Correlated Pollutants, Avoidance, and Local Environmental Policy

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Abstract

We study the impact of local fuel standards targeting sulfur-related air pollution from maritime transport off the U.S. west coast on damages from greenhouse gases (GHGs) and other local air pollutants. By avoiding the regulated area, ocean-going vessels increase fuel use and emissions, shift fuel consumption away from population centers, and forgo emission-lowering speed reductions within the regulated area. These adjustments increase damages from GHGs but reduce damages from local pollution, leading to a shift in the distribution of the environmental burden of shipping. Behavioral adjustments, and correlated pollutant responses, depend on policy design and shipping patterns.

Keywords: correlated pollutants, local air pollution, GHG emissions, environmental policy, shipping
JEL codes: D62, L51, Q51, Q52, Q53, Q58, R41

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1 Introduction

Economists have long understood that the welfare consequences of a policy targeting one externality depend critically on how that policy alters other un- or under-priced externalities (Harberger 1974). This issue is particularly relevant for policies targeting the transportation systems due to a wide range of global (e.g., greenhouse gas emissions) and local externalities (e.g., air pollution, noise, mortality risk, congestion) associated with them. The external environmental costs of transportation are largely associated with the combustion of fossil fuels, which are leading contributors to two of the most significant environmental externalities – global climate change associated with greenhouse gas (GHG) emissions and human health impacts from various local air pollutants (e.g., particulate matter, ozone, carbon monoxide) – both of which remain, at best, under-priced in most jurisdictions. By changing the way goods and people move across space and, therefore, the quantity and location of fossil fuel combustion, policies that target one externality from transportation could have implications for a range of other environmental externalities.

In this paper, we study how behavioral responses to policies targeting sulfur-related local air pollution in the maritime transportation sector alter damages associated with two correlated environmental externalities – GHGs and other unregulated local pollutants. Maritime transportation serves as the backbone of the global economy – carrying over 80% of international trade by volume (UNCTAD 2021) – by providing relatively inexpensive transport of goods at all stages of supply chains, from raw materials and crops, to parts and manufactured goods, to finished consumer products. However, maritime transport is a leading contributor of local air pollution in coastal regions (Corbett et al. 2007), a growing contributor to GHGs (IMO 2015), and its reliance on fossil fuels is unlikely to wane in the near term. Understanding the unintended consequences of efforts to reduce the environmental burden of the maritime transportation sector is of first-order importance, especially in light of the relative paucity of research in this area.

The policies we study are the California and North American emission control areas

(ECAs) off the west coast of the U.S.[1] Both ECAs target sulfur-related particulate matter (PM) by requiring ocean-going vessels (OGVs) to use lower sulfur, but considerably more expensive, fuel in designated coastal waters. However, they differ starkly in their design and timing – the California ECA was established in July 2009 and extends 24 nautical miles (nm) off the coast of California while the North American ECA was established in August 2012 and extends 200 nm off the coast of the U.S. and Canada. Although PM related to fuel sulfur is the primary externality associated with OGVs (Corbett et al. 2007; Liu et al. 2016), OGV fuel combustion also results in emissions of nitrous oxides (NO_x) and volatile organic compounds (VOCs), which contribute to secondarily-formed PM and ozone, and GHGs. ECAs can alter damages from these correlated pollutants by inducing OGVs to change the quantity and location of fuel combustion. Since the switch to low-sulfur fuels itself has a limited impact on emission rates of these correlated pollutants (IMO 2015), these adjustments will alter correlated-pollutant damages in a different manner than the sulfur-related damages.

This paper builds on our prior study of the fuel sulfur-related mortality and compliance cost implications of the California ECA (Klotz and Berazneva 2022). In that study we processed one-minute resolution data on vessels' locations of the U.S. west coast from Automatic Identification System (AIS) transponders, required safety equipment on OGVs, into a voyage-level (e.g., origin-destination pairs) dataset that includes distance traveled and speed, as well as measures of fuel consumption and monetized pollution damages from standard physical relationships and spatially-explicit marginal damage estimates from an integrated assessment model. We then estimated the impacts of the California ECA using sharp temporal variation in within-vessel-by-route outcomes, particularly focusing on sulfur-related mortality and fuel costs.

Here, we start by using a similar approach to analyze how the California ECA alters

[1]ECAs have been established in the North and Baltic Seas and the inland and coastal waters of China. A Mediterranean ECA is planned for 2024 and a number of other jurisdictions (including Japan and Mexico) have considered establishing ECAs.

new outcomes: the monetized damages from GHGs and secondary $PM_{2.5}$ from NO_x and VOC from container vessels, the largest contributors to coastal fuel consumption.[2] We then use new data to extend the analysis to the North American ECA, which allows us to document the behavioral responses to the North American ECA and to compare the correlated pollutant implications of a narrow and broad ECAs.[3] The AIS-based approach allows us to both quantify behavioral responses to the ECAs and link these changes to correlated pollution outcomes. We also assess full behavioral adjustments on voyages to/from foreign ports by analyzing new datasets on voyages between west coast ports and Alaska and Hawaii and speed profiles for voyages that cross the North American ECA, and use simulations to connect this empirical evidence to changes in pollution damages.

We find that both ECAs induce drastic changes in the behavior of container ships, but – due to the interaction between the design of the regulated area and pre-existing traffic patterns – they affect behavior on different types of routes. As shown in Klotz and Berazneva (2022), the implementation of the California ECA leads to large reductions in within-ECA distance traveled and speed, particularly on routes connecting west coast ports. Here, we show that the broader North American ECA primarily affects behavior on routes connecting to foreign ports. When the North American ECA is established, average within-study area distances on routes connecting California to foreign ports fall by 11-13%, total distances traveled increase by upwards of 4%, and speeds within the ECA fall by 3%. When the fuel sulfur limit of the North American ECA is tightened in 2015 to effectively align with the limit of the California ECA, the avoidance and speed responses on routes to/from foreign ports are amplified and avoidance of the California ECA on coastal routes is eliminated.

The behavioral adjustments induced by local policies have global implications because distance traveled and speed are primary determinants of OGVs' fuel consumption. In response to the California ECA, average fuel consumption increases (by 2.7 tons per voyage

[2]The secondarily-formed $PM_{2.5}$ from NO_x and VOCs is a correlated pollutant because the fuel sulfur requirements of the ECAs do not target primary $PM_{2.5}$ and secondarily-formed $PM_{2.5}$ from SO_x.

[3]In addition to processing more years of AIS data, this analysis required merging the AIS data with entrance/clearance records to better classify voyages to particular routes.

or 3.6%) on coastal routes, which leads to additional GHG damages of $400-1,700, depending on the social cost of carbon (SCC). This increase is relatively modest because it combines behavioral responses across routes with different avoidance options and across vessels that avoid the California ECA and those that do not. When we focus on the vessels that avoid the ECA, we find more drastic increases in GHG damages and show that avoidance allows vessels to forgo fuel-saving speed reductions that would otherwise occur within the regulated area. Implementation and especially the tightening of the North American ECA lead to strong increases in GHG damages, upwards of $1,400-5,700 per voyage, on routes connecting to Asia.

However, ECAs also reduce damages from NOx and VOC emissions, as vessels' behavioral responses shift fuel consumption to relatively low marginal damage areas. Average correlated local pollutant damages fall by $1,600 or 10% per voyage on coastal routes with the implementation of the California ECA. The implementation of the North American ECA leads to modest average reductions in damages from local pollution on routes to the west, but simulations suggest these reductions could be much larger (upwards of $14,000 or 55%) for vessels that avoid on the most affected routes. Due to the strong local pollution impacts, accounting for correlated pollutants tends to motivate the expansion of the ECAs we study, except at higher values of the social costs of carbon.

In total, our estimates suggest that changes in vessel behavior in response to the California ECA generated local pollution co-benefits in the range of $2.3 million per year and GHG co-costs of between $0.6-2.5 million per year, which are a sizable fraction of estimates of monthly compliance costs (Klotz and Berazneva 2022). For the routes most affected by the North American ECA, reductions in correlated local pollution damages offset upwards of 50% of compliance costs. While in aggregate the co-benefits partially cancel out the co-costs, considering the local pollutant and GHG impacts separately illustrates important distributional tradeoffs – the local pollution benefits accrue to the west coast of the U.S., while the climate damage costs are borne globally. One way of interpreting our findings is

that avoidance of ECAs partially shifts the environmental burden of shipping from the local jurisdiction onto the global community.

This paper contributes to two threads of the economics literature on environmental policy. First, we extend the literature on the impacts of environmental policy on correlated pollutants, which has typically focused on stationary sources (e.g., power plants) and/or broad-based policies (e.g., climate policy), by analyzing policies that target local pollutants from mobile sources. Although a policy's impact on correlated pollutants is theoretically ambiguous (Fullerton and Karney 2018), many studies have found that climate policy generates considerable co-benefits by also reducing damages from local pollutants through fuel switching and reduced fuel consumption (Burtraw et al. 2003; Shindell et al. 2012; Zwickl et al. 2021). The only evidence related to GHG impacts of regulating local pollutants comes from the energy sector (Brunel and Johnson 2019; Chan and Zhou 2021). By examining a different context, we show that policies can drive damages from local pollution and GHGs in opposite directions and are able to isolate a mechanism – avoidance – that has not been emphasized in the previous literature.[4]

Second, we contribute to the literature on policies that target externalities associated with transportation systems. Although there is a large literature focused on policies targeting passenger vehicles (some examples include Parry and Small (2005), Davis (2008) and Gehrsitz (2017)), far less attention has been paid to transportation systems that move freight in general, and maritime transportation more specifically, despite the global importance of this sector and the growing interest in reducing the environmental impacts of supply chains (IMO 2015; U.S. Department of State 2022).[5] We study environmental policies in the maritime transportation sector and find that policies that regulate a portion of a transportation system

[4]Although term avoidance is sometimes used to describe actions taken to reduce exposure to environmental hazards, we use avoidance to describe polluting sources adjusting location to reduce exposure to a regulation. Avoidance is distinct from the spatial shifts identified in other correlated pollutant papers (e.g., Fullerton and Karney (2018)) because, with avoidance, the spatial shift itself partially drives the changes in pollution levels and damages.

[5]Sheng et al. (2018), who study the welfare implications of a CO_2 charge on bunker fuel, is a notable exception.

can lead to local-global trade-offs through changes in correlated pollutants. The avoidance-type response we highlight has been documented in a variety of other contexts (e.g, Leape (2006); Gibson and Carnovale (2015); Zhai and Wolff (2021)), but how this mechanism alters damages from correlated pollutants has not been studied.

