *The costs of GHG reduction in international shipping.* Submitted to the Intersessional Meeting of the Working Group on Reduction of GHG Emissions from Ships under the International Maritime Organization as "ISWG-GHG 3/3" on 16 February 2018.

Jonson, J. E., Jalkanen, J. P., Johansson, L., Gauss, M., & Denier van der Gon, H. A. C. (2015). Model calculations of the effects of present and future emissions of air pollutants from shipping in the Baltic Sea and the North Sea. *Atmospheric Chemistry & Physics*, 15(2), 793–798. doi:10.5194/acp-15-783-2015

Li, C., Yuan, Z., Ou, J., Fan, X., Ye, S., Xiao, T., … & Zheng, J. (2016). An AIS-based high-resolution ship emission inventory and its uncertainty in Pearl River Delta region, China. *Science of The Total Environment*, 573, 1–10. doi:10.1016/j.scitotenv.2016.07.219

Lindstad, H., Asbjørnslett, B. and Jullumstrø, E., 2012. *Assessment of profit, cost and emissions by varying speed as a function of sea conditions and freight market.* Transportation Research Part D , Vol. 19 (2013), pp. 5–12.

Mao, X., Cui, H., Roy, B., Olmer, N., Rutherford, D., & Comer, B. (2017). *Distribution of air pollution from oceangoing vessels in the Greater Pearl River Delta, 2015.* Retrieved from The International Council on Clean Transportation, http://www.theicct.org/sites/default/files/publications/China-GPRD-Baseline-Emissions-Inventory_ICCT-Working%20Paper_23082017_vF.pdf.

National People's Congress of the People's Republic of China. (1998). 中华人民共和国专属经济区和大陆架法 (The People's Republic of China Exclusive Economic Zone and the Continental Shelf Law). Retrieved from http://www.npc.gov.cn/wxzl/gongbao/2000-12/05/content_5004707.htm

Notteboom, T., Delhaye, E., & Vanherle, K. (2010). *Analysis of the consequences of low sulphur fuel requirements*. Retrieved from the Clean Water Platform website: https://www.schonescheepvaart.nl/downloads/rapporten/doc_1361790123.pdf

Océane King. (2017, June 20). *Overview of scrubbers installations.* DNV-GL presentation at an internal event on June 20, 2017.

Roy, B. & Comer, B. (2017). *Alternatives to heavy fuel oil use in the Arctic: Economic and environmental tradeoffs.* Retrieved from the International Council on Clean Transportation, http://www.theicct.org/publications/alternatives-heavy-fuel-oil-use-arctic-economic-and-environmental-tradeoffs

U.S. Environmental Protection Agency. (2009). *Proposal to designate an emission control area for nitrogen oxides, sulfur oxides and particulate matter* (Technical Support Document EPA-420-R-10-013). Retrieved from https://nepis.epa.gov

U.S. Energy Information Agency. (2018). Annual Energy Outlook 2018. Retrieved from https://www.eia.gov/outlooks/aeo/tables_side.php

World Bank. (2017, October 26). World Bank commodities price forecast (nominal US dollars). Retrieved from http://pubdocs.worldbank.org/en/678421508960789762/CMO-October-2017-Forecasts.pdf

APPENDIX A

BUNKER FUEL PRICE SCENARIOS AND SENSITIVITY ANALYSIS

Fuel prices are volatile and future fuel prices are hard to predict. Price differentials between ECA-compliant fuels and post-2020 compliant fuels outside of ECAs, rather than absolute prices, will largely determine economic incentives to reroute. Thus, varying price differentials were incorporated in the main analysis. This appendix summarizes a sensitivity analysis on whether absolute fuel prices also influence individual ship's routing decisions.

Two types of bunker fuels were used to predict prices for this analysis: 2025 distillate fuel (ECA-compliant fuel), and 2025 low-sulfur heavy fuel oil (LSHFO, or post-2020 compliant fuel). The 2025 crude oil costs were also important because distillates and LSHFO prices tend to track closely with crude oil prices. Two sources were used for crude oil prices. The U.S. Energy Information Administration (2018) provides annual outlooks for the energy market, which includes high and low estimates for future crude oil prices. The crude oil price used in the main analysis, from World Bank's (2017) quarterly-updated projections for commodity prices, lies between EIA's high and low estimate numbers and was used as the medium crude oil price.

In IMO's fuel oil availability study (Faber et al., 2016), CE Delft predicted distillate fuel's price for 2020. The price ratio between distillates and crude oil was calculated using the 2020 distillate price and 2020 crude oil price based on World Bank's prediction. This percentage ratio is held constant throughout the years and scenarios. In this way, we were able to estimate high, medium, and low estimates for future distillate prices. Lastly, the LSHFO prices were estimated using the same set of price differential percentages developed in the main study. Table A1 summarizes all the future bunker fuel price scenarios. All prices were converted to 2015 U.S. dollars.

Table A1. Future crude oil and bunker fuel price scenarios

Bunker fuel type		2020 ($/mt)[a]	2025 ($/mt)[a]		
			High	Medium	Low
Crude oil		458	1213	438	260
Marine gas oil (MGO)		573	1517	547	325
LSHFO	**High differential**	-	1214	438	260
	Medium differential	-	1335	482	286
	Low differential	-	1456	525	312

[a] All prices in 2015 U.S. dollars

For each 2025 crude oil price scenario, we used the set of corresponding distillates and LSHFO prices to determine rerouting decisions of our sample ships. Identical rerouting results were obtained for all scenarios, indicating no sensitivity of our findings to absolute future fuel prices.