The economics literature on sulfur regulations in the maritime sector has focused on analyzing the air quality implications of ECAs (Zhu and Wang 2021; Hansen-Lewis and Marcus 2022) and, in our previous work, examining the impacts of behavioral responses to the California ECA on the compliance cost and fuel sulfur-related damages (Klotz and Berazneva 2022). This paper is the first to study how ECAs affect damages from correlated (unregulated) pollutants. Our main findings – that ECAs can induce changes in correlated pollution damages large enough to justify their inclusion in evaluations of ECAs or other local maritime policies and motivate the expansion of the ECAs we study – cannot be inferred from previous research because behavioral responses have different implications for correlated pollutant damages than for sulfur-related damages. Klotz and Berazneva (2022) show that behavioral adjustments erode the sulfur-related benefits of ECAs – because vessels continue using high-sulfur fuel outside the ECA – while here we find that behavioral responses reduce damages from other local pollutants and, for broader ECAs, these reductions can be large enough that behavioral adjustments actually improve environmental outcomes (sulfur-related damages included).[6]

This paper also differs from all prior economics research on ECAs by bringing new data and empirical approaches to study behavioral responses to both a narrow and much broader ECA. A priori, it is not clear that broader ECAs would induce the same types of responses as narrow ECAs because these responses depend on private tradeoffs between time and fuel costs. We find that regulations with alternative layouts distort behavior on different types of routes, which directly informs the design of local maritime policies, even those not targeting

[6]The relative importance of each behavioral response (e.g., speed vs. avoidance) also differs across pollutants. For example, speed reductions play a more important role in determining changes in correlated pollutant damages, relative to sulfur-related damages, because these occur when vessels are using low-sulfur fuels.

fuel sulfur.

2 Background and Policy Context

Combustion of maritime fuels generates many pollutants that affect local air quality and contribute to climate change. The most important set of pollutants, in terms of external costs, are the primary particulate matter (PM) and sulfur oxides (SO_x), which are precursors to PM, related to the high-sulfur content of maritime fuels (Corbett et al. 2007). However, OGVs also contribute substantial quantities of nitrogen oxides (NO_x) and volatile organic compounds (VOCs), which contribute to secondarily-formed PM and ground-level ozone, as well as GHGs. Container ships, which are the focus of our analysis, are the largest users of fuel and emitters across all vessel categories.[7]

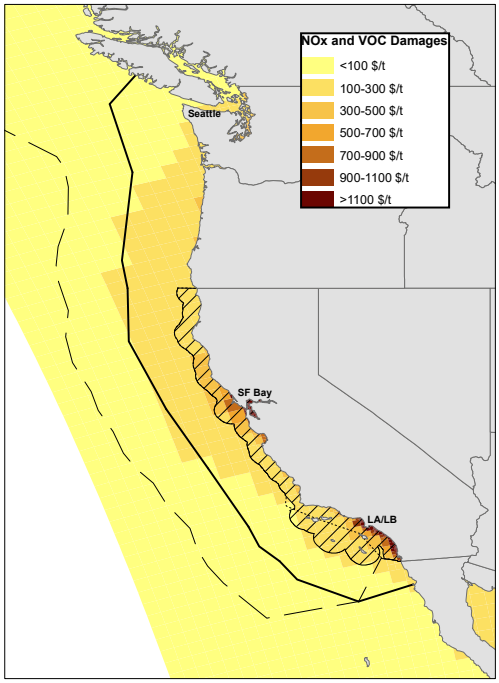
The sulfur-related emissions primarily depend on the type of fuel used. Large OGVs involved in maritime transport are equipped with low-speed two-stroke engines that can burn high-sulfur residual fuels and low-sulfur distillate fuels interchangeably. OGV operators opt for high-sulfur fuels due to the price premium for low-sulfur fuels.[8] Policies targeting local pollution from maritime transport have mainly focused on spurring the use of low-sulfur fuels, particularly in coastal areas. While the switch to low-sulfur fuels has, at best, a marginal impact on correlated emissions of NOx, VOCs, and GHGs per physical unit of fuel (IMO 2015), such policies alter the damages associated with correlated pollutants by changing the quantity and location of fuel combustion.

The "California Emission Control Area" (CA ECA) was established by California's Ocean-Going Vessel Fuel Rule and came into force on July 1, 2009 with the stated goal of reducing adverse health impacts from exposure to PM in the state's coastal regions (CARB 2011). It required the majority of vessels to use distillate fuels (either marine gas

[7]Container ships carry containerized cargo and mostly provide regular service between ports. They are more powerful, travel faster, and consume more fuel per kilometer traveled than other cargo vessels (e.g., dry or refrigerated bulk carriers) and tankers that mainly carry large consignments of a single commodity and travel on flexible routes.

[8]Until 2020, residual fuel oil had a maximum sulfur content of 3.5%. Distillate fuels typically have sulfur levels closer to 0.1% (IMO 2015). Between 2008 and 2016, the price of distillate fuel oil substantially exceeded and was often more than double the price of residual fuel oil.

oil with a maximum of 1.5% sulfur or marine diesel oil with a maximum of 0.5% sulfur) when operating within regulated waters, which extended 24 nm from the California coast (Figure 1).[9] In December of 2011, the ECA regulatory boundary was modified – mainly expanded – in southern California. The sulfur limits were tightened twice between 2009 and 2014, eventually reaching 0.1% for all distillate fuels. However, these changes did not bind because the sulfur content of available distillate fuels was below the sulfur limits (CARB 2008).



Notes: Major west coast container ports are labeled. Small dashed line is original California ECA boundary. Hashed area is California ECA after boundary change in 2011. Large dashed line designates the North American ECA which comes into place in 2012. Solid line delineates our 100 nm study area. Colored shading represents ISRM estimates of the marginal damages due to secondarily-formed PM from NO_x and VOC emissions from the combustion of one ton of fuel oil.

Figure 1: Study Area, ECA Boundaries, and Marginal Damages

Under the auspices of the International Maritime Organization's (IMO) International Convention on the Prevention of Pollution from Ships (MARPOL), the United States and

[9]The California Air Resources Board (CARB) enforces the CA ECA through random collection of fuel samples and review of records and fuel switching procedures. Failure to switch to compliant distillate fuels results in fines starting at $45,500 per port visit and an administrative penalty ($10,000). Between 2009 and 2017 only about 5% of inspections resulted in fines or penalties (CARB 2018).

Canada established the North American Emission Control Area (NA ECA) on August 1, 2012 (IMO 2012). The NA ECA extends 200 nm off the coast of the U.S. and Canada (Figure 1). The initial fuel sulfur limit of 1.0% was reduced to 0.1% on January 1, 2015. Unlike the California ECA, the North American ECA does not require the use of distillate fuels.[10] Only when the NA ECA stringency fell to 0.1% in 2015, which effectively forced vessels to use distillate fuels, did the North American ECA subsume the California ECA.

Our empirical analysis focuses on the establishment of the California and North American ECAs, which, unlike in prior work on ECAs, allows us to compare the impacts of a narrow ECA to those of a broader ECA (albeit in the presence of a narrower and more stringent ECA). Unfortunately, our ability to analyze the tightening of the Northe American ECA in 2015 is hindered by contemporaneous labor disputes at west coast ports that resulted in significant port slowdowns (Phillips 2015), so here we provide qualitative and simulation evidence. We also analyze the impacts of the California ECA boundary change in 2011 as a robustness check.

3 Data

Our data procedures follow Klotz and Berazneva (2022), but for this work we expand the temporal coverage of the voyage dataset, better classify longer distance voyages to particular routes, and construct new datasets of routes between west coast ports and Hawaii and Alaska and speed profiles around the NA ECA boundary.

3.1 Voyage Data

Our main data come from Automatic Identification System (AIS) transponders, which are required navigation safety devices on the majority of OGVs that transmit the location and speed of a vessel to other nearby vessels. The U.S. Coast Guard operates a network of on-shore receivers to collect AIS signals. Since coverage by the on-shore receivers falls with

[10]The NA ECA allows for compliance through the use of exhaust gas cleaning devices ("scrubbers"). Scrubber uptake was negligible for cargo vessels during our study period (IMO 2020). The NA ECA also includes tiered engine-based NOx standards, but these standards only came into force in 2016 after our study period. The NA ECA is enforced by the U.S. Environmental Protection Agency and the Coast Guard. Civil penalties for noncompliance have a maximum of $25,000 per violation per day.

distance to the coast, our main analysis focuses on a study area that extends 100 nm (185 km) off the U.S. west coast (Figure 1) and we explore larger study area definitions as a robustness check.[11]

We process one-minute scale AIS records for the years 2009 to 2016 (BOEM/NOAA 2017) into individual voyages using an algorithm that connects temporally consecutive records, and then classify voyages to specific routes.[12] Each voyage is characterized by distance and location of travel and a speed profile, which are the primary margins through which OGVs can respond to the policy. To measure how adjustments on these margins jointly alter correlated pollutants, we translate the observed data to measures of fuel consumption and pollution damages using simple and transparent assumptions.

We calculate fuel consumption from vessels' main and auxiliary engines for each voyage using a well-established approach in the literature (see Appendix Section D.5). Fuel consumption by the main engine for each segment (path between two AIS records) of a voyage is a function of vessel characteristics, distance traveled, and the square of speed, while fuel use by auxiliary engines depends on vessel characteristics and hours of operation.

3.1.1 Damages from Correlated Pollutants

For correlated local pollutants, we value the mortality damages associated with secondarily-formed $PM_{2.5}$ due to NO_x and VOC emissions. To estimate damages per voyage, we first calculate emissions of each pollutant for each segment of a voyage using estimated fuel consumption and emission factors from IMO (2015). Then we multiply these emissions by a location- and pollutant-specific marginal damage estimate ($ per ton of pollutant), and sum across all segments and pollutants to obtain total damages.[13] Marginal damages from NO_x-

[11] AIS radio signals weaken over space. The Coast Guard receivers are designed to record signals within 50 miles (US Coast Guard 2018), but in practice collect signals much farther off the coast.

[12] We merge in weekly marine fuel prices in Los Angeles from S&P Global and vessel characteristics from Clarksons Research and Marine Traffic (if valid vessel identifiers are available). AIS records between June 5 and June 30 of 2009 are missing from the database underlying the MarineCadastre.gov data (Office of Coastal Management 2020). Figure A.1 in the Appendix provides a graphical depiction of these voyages. The missing days are purely a data issue and not related to any economic trends in shipping.

[13] Emission factors are discussed in Section D.6 in the Appendix. The slightly higher energy content of some low-sulfur fuels (distillates) implies that ECAs could mechanically lower emissions of local pollutants and GHGs (IMO 2015). We do not adjust for energy content, but note that with such adjustment avoidance

and VOCs-derived $PM_{2.5}$ emissions are from InMAP Source-Receptor Matrix model (ISRM) (Goodkind et al. 2019).[14] As shown in Figure 1, damages per ton of fuel combusted are very high close to the population centers of Los Angeles and San Francisco (at least 700 \$/t), but decrease with distance away from the coast and are low – less than 100 \$/t – outside of our study area.[15]

To calculate GHG damages, we multiply fuel consumption by the carbon-dioxide-equivalent GHG emission factor per ton of fuel combusted and the social cost of carbon (SCC), which captures the long-term climate damages related to GHGs. Since the valuation of CO_2 damages is complicated, especially by the relatively small probability of catastrophic outcomes (Weitzman 2014), throughout the text we present results using 50 \$/tCO_2, which is a central estimate from IWG (2016) and often used in the literature, and 200 \$/tCO_2, which is consistent with more recent estimates of the social cost of carbon (Rennert et al. 2022).

3.1.2 Route Definitions

We classify voyages as either "port-to-port" – between west coast ports – or "entrances/exits" – between a west coast port and the study area boundary. Port-to-port routes are defined based on origin-destination pairs (e.g., San Francisco Bay–Seattle).[16] To enable our analysis of the NA ECA, we define entrance/exit routes in two ways. First, we define routes based on a west coast port and the broad location where the voyage crosses our study area boundary. Second, we determine the foreign origin/destination port for a large fraction of entrance/exit voyages using the U.S. Army Corps of Engineers Entrance/Clearance dataset (US ACE 2018) (details are discussed in Appendix Section D.2.1). We then group origin/destination ports

would further undercut emission-reducing changes in the regulated area.

[14]ISRM obtains spatially explicit marginal damage estimates by combining transfer coefficients from the Intervention Model for Air Pollution (InMAP), standard concentration-response functions for mortality, and estimates of the value of a statistical life (in 2011 US \$).

[15]By focusing on $PM_{2.5}$-induced mortality related to NO_x and VOC emissions, our results likely underestimate changes in damages from correlated local pollutants. We do not capture the contribution of NOx and VOCs to ozone formation, or other local pollutants generated by OGVs (e.g., carbon monoxide).

[16]Our definition of ports relies on vessel choke points at the entrance of geographical features and, therefore, may include several ports. For example, Seattle is defined as entering/exiting the Strait of Juan de Fuca and includes the ports of Seattle, Vancouver, and Tacoma.

to broadly capture the direction of travel to/from U.S. west coast ports.[17]

3.2 Data on Vessel Behavior Outside the Study Area

Our main voyage-level dataset, which covers activities within 100 nm of the coast, is sufficient to capture the majority of changes in local pollution damages on entrance/exit routes, but changes in fuel use outside the study area could have important GHG impacts, particularly for the the broader NA ECA. To estimate changes in behavior outside the study area we construct two additional datasets from the AIS data.

First, we use an interpolation procedure (see Appendix Section D.1) to calculate distance traveled on voyages between west coast ports and two distant locations with AIS coverage: Honolulu, Hawaii and the Unimak Pass in Alaska (a traffic choke point through the Aleutian Islands). We show below that, due to geography, changes in total distance for all western entrances/exits should be, roughly, bounded by changes on the Hawaii and Unimak routes.

Second, we construct a dataset of vessel speed profiles for voyages that cross the NA ECA to analyze how vessels' speeds around the ECA boundary respond to the North American ECA. Due to limited AIS coverage we observe only 18% of all entrance/exit voyages crossing the NA ECA boundary, however, vessel characteristics for the crossing sample are broadly consistent with our full sample of entrances/exits (Table A.1 in the Appendix).

3.3 Summary Statistics

Appendix Section C and Table A.3 describe voyages appearing in the AIS data. In total, we observe almost 85,000 voyages that connect to California ports, about half of which are by container ships. Roughly two-thirds of container voyages are entrances/exits and we are able to obtain the origin/destination ports from the Entrance/Clearance dataset for around 80% of these voyages. Tabulations by port indicate that voyages connecting to southern California ports (LA/LB) primarily travel to/from San Francisco Bay, ports in Asia, or the south (e.g., Mexico or elsewhere via the Panama Canal). Vessels connecting to the northern

[17]For consistency, our main estimation sample only includes entrance/exit voyages that we match to the Entrance/Clearance data. Voyages unable to be matched to the Entrance/Clearance data are generally similar to those in our main sample in terms of observed behavior and vessel characteristics.

California ports — solely the San Francisco Bay ports — travel to/from Seattle or ports in Asia. Two-thirds of southern California interpolated voyages are to/from Honolulu, while two-thirds of northern California interpolated voyages are to/from the Unimak Pass.[18]

3.4 Changes in the Location of Vessel Activity

To emphasize the differential impacts of the CA ECA and the NA ECA on the location of container ship activity, we collapse our voyage dataset to a spatial grid and display monthly average distance traveled in each grid cell under different ECA configurations in Figure 2.

Prior to the establishment of the California ECA (panel (a)) container vessels on port-to-port voyages travel close to the coast and often within the ECA boundary, especially in southern California. Many vessels traveling to/from LA/LB use the Santa Barbara Channel.[19] Entrance/exit route patterns make clear that routes to/from Honolulu and the Unimak Pass provide reasonable bounds for the exposure to the ECAs.[20]

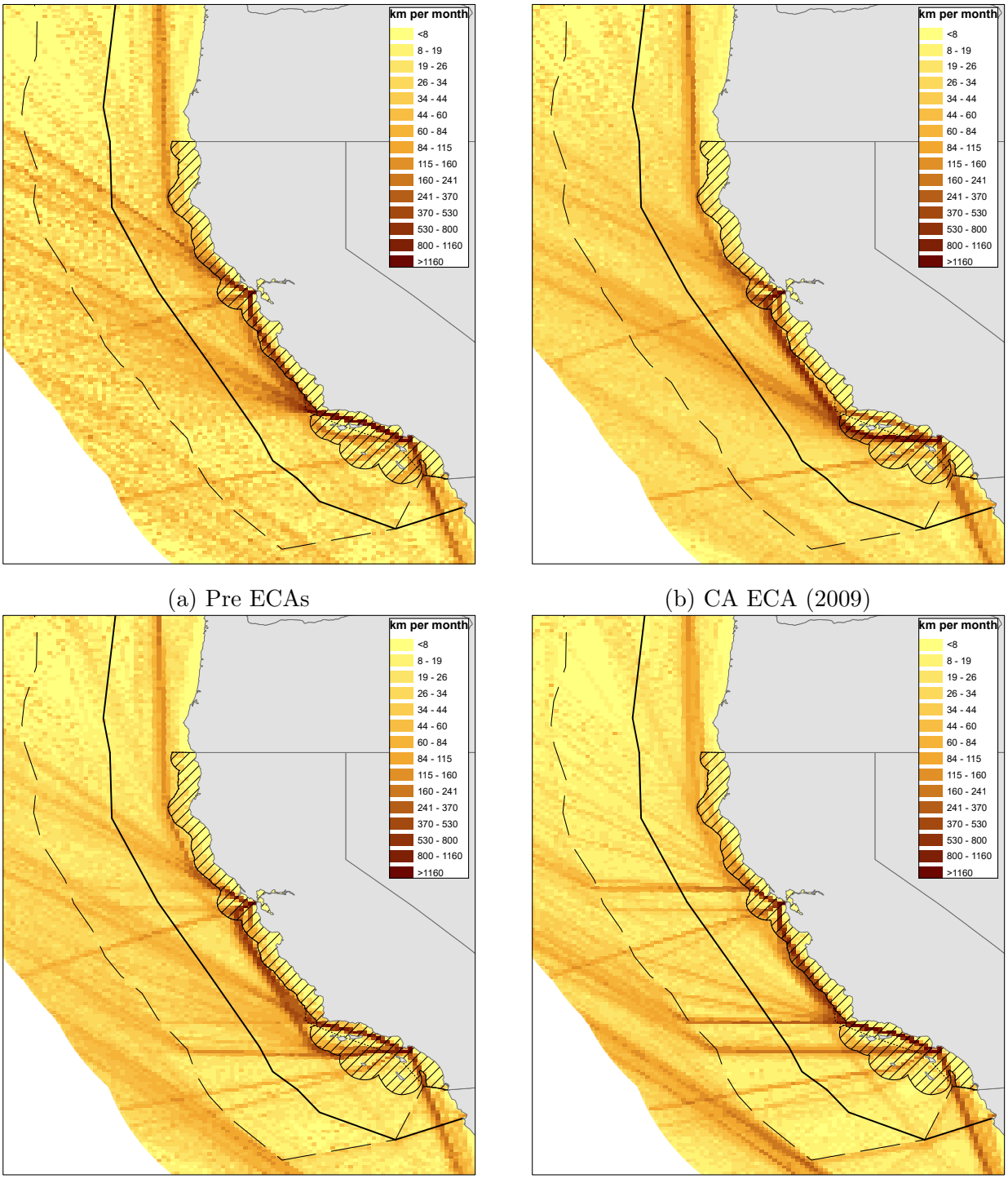
After the California ECA is established (panel (b)), vessel activity clearly shifts out of the ECA. Given the geography of the California coast, avoidance opportunities are greater for southern California routes but these adjustments do not appear to cause substantial changes in where vessels enter/exit the study area.

Establishment of the North American ECA has little impact on port-to-port traffic (panel (c)) because the CA ECA is still binding, although traffic patterns in southern California adjust to the updated CA ECA boundary. Most coastal vessel activity returns to the CA ECA when the North American ECA sulfur limit is tightened to 0.1%. The NA ECA has stronger impacts on entrances/exits. "Hockey stick" shaped traffic lanes due west of LA/LB and San Francisco Bay, which minimize travel in the ECA, form when the NA ECA is established and become more heavily traveled when the sulfur limit is lowered.

[18] We do not observe changes in the share of voyages between LA and San Francisco – the most exposed route – under different policy configurations, which we interpret as evidence against shifts to alternative modes of transportation.

[19] The Santa Barbara Channel is located between the coast and the Channel Islands in southern California and is within the CA ECA.

[20] Entrances/exits are highly concentrated to/from the northwest of LA/LB and the San Francisco Bay, many of which will travel through the Unimak Pass, and to/from the south of LA/LB. There are also notable shipping lanes to the southwest of the California ports with vessels moving to/from Hawaii.



(a) Pre ECAs

(b) CA ECA (2009)

(c) CA + NA (1%)

(d) CA + NA (0.1%)

Notes: Small dashed line is original California ECA boundary. Hashed area is California ECA after boundary change in 2011. Large dashed line designates the North American ECA which comes into place in 2012. Solid line delineates our 100 nm study area. Colored shading represents monthly average distance traveled by container vessels in each grid cell. Averages include voyages that do not connect to west coast ports. Panels reflect different ECA configurations.