APPENDIX B

SAMPLE CALCULATION OF HOW A REROUTING DECISION IS MADE FOR INDIVIDUAL SHIPS

Fuel cost is a major part of a ship's operational cost. When scheduling and routing conditions allow, ships may choose to reroute outside of ECAs to take advantage of cheaper but dirtier bunker fuels. The specific decisions would vary for different ships navigating the same routes. To limit the scope of the analysis, we adopted a simplified approach using 10 sample ships, two per shipping leg, and simulated their rerouting decisions for each of the four delineation scenarios. Here is an example of the simulation.

This is a container ship navigating between Shanghai and Shenzhen. It is a China-flagged OGV with a main engine power of 40,040 kW. The ship's average speed over ground over this shipping leg is 12.8 knots. The original leg length is 823 nm and it was positioned within 12 nm from the coastline during its 64-hour trip. Based on this information, we were able to calculate fuel consumption and thus fuel cost for this ship navigating this leg originally. In this case, the fuel type would be MGO because the original leg is within boundaries of all ECA scenarios.

The length of alternative legs corresponding to each delineation scenario were measured in ArcMap. The average speed the ship would travel on these alternative legs was determined by first assuming it to be the same as on the original leg, 12.8 knots. However, the alternative legs are longer, so the overall travel time would increase. If the extra time surpasses the delay allowance for that specific ship class, then the travel time would be capped at this delay, in this case, 68 hours. The corresponding average speed would then be increased proportionately, and the fuel cost for alternative legs calculated. There are two fuel types involved here, as there are two stretches for the alternative legs—the within-ECA stretch and the outside-ECA stretch— corresponding to MGO and LSHFO. Table 2 summarizes the calculation matrix.

Table B1. Calculations for rerouting decisions

Calculation items		Delineation scenarios			
		12 nm	24 nm	50 nm	100 nm
Length_alternative leg_inECA (nm)		88	112	164	264
Length_alternative leg_outECA (nm)		759	759	759	759
Average speed on alternative leg (knots)		12.8	12.8	13.5	15.0
Fuel cost alternative ($)	**High differential**	28,000	29,000	34,600	48,000
	Medium differential	30,400	31,400	37,300	51,400
	Low differential	32,900	33,800	40,000	54,700
Fuel cost original ($)		33,100	33,100	33,100	33,100
Fuel cost differential ($)	**High differential**	-5,140	-4,180	1,480	14,900
	Medium differential	-2,700	-1,730	4,200	18,200
	Low differential	-255	711	6,930	21,600

The negative fuel cost differential indicates that under the specific delineation and price differential scenario, the ship would reroute to save money. In contrast, the positive fuel cost differentials mean that the ship would not reroute because doing so would increase fuel costs.

APPENDIX C

SAMPLE CALCULATION OF EMISSION RETENTION RATE FOR A DELINEATION SCENARIO

To calculate the emission retention rate for a delineation scenario, we first calculated the emission retention rates of individual sample ships. The emission retention rate for the ship analyzed in Appendix B was calculated using Equation 5. The results, summarized in Table C1, were generated using the following steps:

1. The SO_x emission factor included for clarity in Equation 5 is not used because it was canceled out in constructing the ratio.
2. Fuel consumption for the original route, or "voyage fuel consumption," remains constant at 61 metric tons (mt) across different delineation scenarios.
3. Fuel consumption for the alternative routes is separated into two parts: for the within-ECA stretches and for the outside-ECA stretches. The within-ECA stretches are the unavoidable distances a ship must travel to get outside of an ECA, or the "rerouted fuel consumption" in Equation 5. In this example, the ship consumes 6 mt, 8 mt, 13 mt, 27 mt, and 38 mt to escape ECA widths of 12 nm, 24 nm, 50 nm, and 100 nm, respectively.
4. The emission retention rate for this particular ship for all delineation scenarios is calculated by dividing the "rerouted fuel consumption" by the "voyage fuel consumption." Note that if a ship decides not to reroute, its "rerouted fuel consumption" is equal to its "voyage fuel consumption" since both are the original leg. The emission retention rates for this example ship are presented in Table C1.

Table C1. Calculations for rerouting decisions

Calculation items 12 nm		Delineation scenarios			
		12 nm	24 nm	50 nm	100 nm
Voyage fuel consumption /mt		61	61	61	61
Rerouted fuel consumption /mt	High differential	6	8	61	61
	Medium differential	6	8	61	61
	Low differential	6	61	61	61
Emission retention rate	High differential	11%	14%	100%	100%
	Medium differential	11%	14%	100%	100%
	Low differential	11%	100%	100%	100%

This method generates three sets of 10 emission retention rates for each delineation scenario corresponding to the three price differentials over 10 ships. Take the medium price differential case for example; Table 4 summarizes the 10 emission retention rates by ship for the medium fuel price differential case. These ships and routes are believed to be generally representative of overall traffic patterns because they were chosen using traffic density maps. That said, developing a precise weighting methodology for each ship, leg, and route is beyond the scope of this work. The overall emission retention rate for a delineation scenario, shown in the bottom row of Table C2, was estimated as a simple average of the 10 ships.

Table C2. Emission retention rate by delineation scenario, medium fuel price differential case

Ship ID	Delineation scenarios			
	12nm	24nm	50nm	100nm
1	11%	14%	100%	100%
2	11%	14%	100%	100%
3	100%	100%	100%	100%
4	100%	100%	100%	100%
5	25%	100%	100%	100%
6	25%	100%	100%	100%
7	7%	8%	10%	100%
8	7%	8%	10%	100%
9	20%	100%	100%	100%
10	20%	100%	100%	100%
Average	**33%**	**64%**	**82%**	**100%**