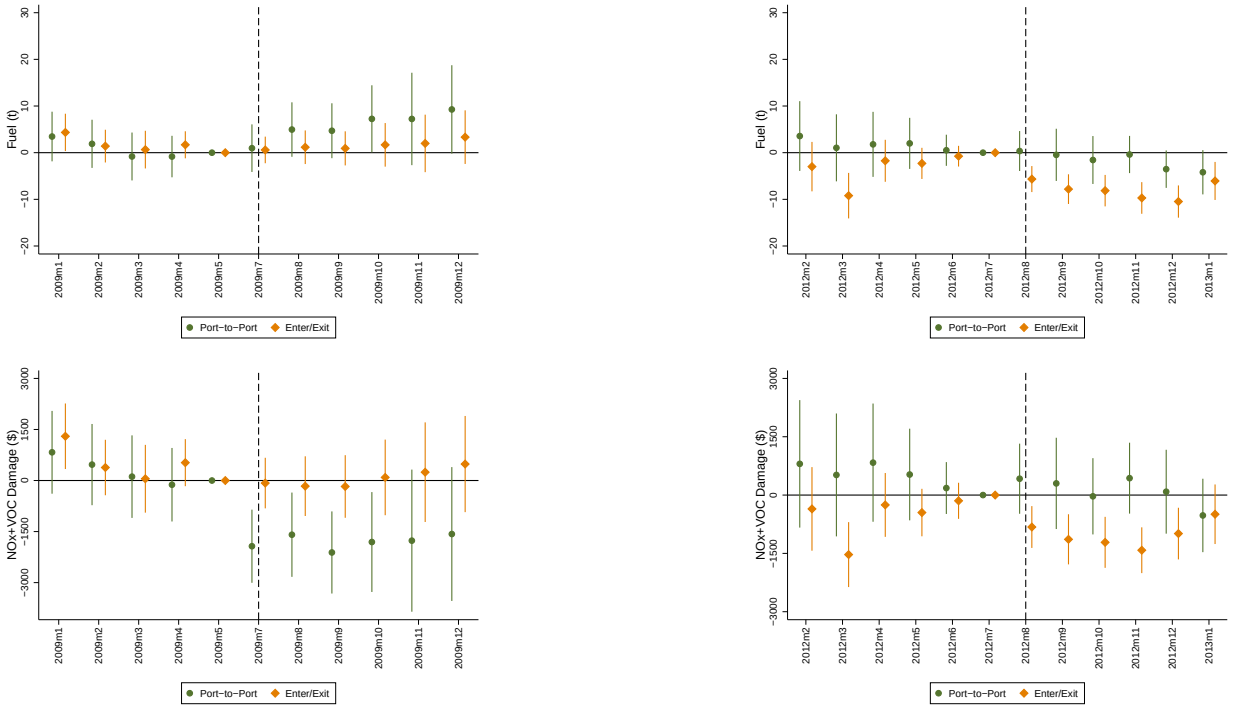
Figure 2: Impact of ECAs on Location of Vessel Activity

3.5 Time-Series Discontinuities

The changes in vessel behavior illustrated above occur in close temporal proximity to the changes in ECA configurations and are persistent over time, which motivates our empirical strategy. The markers in Figure 3 are monthly average outcomes after removing any time-invariant factors common to a particular vessel on a particular route and the influence of fuel prices, closely matching the variation used in our empirical analysis. In response to the California ECA (column (a)), fuel consumption rises and NO_x and VOC damages drop for port-to-port voyages in the first two months after the California ECA establishment (diamond markers). In contrast, there are no discernible discontinuities on entrance/exit routes. These results are driven by the avoidance and speed responses to the CA ECA emphasized in Klotz and Berazneva (2022).[21] The implementation of the North American ECA (column (b)) leads to drops in fuel consumption and local pollution damages entrance/exit routes, but not on port-to-port routes. These changes indicate that vessels on entrance/exit routes are reducing fuel consumption and associated emissions within the NA ECA, though the full impact on fuel consumption remains unclear.

Figure 3 also illustrates that trends in fuel consumption and local pollution damages are limited in the months leading up to each policy change, but there are notable changes in months farther from the implementation of the NA ECA for entrance/exit routes. Figure A.3 suggests that this is due to seasonality in vessels on trans-Pacific voyages opting for either a northern Great Circle route or a more southern route, possibly in pursuit of calmer seas or favorable winds and currents. However, the drop in distance traveled within the study area that occurs the month the NA ECA is established is well in advance of, and larger than, the seasonal variation, especially for southern California ports.

[21] To illustrate the discontinuities in vessel behavior and to illustrate the longer run impacts of the ECAs, we plot quarterly average changes in distance traveled for our entire study period in Figure A.2. This figure makes clear that the responses to the ECAs are persistent changes in an otherwise stable time series.



(a) CA ECA (b) NA ECA

Notes: Points are monthly averages of outcome variables after partialling out route-by-vessel fixed effects and fuel prices. The first month prior to each policy change for which we have observations is omitted, so that the coefficients are all differences from this month. Lines represent 95% confidence intervals, clustered by vessel, which are relevant for pairwise comparisons to the omitted month. For entrance/exit voyages changes reflect only adjustments within the study area and routes are defined according to the study area boundary for the CA ECA and by origin/destination for the NA ECA. Within CA ECA values use 2009 boundaries for CA ECA and 2011 boundaries for NA ECA.

Figure 3: Time Series Residual Plots

4 Empirical Strategy

4.1 Voyage Data

We follow Klotz and Berazneva (2022) to analyze the voyage-level data – albeit with a focus on different outcomes and additional policy change – and estimate the impacts of changes in ECA configurations with the following regression discontinuity in time design:

$$y_{irt} = \beta ECA_t + \delta_{rt} t + \gamma X_t + \lambda_{ir} + \epsilon_{irt}. \tag{1}$$

where y_{irt} is an outcome (distance traveled, speed, modeled fuel use or emissions) for a voyage by vessel i traveling on route r starting on date t (t is rescaled to equal 0 on the date of the policy change). ECA_t is an indicator variable equal to one after a particular ECA change and zero otherwise, so that β is parameter of primary interest. $\delta_{rt} t$ are linear time trends,

which we vary by route and pre and post policy. X_t are other time-varying control variables, specifically marine fuel prices – weekly prices for high-sulfur fuel oil and distillate fuel oil – as OGV operators may adjust vessel behavior (e.g., speed) in response to prices. Vessel-by-route fixed effects, λ_{ir}, adjust for baseline differences in vessel outcomes on each route and prevent bias from route-level changes in the composition of vessels. ϵ_{irt} represents all remaining unexplained voyage-level variation. We estimate (1) using fixed-effects regressions, but we restrict the sample to a small window around each ECA configuration (e.g., 90 or 150 days on each side).[22] Standard errors are clustered by vessel because vessel management or maintenance (or other factors that may influence vessel behavior) may be correlated across voyages for a particular vessel.

We include time trends to capture unobservable time-varying factors that might alter vessel behavior other than fuel prices. Routing and speed decisions depend primarily on fuel and time costs. Time costs could include things like labor costs, but also opportunity costs related to future loads and voyages, which would generally be related to the strength of the economy. We allow for route-specific time trends to account for the fact that time costs might vary depending on the ports being served (e.g., based on the strength of the local economies at origins and destination port). Following the best practice (Imbens and Lemieux 2008), we allow for different slopes on either side of the policy change so that pre-policy conditional expectations are estimated using only pre-policy observations and post-policy conditional expectations are estimated using only post-policy observations.[23] We show that our main conclusions are robust to many alternative specifications of the time trends, including a common trend for all routes, trends that do not change at the cutoff, and dropping the trends altogether.

[22]This is equivalent to a local linear approach using a rectangular kernel. Given this empirical strategy, these results should be interpreted as short-run estimates of within-voyage adjustments (i.e., conditional on a voyage being taken). The avoidance effects we capture, however, are persistent over the study period.

[23]One could view our specification as allowing for time-varying treatment effects. Since changes in the estimated slopes will partially reflect changes in unobservable macroeconomic trends that alter vessel behavior, we do not interpret the change in slopes as being causally linked to the ECAs and take a time-invariant interpretation of the policy effects.

Identification of the ECAs' impact comes from discontinuous temporal variation in within-vessel-by-route outcomes and will be valid if time-varying unobservables vary smoothly at the time of the policy change (i.e., economic or shipping trends do not induce sharp changes in how a particular vessel travels on a particular route). We conduct several robustness checks to validate our results, particularly those suggested by Hausman and Rapson (2018) that are relevant in our context, which include showing that our estimates are insensitive to specification choices, evaluating alternative bandwidths, and conducting placebo tests using alternative policy dates.

In order to minimize the potential impacts of seasonality in our analysis of the California ECA, we define entrance/exit routes based on the location at which a voyage crosses the study area boundary so that estimates are based on comparisons of voyages that are traveling in a similar manner close to the California coast. This is a reasonable approach because the California ECA is unlikely to drive large changes in where vessels cross the study area. We analyze the impacts of the North American ECA using routes defined based on origin/destination ports but focus on estimates using a smaller time bandwidth (90 days) in order to capture the large changes in where voyages exit the study area and to minimize the influence of seasonality (motivated by Figure 3 and Figure A.3). Importantly, our placebo tests shift the policy dates forward or backward by one year so that we can explore the potential impacts of seasonality.

4.2 Vessel Behavior Outside the Study Area

In order to analyze our dataset of interpolated voyages between California ports and Honolulu and the Unimak Pass, we plot the distribution of distance traveled on these routes under the four ECA configurations after subtracting the minimum observed total distance (by route) from each observation. Given that the minimum distance path on any route is time invariant, systematic changes in these distributions can be attributed to the ECAs.

To analyze speed changes at the North American ECA boundary, we calculate average speeds in 40 km bins for the 240 km traveled on either side of the ECA boundary for each

voyage to/from Asia that crosses the NA ECA.[24] We then estimate the average within-voyage changes in speed profiles in response to the implementation and tightening of the NA ECA by regressing speed in each bin (kmh_{irtb}) on the interaction of distance bins (BIN_b) and policy indicators (ECA_{tp}) for the two policy changes (p) and bin (μ_b) and voyage fixed (η_{irt}) effects:

$$kmh_{irtb} = \sum_b \sum_p \alpha_{bp} BIN_b * ECA_{tp} + \mu_b + \eta_{irt} + \epsilon_{irtb}. \quad (2)$$

We omit the indicator for the bin farthest outside the ECA, so that coefficients on the interactions (α_{bp}) represent average changes, relative to pre North American ECA time period, in within-voyage speed profiles. We estimate separate models for voyages entering and exiting the ECA and cluster standard errors by vessel.

In both of these analyses we use all observed voyages under each ECA configuration, so changes may reflect longer-run adjustments than our voyage-level regression results. We note, however, that Figure A.2 suggests the changes in vessel behavior tend to happen quickly and be persistent over time.

5 Results

5.1 Impacts of the California ECA

Estimated impacts of the establishment of the California ECA on correlated pollutants are reported in Table 1. The columns reflect different measures of vessel behavior and resulting pollution damages.[25] Throughout this section we report the changes in within ECA distance, speed and fuel (for the CA ECA) from Klotz and Berazneva (2022) to highlight the mechanisms driving the correlated pollutant outcomes. We estimate Equation (1) separately for port-to-port and entrance-exit voyages using the sample of voyages that took place within 150 days before or after the policy change. Since we only observe entrance/exit voyages to

[24] We exclude voyages that do not have a speed observation in each distance bin, that cross the boundary more than once, and that occur during the west coast port slowdown. Note that speeds around the NA ECA boundary (200 nm off the coast) should not be affected by the California ECA, other coastal policies (e.g., slow zones to reduce the risk of vessel collisions with whales), or by acceleration/deceleration around ports.

[25] For each outcome, we report the predicted mean value for both the date of the policy change ($t = 0$) and one month prior ($t = -30$) to demonstrate that pre ECA time trends are limited and that the impact of missing data in the month prior to the implementation of the CA ECA does not pose an empirical concern.

the edge of the study area, our analysis will not pick up changes in fuel consumption well off the coast, thus influencing our fuel and GHG estimates. Our local pollution damage estimates will be less affected because marginal damages are low outside the study area.

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Fuel in CA ECA (t)	(4) Distance (km)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) Container – Port-to-Port (n=1,239, vessels=268)							
CA ECA (2009)	-239.6***	-4.352***	-26.37***	39.36***	2.720	-1,602***	-30.19***
	(19.68)	(0.647)	(2.548)	(4.851)	(1.774)	(389.6)	(4.365)
R-squared	0.852	0.685	0.836	0.996	0.957	0.925	0.815
Mean (t=0)	531.7	31.45	49.81	831.7	75.24	18445	253.3
Mean (t=-30)	534.7	31.43	50.28	832.1	76.56	18696	253
% change	-45.07	-13.84	-52.95	4.732	3.615	-8.687	-11.92
CO_2 Damage (SCC=50 $/t)					429.7		
CO_2 Damage (SCC=200 $/t)					1719		
(ii) Container – Ent/Exit (n=1,387, vessels=273)							
CA ECA (2009)	-35.10***	-1.912***	-3.895***	7.113	1.490	-231.5	-5.004
	(7.353)	(0.662)	(0.995)	(6.374)	(1.247)	(295.5)	(5.767)
R-squared	0.883	0.764	0.858	0.972	0.956	0.932	0.822
Mean (t=0)	174	27.78	14	411.3	39.21	8573	229.3
Mean (t=-30)	175.6	27.96	14.72	413	40.27	8824	230.5
% change	-20.17	-6.883	-27.82	1.729	3.799	-2.701	-2.182

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel by route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. We drop infrequently traveled routes, which we define as routes with less than 5 voyages both pre and post cutoff.

Table 1: Impact of California ECA on Correlated Pollutants

On port-to-port routes total fuel consumption (panel (i) column (5)) increases slightly (2.7 tons or 3.6%) due to avoidance, however, this estimate is not statistically different from zero. The GHG damages associated with the point estimate of the change in fuel consumption are $430-1,700 per voyage, depending on the SCC used (final rows of panel (i)). As we explore further in Section 5.1.2, the small fuel and GHG impacts are partly attributed to heterogeneous avoidance responses. Vessels that avoid the ECA increase fuel consumption by traveling farther and increasing speed, while vessels that remain in the ECA conserve fuel by reducing speed. In terms of local pollutants, the ECA generates reductions in NO_x and VOC damages of $1,600 per voyage or a 8.7% reduction from baseline levels, due to the relocation of fuel consumption to lower marginal damage areas (NOx and VOC damages per ton fall by 12%).[26]

Avoidance is weaker for ships on entrance/exit routes (panel (ii)), though total distance and fuel consumption within the study area do increase slightly. This indicates that the

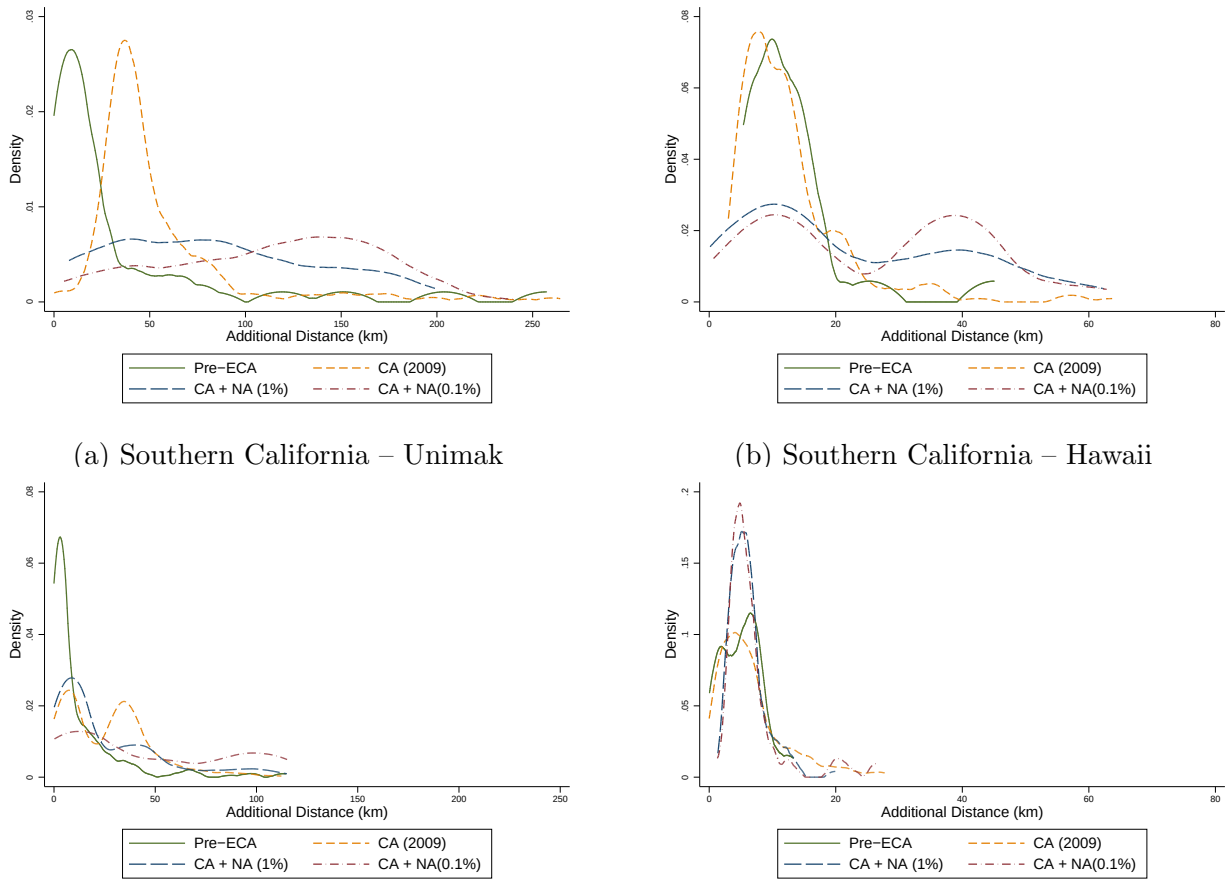
[26]These reductions in predicted local pollution damages work against the increased sulfur-related damages induced by behavioral responses to the ECA reported in Klotz and Berazneva (2022).

within-ECA fuel savings are undone by compensating changes within 100 nm off the coast, although additional compensating adjustments could also occur outside our study area. NOx and VOC damages from vessels on entering/exiting voyages are effectively unchanged as the ECA does not induce large changes in the location of fuel consumption (damage per ton fuel only falls by 2.2%). In Section A.1, we present an analysis that shows that behavioral responses and correlated pollution outcomes are much stronger for southern California ports than for northern California ports because the southern California ports are more exposed to the ECA.

5.1.1 Changes Outside the Study Area

Unlike the vovage-level analysis from above, analysis of our dataset of interpolated voyages between California ports and Honolulu and the Unimak Pass can provide reasonable bounds on changes in total distance and fuel consumption on entrance/exit routes. Each panel of Figure 4 reports the distribution of distance traveled on routes between California ports and Honolulu and the Unimak Pass under the four ECA configurations.

Prior to the ECA total distance traveled (solid green line) is tightly clustered around the minimum observed distance – within 20-30 km – for all routes. The distribution of distances on routes to/from the Unimak Pass shifts right after the establishment of the CA ECA (orange dashed line in panels (a) and (c)). The distance distribution shifts up by about 50 km for southern California as vessels re-route around the Santa Barbara Channel, while it becomes multimodal for northern California, with about half of voyages adding 30 km in total distance. In contrast, the California ECA has very limited impacts on distance traveled to Hawaii ports because vessels already travel straight through the ECA even prior to its establishment. Assuming baseline fuel use (0.091 tons per kilometer), these changes in distance imply increases in fuel as large as 2.7-4.6 tons, or around the same magnitude as the fuel increases, and GHG implications, on the most exposed port-to-port routes.



(a) Southern California – Unimak

(b) Southern California – Hawaii

(c) Northern California – Unimak

(d) Northern California – Hawaii

Notes: Lines reflect distributions of distance traveled under different ECA configurations (lines) on a particular route (panels). We subtract the minimum observed total distance by route from each observation, so that the distributions represent distance traveled above the minimum distance path. For clarity, we do not report the distribution of distances for the California ECA under the 2011 boundaries.

Figure 4: Distribution of Distances On Interpolated Voyages

5.1.2 Within-route Heterogeneity

Within-route heterogeneity further highlights the importance of avoidance in determining impacts on correlated pollutants. We separately analyze impacts of the container ships that remain in the ECA ("Remainers") and those that avoid the ECA ("Avoiders") on the busiest and most exposed route in our sample – LA/LB–San Francisco Bay – where use of the Santa Barbara Channel is a strong indicator for the extent to which vessels avoid the ECA. Almost 90% of container traffic used the channel prior to the ECA, but usage fell drastically after the ECA establishment to only 15% six months after.

Estimates in panel (i) of Table 2, again focusing on columns (5)-(7), show that vessels that

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Fuel in CA ECA (t)	(4) Distance (km)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) Avoiders (n=516, vessels=117)							
CA ECA (2009)	-441.0***	-6.527***	-46.63***	69.46***	12.22***	-2,062***	-69.66***
	(12.01)	(1.066)	(2.813)	(7.431)	(2.657)	(588.8)	(6.606)
R-squared	0.968	0.744	0.894	0.808	0.870	0.859	0.807
Mean (t=0)	606.1	31.47	60.32	700.2	67.41	18265	270.1
% change	-72.76	-20.74	-77.30	9.920	18.13	-11.29	-25.79
$ CO_2 Damage (SCC=50 $/t)					1931		
$ CO_2 Damage (SCC=200 $/t)					7724		
(ii) Remainers (n=324, vessels=86)							
CA ECA (2009)	-114.8***	-2.619***	-16.92***	23.01***	-5.183*	-1,322*	-2.248
	(23.45)	(0.725)	(3.368)	(4.587)	(2.643)	(694.4)	(5.249)
R-squared	0.756	0.580	0.858	0.630	0.884	0.874	0.529
Mean (t=0)	603.2	32.68	61.38	698.7	75.01	19269	263.5
% change	-19.03	-8.013	-27.57	3.293	-6.910	-6.862	-0.853
$ CO_2 Damage (SCC=50 $/t)					-819		
$ CO_2 Damage (SCC=200 $/t)					-3276		

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. Bandwidth is 150 days. Sample includes container ships on the LA/LB–San Francisco Route. We restrict the sample to those vessels that used the Santa Barbara Channel prior to the ECA, then classify vessels based on whether they use ("remainers") or do not use ("avoiders") the channel post policy. We then restrict our sample further to include only vessels that were observe both pre and post policy.

Table 2: Heterogeneity Due to Avoidance, California ECA

avoid the channel generate substantial increases in GHG damages ($2,000-8,000 per voyage) and reductions in NO_x and VOC damages ($2,000 per voyage). The GHG damages are driven by increases in distance and speed – fuel consumption increases proportionally more than distance traveled (18% compared to 10%), which implies that average per kilometer fuel consumption across the voyage increased and that increases in speed outside the ECA overwhelmed any reductions in speed within the ECA. The reductions in NO_x and VOCs are due to changes in the location of emissions – damages per ton fall by more than twice as much as total damage. In contrast, vessels that stay in the channel (panel (ii)) reduce both GHG and local pollution damages for a total benefit of $2,100-4,500 per voyage. Speed reductions drive this decrease in damages: within-ECA speeds fall by 8% and fuel use falls by 7% but there is no change in damages per ton.

Comparing outcomes for avoiders and remainers suggests that, on this route, avoidance contributes to substantial increases in correlated pollutant damages.[27] Relative to vessels that remain in the channel, vessels that avoid lower local pollution damages by only about $700, but they do so with increases in GHG damages of $2,700-11,000 per voyage. A key driver underlying this outcome is that avoiding the ECA allows vessels to forgo fuel-

[27]This comparison may be affected by selection bias, but we expect this concern to be limited because this comparison mostly reflects differences between early and late adopters.

saving, and correlated-pollutant-reducing, speed reductions within the regulated area. This mechanism is relatively muted for sulfur-related damages because the speed reductions occur when vessels use low-sulfur fuel.

5.1.3 Interpreting Net Damages from Correlated Pollutants

Results thus far indicate that avoidance leads to co-benefits due to local pollution that are somewhat offset by the co-costs due to increased GHGs. However, directly comparing the local pollutant and GHG impacts masks important distributional considerations. The co-benefits of the CA ECA largely accrue to the jurisdiction setting the policy (i.e., California), while the damages from increased GHGs are borne globally. One interpretation of our correlated pollution results is, therefore, that avoidance of the ECA shifts the environmental burden of shipping from the local jurisdiction onto the global community, albeit through different types of pollution. As we discuss in Section 6, this shift in environmental burden has implications for policy choice if local regulators do not fully account for policies' global implications. Moreover, future policies (e.g., tightening of the IMO's NOx standards) and trends (e.g., improved engine technologies) could change the relative importance of how avoidance and speed adjustments alter local pollutant and GHG damages, while changes in speed tend to push GHGs and local pollution damages in the same direction.

5.1.4 Robustness Checks

We use a series of checks to validate our central results that the CA ECA increases GHGs but lowers local pollution damages on port-to-port routes, but has a limited impact on local pollution damages on entrance/exit routes. There are six main takeaways from these checks. First, vessels also adjust behavior in response to the boundary change in 2011 (Table A.5 in the Appendix), with some vessels ceasing to avoid the ECA and others avoiding the updated boundary (Table A.6). Second, estimates using smaller bandwidths (90 days) are somewhat smaller in magnitude (Tables A.7 and A.8), which is consistent with the reduction in within-ECA distance and speed starting just prior to the ECA's implementation (Figure 3). Third, placebo tests where we shift the policy date forward by one year (with

either bandwidth) recover small (and statistically insignificant) changes in all outcomes for port-to-port routes (Table A.7) and for entrance/exit routes (Table A.8) if routes are defined as we do in our main results, which supports our empirical strategy.[28] Fourth, estimates of behavioral adjustments and changes in correlated pollution damages are nearly unchanged when we use common linear trends rather than route-specific trends, do not allow the time trends to change at the policy cutoff, drop time trends altogether, drop fuel prices, include a weekend dummy variable, or include route fixed effects and control for vessel characteristics (Tables A.9 and A.10). Fifth, estimates that use broader definitions of our study area support our finding of limited changes in damages from correlated local pollutants on entrance/exit routes as estimated changes approach zero when we extend the study area farther off the coast (Table A.11). Finally, there are no short-run changes in the characteristics of the vessel fleet around the implementation of the ECAs (Table A.12) and vessel call patterns are fairly stable over time (Table A.3), alleviating concerns about other potential responses to the ECA such as shifts to from sea to road or rail, or vessel operators changing the composition of the fleet using California ports.

5.2 Impacts of the North American ECA

Estimated impacts of the establishment of the North America ECA are reported in Table 3. Due to the vast differences in exposure to the NA ECA, we report results separately for routes to/from northern and southern California ports, and, for southern California, whether vessels are entering/exiting from/to the west. As discussed above, in this analysis we define entrance/exit routes according to origin/destination ports in order to capture the larger changes in course induced by the broader ECA but use a 90-days bandwidth to limit potential confounding due to seasonality. Here we emphasize both the vessel behavior and correlated pollution results because the vessel behavior adjustments to the NA ECA have not been studied.

[28] Defining entrance/exit routes according to origin/destination ports appears to open the estimates up to seasonality – as changes in total distance and fuel vary more widely with bandwidths in these cases – but reducing the bandwidth limits this concern (Table A.8).

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Distance (km)	(4) Speed out CA ECA (km/h)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) So. Cal – Port-to-Port (n=973, vessels=201)							
CA(1%) NA(1%)	12.68	0.102	-3.302	0.549	-0.971	229.2	3.242
	(12.34)	(0.528)	(4.323)	(0.957)	(2.370)	(553.6)	(4.897)
R-squared	0.844	0.552	0.806	0.527	0.793	0.728	0.724
Mean (t=0)	338.9	27.30	754.6	34.32	70.90	15413	224.6
% change	3.741	0.375	-0.438	1.600	-1.370	1.487	1.444
CO_2 Damage (SCC=50 $/t)					-153.5		
CO_2 Damage (SCC=200 $/t)					-613.8		
(ii) No. Cal – Port-to-Port (n=168, vessels=41)							
CA(1%) NA(1%)	21.47	1.105	-7.658	-2.369	-6.719	-489.2	4.583
	(14.99)	(2.888)	(6.876)	(1.984)	(10.27)	(2,262)	(6.792)
R-squared	0.598	0.596	0.832	0.611	0.698	0.660	0.689
Mean (t=0)	98.84	28.45	1347	35.71	139	23455	169.1
% change	21.73	3.883	-0.569	-6.632	-4.835	-2.086	2.711
CO_2 Damage (SCC=50 $/t)					-1062		
CO_2 Damage (SCC=200 $/t)					-4246		
(iii) So. Cal – Ent/Exit West (n=479, vessels=129)							
CA(1%) NA(1%)	-0.259	0.477	-65.54***	-1.686	-11.15***	-1,277**	14.03**
	(8.368)	(0.960)	(21.34)	(1.133)	(3.472)	(514.5)	(6.531)
R-squared	0.848	0.656	0.804	0.636	0.798	0.819	0.654
Mean (t=0)	224.5	23.65	571.9	33.80	52.62	8331	161.1
% change	-0.116	2.015	-11.46	-4.989	-21.19	-15.33	8.711
(iv) So. Cal – Ent/Exit South (n=221, vessels=52)							
CA(1%) NA(1%)	14.27	0.523	0.0211	-1.026	1.823	467.0	7.724
	(8.581)	(1.610)	(2.530)	(3.179)	(1.479)	(350.0)	(9.664)
R-squared	0.882	0.423	0.990	0.500	0.890	0.876	0.711
Mean (t=0)	78.79	20.59	242.4	31.20	16.09	3540	213.8
% change	18.11	2.540	0.00869	-3.287	11.33	13.19	3.614
(v) No. Cal – Ent/Exit (n=354, vessels=119)							
CA(1%) NA(1%)	-1.447	-0.547	-48.20*	-1.925*	-8.065***	-1,297	47.79***
	(2.276)	(1.108)	(26.78)	(1.138)	(2.835)	(788.6)	(16.96)
R-squared	0.810	0.731	0.742	0.777	0.834	0.872	0.647
Mean (t=0)	101.3	28.17	357.5	31.91	29.32	8746	297.4
% change	-1.429	-1.942	-13.48	-6.032	-27.51	-14.83	16.07

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days for port-to-port samples and 90 days for entrance/exit samples. We drop infrequently traveled routes, which we define as routes with less than 5 voyages both pre and post cutoff.

Table 3: Impact of Establishment of NA ECA on Correlated Pollutants

As the California ECA is still binding due to its distillate requirement, port-to-port routes are relatively unaffected by the establishment of the NA ECA (panels (i) and (ii)). For northern California routes speeds in areas outside the CA ECA – which are the areas affected by the NA ECA fuel requirements – do appear to fall (column (4)) but this change is not statistically significant.

The impacts of the NA ECA in the study area are clearly apparent for entering/exiting voyages (panels (iii)-(v)). There are notable reductions in total study area distance and fuel use for western entrances/exits from southern California and entrances/exits from northern California ports, with total distance falling by more than 10% and fuel use falling by more than 20% within the study area. Damages from local pollutants fall on entrances/exits from

both southern and northern California ports by about $1,300 per voyage, which is due to particularly strong reductions in fuel use in low marginal damage areas (damages per ton of fuel increase). These changes should be interpreted as partial responses to the NA ECA that are indicative of avoidance and speed changes, the full impacts of which we explore in more detail below.

5.2.1 Robustness Checks

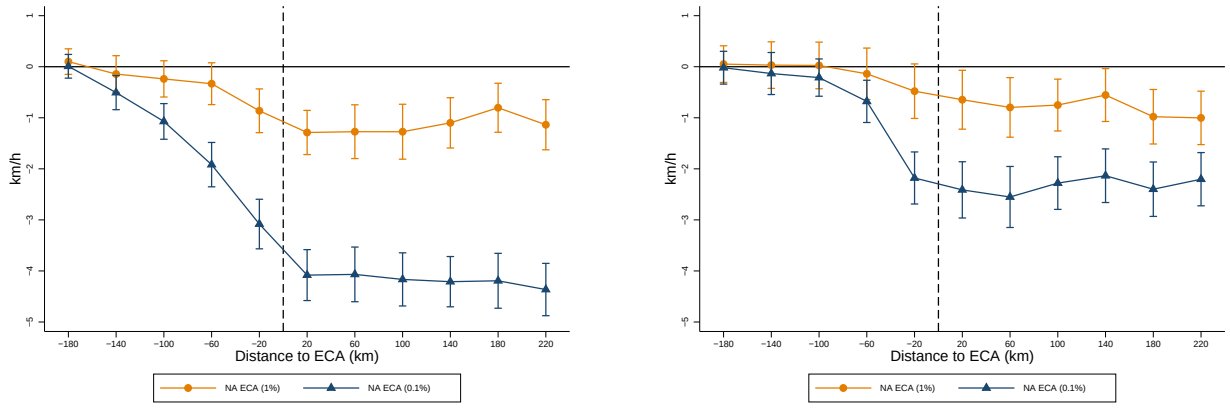
Appendix Tables A.13 and A.14 show that estimated changes on entrance/exit routes at the true policy date greatly exceed those from placebo tests that shift the policy date backward and forward by one year. These tables also show that the shorter bandwidth limits the impacts of seasonality. When we shift the policy date backward one year, the estimated change in local pollution damages is modest with the 150 day bandwidth, but no different than zero with the 90 day bandwidth. Specification checks, reported in Tables A.15 and A.16, are also generally supportive of our main results. Finally, our estimated changes in NOx and VOC damages within the 100 nm study area tend to understate the impacts of the North American ECA, particularly for southern California routes (Table A.17 in the Appendix). The North American ECA induces additional reductions in fuel consumption and emissions outside our study area (but still within the NA ECA), but the reductions in damages due to these changes are limited. As with the California ECA, we find little evidence of changes in the composition of the vessel fleet (Table A.18) or port calls (Table A.3).

5.2.2 Impacts Outside the Study Area

Two analyses of vessel behavior outside the regulated area corroborate the evidence in the regressions above that show important behavioral and correlated pollution responses to the implementation of the NA ECA. First, there are rightward shifts in the distributions of distance for interpolated voyages on all routes except the northern California–Honolulu route when the North American ECA is in place with a sulfur limit of 1% (blue wide-dashed lines in Figure 4). Increases in total distance are most notable on the southern California–Unimak route, where a modest share of voyages travel an additional 100-150 km. Voyages of this

length were almost never observed pre ECA or when the California ECA was in place. Figure 4 also makes clear that the somewhat muted average impacts of the implementation of the NA ECA shown in Table 3 are partly due to the fact that only a fraction of vessels avoid the NA ECA.

Second, sharp reductions in vessels' speeds are evident at the NA ECA boundary, when the NA ECA is in place, for voyages between ports in California and Asia. The estimated coefficients on the interaction terms from equation (2) are depicted in Figure 5. Relative to pre NA ECA speed profiles, entering vessels reduce speed by about 1 km/h inside the ECA (line with circle markers in panel (a)) or 3%, which is consistent with estimated reductions in speeds outside the California ECA in Table 3. Vessels start cutting speed around 80 km outside the ECA, which may be partially due to fuel switching operations, and then maintain a relatively constant speed once inside the ECA. Exiting vessels also maintain lower speeds within the ECA and accelerate outside the ECA (panel (b)).



(a) Entrances

(b) Exits

Notes: X-axis denotes distance to the North American ECA boundary in 40 km bins. Negative values lie outside the ECA. Tick marks denote center of each bin (e.g., 20 represents bin from 0-40 km). Points are estimated coefficients from regression of average speed in each distance bin on the interaction of indicators for each bin and each policy period and voyage and distance bin fixed effects. We omit the indicator for the bin farthest outside the ECA, so that coefficients on the interactions represent average changes, relative to pre North American ECA time period, in within-voyage speed profiles. Error bars denote 95% confidence intervals clustered by vessel. Sample includes voyages between Asia and California. We exclude voyages that do not have a speed observation in each distance bin, that cross the boundary more than once, and that occur during the west coast port slowdown. Due to the typical routing of container ships, the majority of entrances connect to LA/LB, while the majority of exits are from San Francisco Bay.

Figure 5: Speed Profiles Around North American ECA

5.2.3 Tightening of the North American ECA

Although empirical analysis is complicated by the coincidental port slowdown (Phillips 2015), there is strong evidence that the tightening of the NA ECA amplifies the behavioral adjustments we observe with the initial implementation of the NA ECA on entrance/exit routes and eliminates avoidance on port-to-port routes.

Increased avoidance on entrances/exits can be seen in the distributions of distance traveled on Unimak Routes in Figure 4. With the tightening of the sulfur limit (red dash-dot lines), there is a larger mass of voyages traveling the longer distances first observed when the NA ECA is established. There are also more pronounced average speed responses. The blue lines with triangle markers in Figure 5 show that within-voyage average speeds are 2.5-4 km/h lower inside the NA ECA than well outside the ECA for both entrances and exits.

Figures 2 and A.2 illustrate that harmonizing the two ECAs effectively eliminates avoidance of the California ECA. On port-to-port routes, distance traveled within the CA ECA increases to almost pre-policy levels soon after the tightening of the NA ECA, and this increase persists months after the port slowdown is resolved. Given our analysis of within-route heterogeneity in Section 5.1.2, we expect these adjustments to translate into higher damages from local pollutants as vessels travel closer to the coast, but lower GHGs damages.

5.2.4 Simulated Impacts of the North American ECA

The empirical analysis above provides clear evidence of systematic avoidance and speed reductions in response to the NA ECA on entrance/exit routes (especially when the sulfur limit is tightened). Using this evidence as a guide, we simulate the full impacts the North American ECA for routes to/from Hawaii and the Unimak Pass by constructing cost-minimizing voyages and speed profiles that mimic observed vessel behavior, then calculating voyage-level fuel consumption and pollution damages in the same manner as we do for observed voyages (details are in the Appendix Section B). Simulated responses to the NA ECA (Table 4) are noticeably stronger than our empirical results because they reflect adjustments across full route-specific outcomes conditional on avoidance, as opposed to

averages across routes and avoidance choices, and the impacts of the tighter sulfur limit relative to a counterfactual without the CA ECA in place.[29]

	So. Cal – Unimak	So. Cal – Hawaii	No. Cal – Unimak	No. Cal – Hawaii
Baseline				
Distance (km)	4,372.7	4,244.6	3,748.1	3,975.1
in ECA	1,245.1	566.4	736.3	412.7
Fuel (t)	385.7	374.4	330.6	350.6
NOx+VOC Damage ($)	25,360.8	10,199.7	20,908.0	11,268.5
CO2 Damage ($50)	60,937.7	59,152.5	52,232.9	55,395.8
CO2 Damage ($200)	243,750.8	236,610.0	208,931.5	221,583.2
Impacts of ECA				
Δ Distance (km)	170.1	27.8	103.0	0.0
Δ Fuel (t)	9.1	-2.8	4.2	-4.2
Δ NOx+VOC Damage ($)	-14,110.8	-2,197.9	-7,015.3	-983.6
Δ CO2 Damage ($50)	1,433.2	-436.1	660.5	-669.8
Δ CO2 Damage ($200)	5,733.0	-1,744.3	2,641.9	-2,679.1
Impacts of ECA - no avoid				
Δ Fuel (t)	-12.8	-5.8	-7.6	-4.2
Δ NOx+VOC Damage	-2,586.6	-1,025.8	-1,881.8	-983.6
Δ CO2 Damage ($50)	-2,020.9	-919.3	-1,195.1	-669.8
Δ CO2 Damage ($200)	-8,083.5	-3,677.1	-4,780.3	-2,679.1

Notes: Simulated outcomes on four representative routes. "in ECA" and "in Study Area" report outcomes calculated within the North American ECA and within our 100nm study area. "no avoid" rows report outcomes had vessels remained on pre-ECA trajectories vessels but had reduced speed within the ECA. Simulations do not account for adjustments due to the California ECA or the North American ECA around Hawaii.

Table 4: Simulated Impacts of North American ECA on Representative Routes

Avoidance of the North American ECA induces sizable reductions in local pollution damages on routes to/from the Unimak Pass (upwards of $14,000 or 50% per voyage). The corresponding increased damages from GHGs are upwards of $5,700 per voyage. In a counterfactual where vessels do not avoid the ECA but did slow down within the regulated area ("no avoid" rows), local pollution falls slightly but GHG damages fall substantially, which indicates that forgone fuel savings make up a substantial portion of the effect of avoidance on GHG damages but is much less important for local pollutants.[30] Avoidance opportunities, and impacts on correlated pollutants, are limited on the Hawaii routes.

6 Policy Implications

Our analysis has illustrated that behavioral responses to narrow and broad ECAs drive changes in local and global pollutants that were not targeted by the policies. These results have several implications for the evaluation and design of ECAs and other maritime policies.

[29]There is, however, general accordance between the simulated changes in distance traveled shown in Table 4 and distance distribution plots in Figure 4. In particular, there is no or limited avoidance possible on the two Hawaii routes, while much more avoidance is possible on the Unimak Pass routes, especially from Southern California.

[30]For southern California–Unimak voyages, the increase in fuel consumption due to avoidance and speed changes was 9.1 tons, but would have been -12.8 tons had vessels been unable to avoid the ECA. The contribution of foregone fuel savings makes up 58% of the total increase ($= 12.8/(9.1 - (-12.8))$).

Changes in behavior induced by ECAs lead to economically important changes in correlated pollutants, which provides a clear motivation to consider changes in correlated pollutants in cost-benefit analyses of these policies. Regression coefficients and vessel counts suggest that the local pollution co-benefits due to the California ECA are in the range of $2.3 million per year, while the GHG co-costs are $0.6-2.5 million per year. Either of these changes is of the same magnitude as one month of the increase in fuel costs imposed by the California ECA on container ships (Klotz and Berazneva 2022). Our simulation results indicate that changes in correlated pollution might offset as much as 50% of the compliance costs associated with the North American ECA on the most affected routes.[31] Analyses of maritime policies that do not account for changes in vessel behavior, such as inventory studies (e.g., Liu et al. (2016)), would be unable to capture these effects.

With respect to the design of ECAs, our results suggest that accounting for impacts on correlated pollutants tends to motivate the expansion of the ECAs we study, except at higher values of the social costs of carbon.[32] For coastal routes, an expanded ECA can reduce avoidance and provide net benefits from changes in correlated pollutants. For entrance/exit routes where avoidance is possible, increasing the size of the ECA leads to a direct tradeoff between local pollution benefits and increased GHG damages. Extending our simulation analysis to consider ECAs of different widths (Figure A.4) suggests that accounting for correlated pollutants would imply a somewhat larger North American ECA under a relatively low SCC and a somewhat smaller ECA under a higher SCC.[33] On routes where avoidance is not possible, correlated pollution damages are minimized with the broadest ECA, since speed reductions drive both local and GHG pollution damages down. Broader ECAs are also likely to be favored by regulators that place less weight on GHG damages (e.g., if regulators

[31] In unreported simulation results, we find that fuel costs increase by $17,500 on the LA/LB–Unimak route. The reduction in correlated local pollution offsets 80% of these costs, but increases in CO_2 damages add up to 30% to these costs.

[32] A formal evaluation of the optimal size of an ECA is out of the scope of this paper.

[33] We consider ECAs ranging from 100km to 400km (which is essentially comparable to the NA ECA) off the coast. If the social cost of carbon is $50, the net correlated pollutant damages are lowest for the largest ECA considered for all routes. However, if the social cost carbon is $200, then net damages are minimized for ECAs between 200 and 300km on the Unimak routes.

only accounted for domestic damages from GHGs, which for the US would be 11% of the social cost of carbon according to Ricke et al. (2018)). More generally, our results suggest that regulators may want to encourage avoidance of broader ECAs because the changes in correlated pollutants are large enough to make these behavioral adjustments improve aggregate environmental outcomes (in addition to reducing fuel costs), which is not the case with narrow ECAs (Klotz and Berazneva 2022).[34]

Our results also point to other contexts where correlated pollution impacts could be important. If there is widespread avoidance of the narrow (22 km) coastal ECA recently imposed by China it could lead to substantial unintended local pollution benefits due to the quantity of coastal maritime traffic in this region (Liu et al. 2016). The geographically contained ECAs established in the North and Black Seas and approved in the Mediterranean Sea may yield correlated pollution co-benefits through speed reductions, provided that these ECAs do not induce other drastic changes in shipping patterns (e.g., rerouting around the Cape of Good Hope). Other maritime policies that target speed (e.g., the proposed expansion in coastal slow zones to protect Right Whales along the east coast of the U.S. (NOAA Fisheries 2022)) or the location of vessel traffic (e.g., "areas to be avoided" or shipping lanes) could also have pollution implications. Indeed, our simulation results imply that coastal speed limits could provide sizable reductions in pollution damages ("speed only" lines in Figure A.4).

7 Conclusion

In this paper we analyze how behavioral responses to emission control areas targeting sulfur-related pollution from maritime transport off the U.S. west coast impact damages from GHGs and other local air pollutants. Our results suggest that avoidance – the spatial adjustments that ocean-going vessels undertake to reduce exposure to the policy – is a key mechanism driving changes in damages from correlated pollutants. In our context, avoidance increases

[34]For a broader ECA, avoidance and speed responses have a relatively minor impact on sulfur-related damages because low-sulfur fuel continues to be used even far from the coast, meaning that the correlated pollutant impacts determine the environmental consequences of behavioral adjustments.

fuel consumption and emissions due to both longer distance traveled and foregone speed reductions within the ECA, but also shifts fuel consumption to lower marginal damage areas. As a result, damages from GHG emissions increase, generating a co-cost of the policy, but local pollution damages fall, generating a co-benefit. The changes in correlated pollution induced by the ECAs are economically important, and, therefore, should be considered in the design and evaluation of ECAs and other maritime policies.

Our analysis of different ECA configurations highlights how policy design impacts avoidance and speed responses. We show that the narrow California ECA mainly affects vessels on port-to-port routes but has limited impacts on entering/exiting routes. In contrast, the broader NA ECA induces avoidance by vessels on entrance/exit routes but not on port-to-port routes. These findings imply that the structure of transportation networks affected by ECAs (e.g., size, proximity to and infrastructure at ports, volume of coastal trade) interacts with the design of the ECAs in determining overall impacts on correlated pollutants.

The avoidance and speed adjustments we document may also have implications for a range of other correlated externalities. OGVs also emit carbon monoxide (CO), while the NOx and VOC emissions contribute to ozone formation. Given the estimated decay of CO and ozone (Moretti and Neidell 2011; Schlenker and Walker 2016), the spatial shifts in fuel combustion away from the coast could lower damages from these pollutants. Since sulfates induce temporary and localized cooling by reflecting solar radiation and seeding clouds (Liu et al. 2016), the reductions in the sulfates directly targeted by the ECAs could lead to a local warming effect. Avoidance, however, could somewhat mitigate this effect by reducing travel in areas where vessels are required to switch to low-sulfur fuels.

An important takeaway of our work is that policies targeting local externalities (e.g., local air pollution, congestion, noise), could have global implications by altering GHG levels. This local-global tradeoff is likely to become an increasingly important policy consideration given growing concerns about both the impacts of climate change and the unequal distribution of environmental damages. Beyond maritime polices, any policy that regulates a portion

of a transportation network could induce the avoidance response that primarily drives the global implications of ECAs. For example, Leape (2006) suggest that 25% of drivers re-route to avoid London's congestion charge, while other papers provide evidence consistent with increased travel in unregulated areas in response to congestion charges (Gibson and Carnovale 2015) and Low Emissions Vehicle Zones (Zhai and Wolff 2021), although the evidence is mixed in the later case (Gehrsitz 2017). Since avoidance depends substantially on the structure of the transportation network in relation to the regulated area, adjusting the design of the regulated area is one means to alter this local-global tradeoff.

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Supplemental Appendix for "Correlated Pollutants, Avoidance, and Local Environmental Policy"

March 2025

A Additional Results

A.1 Heterogeneity Across Routes, CA ECA

To assess how exposure to the ECA, due to geography, affects behavioral responses and correlated pollutant outcomes we estimate impacts of the California ECA after splitting our sample by port locations (Table A.4). Avoidance opportunities and the resulting correlated pollution impacts vary considerably across routes. Total fuel use increases most (5%) on southern California port-to-port routes, which exhibit the strongest avoidance response, leading to an increase in GHG damages of \$600-2,400 per voyage. NO_x and VOC damages fall on both northern and southern port-to-port routes, but the reductions are bigger on northern California routes, possibly because there is no increase in fuel use associated with avoidance. NO_x and VOC damages do not fall sharply on all entrance/exit routes, although these changes are not estimated precisely and further changes in fuel use could take place outside the study area.

B Simulation Assumptions

Simulations discussed in Section 5.2.4 are constructed to match observed vessel behavior reported in the text. We assume that vessels adhere to existing traffic patterns around ports (e.g., traffic separation schemes), then travel straight to the ECA boundary and then straight from the ECA boundary to the destination port (from a great circle perspective). These assumptions broadly match the patterns in Figure 2. The cost-minimizing paths may opt for different trajectories around the ports (e.g., western vs northern separation scheme from the San Francisco Bay, or using the Santa Barbara Channel). We consider both time and fuel costs. The value of time is set to 500 \$/h (Ahl et al. 2017), while fuel costs outside the ECA are assumed to be 450 \$/t. Fuel costs within the ECA account for the low sulfur

fuel price premium and the implicit costs of traveling within the ECA and is set in order to match observed vessel behavior. Based on estimates from our sample of voyages that exit the North American ECA, speeds are assumed to be 31.3 km/h outside the ECA and fall by 2.3 km/h inside the ECA (Figure 5).

Since the marginal damage grid does not cover the entirety of these routes, we assume damages decay linearly to zero until the destination port, which is equivalent to setting the marginal damage outside the grid equal to half of the marginal damage from the point where the voyage exited the grid.

C Summary of Voyage Counts

Table A.3 describes voyages observed in the AIS data. In total (panel (i)), we observe almost 85,000 voyages that connect to California ports. We are able to obtain a vessel identifier (IMO number) and vessel characteristics for over 72,000 of these voyages. Voyages by container ships make up roughly half of total observed voyages and about 56% of voyages for which we have vessel characteristics. Roughly two-thirds of container voyages are entrances/exits. We are able to obtain the origin/destination port from the Entrance/Clearance data for about 70% of these voyages (and around 80% for container ships).

We tabulate container ship voyages separately for southern and northern California ports in the next two panels. Voyages that connect to southern California ports (panel (ii)) are almost exclusively to/from the ports of Los Angeles and Long Beach (LA/LB). Almost all port-to-port voyages connect to San Francisco Bay, while entrances/exits are mostly connecting to/from ports in Asia or traveling to/from the south (e.g., Mexico or elsewhere via the Panama Canal). Vessels connecting to the northern California ports — solely the San Francisco Bay ports — travel to Seattle or to ports in Asia (panel (iii)). Comparing across columns indicates that there are no drastic changes in the fraction of vessels traveling on a particular route under different ECA configurations.

The final panel of Table A.3 reports counts of voyages that we are able to interpolate to either the Unimak Pass or Honolulu. Two-thirds of southern California interpolated

voyages are to/from Honolulu, while two-thirds of northern California interpolated voyages are to/from the Unimak Pass.[1]

D Data Procedures

D.1 Track Creation from AIS Data

D.1.1 Selecting Records

The AIS records include geographic coordinates, time, a ship identifier (MMSI), and, for most records, speed over ground (SOG), course over ground (COG), and heading. These records are provided in monthly files for each UTM zone. We create a monthly dataset for the U.S. west coast by merging the records for UTM zones 3 through 11. From this dataset we drop any records with SOG less than 2.5 nautical miles per hour and those records with invalid MMSI codes.[2] Dropping the records with low SOG eliminates the creation of very complicated geometries generated by ships that are moored or otherwise stationary.

D.1.2 Voyage Creation

For each MMSI, the records are then sorted by time and voyages are created by connecting sequential records after checking for potential connectivity. Iterating through the records, a line is generated between the current and subsequent record if one of the conditions holds:

1. the records are within 20 km,
2. the records occur within 2 hours,
3. the records occur within 2 to 24 hours AND are greater than 20 km apart AND the following record falls within a *plausible area* (see below) AND the reported COG or heading of the records is within 25 degrees.

If one of these conditions holds the voyage is continued, otherwise the voyage is ended at the current record and a new voyage is started from the subsequent record. The third condition

[1] It is worth noting the decline in voyages to/from the Unimak Pass in the final column. It is possible that this indicates that some vessels on trans-Pacific routes are shifting south and out of the Unimak Pass in response to avoiding the ECA.

[2] The first three digits of the MMSI codes are Maritime Identification Digits (MID). MIDs between 201 and 775 provide the home country for individual ships. We therefore drop any records with MID codes outside this range.

allows for the possibility of connecting distant records for ships on open water transits. The *plausible area* is the polygon created by the current point and three predicted locations for the ship given that it continued at its current (implied) SOG until the time of the following point. The predicted locations assume that the ship would move at 1) its current COG, 2) its current COG+15, and 3) its current COG-15.

To account for potentially anomalous records (e.g., bad position or time), the subsequent point is skipped if the speed implied by the time and distance between the current and subsequent points is greater than 50 knots/h. The voyage is then, potentially, continued by checking the connectivity between the current and next available record. This procedure is similar to one used by Goldsworthy and Goldsworthy (2015).

The final voyage dataset is a series of lines with MMSI identifiers. Along with the coordinates, the time (date, hour, minute) associated with every vertex is stored to account for the temporal dimension (starting and ending times, speed) of the voyage. The AIS data provides some information on ship characteristics, which is joined to the final voyage dataset. The characteristics that are available in all years are vessel type, length, and width.

Coverage gaps in the AIS data prevent us from creating full voyages for vessel movements between west coast ports and more distant Pacific Rim ports. We are able to partially rectify this issue by interpolating voyages between west coast ports and more distant U.S. ports in Alaska and Hawaii. Figure A.6 provides a graphical depiction of this procedure. If we observe consecutive voyages for the same vessel at a west coast port and an Alaska or Hawaii port, and the time and distance between these voyages imply a reasonable speed, then we interpolate between the two voyages along a Great Circle path. This implies that vessels are traveling on a minimum distance route, which given observed vessel behavior and historic vessel patterns seems to be a reasonable assumption.

D.1.3 Route Classification

Our route classifications are based on lines that define the entrances and exits from major ports and U.S. waters. The major ports we consider are Seattle, Portland, San Francisco Bay,

Hueneme, Los Angeles/Long Beach, and San Diego, although we also track routes to smaller ports (e.g., Coos Bay, Grays Harbor). Port locations are determined by lines spanning the traffic choke-points for each port. Our port definitions are broadly consistent with the U.S. Census District Codes, which subsume traffic from a number of ports (Foreign Trade Division, U.S. Census Bureau 2020). For example, the line defining the San Francisco Bay spans the Golden Gate, the entrance of San Francisco Bay. This port therefore accounts for traffic to the Ports of Oakland, Richmond, and San Francisco. Likewise, the line defining the port of Seattle spans the Strait of San Juan de Fuca, so our classification of Seattle accounts for traffic to Seattle and any other port beyond this line, notably Tacoma, Anacortes, and Vancouver.

The lines defining our study area fall roughly 100 nm from the coast. A distance of 100 nm was chosen to balance classifying ships that are entering/exiting U.S. waters and the limited coverage quality of AIS reports farther from the coast. This boundary is broken into nine segments to capture the rough location from which ships are entering or exiting U.S. waters. Most segments are defined according to the location of the major ports. For example "US 3" lies north of San Diego to south of Los Angeles, "US 4" lies north of Los Angeles to halfway to the San Francisco Bay, and "US 5" lies from halfway between Los Angeles and San Francisco Bay to the San Francisco Bay.

To classify the voyages to routes, each voyage is split where it intersects a port or study area boundary. We then determine which port or boundary section, if any, intersect with the endpoints of each of the generated (split) voyages. In this step, we allow voyages between ports to cross the study area boundary to remain intact for two reasons: 1) it allows classification of a voyage to a route between two ports even if a portion of the voyage is outside the study area boundary; and 2) classification of a route between a port and the boundary will only account for voyages that terminate outside the boundary (and not voyages that eventually reenter U.S. waters). The direction of transit (e.g., whether the ship on a voyage that intersects San Francisco and LA is moving from LA to San Francisco or

from San Francisco to LA) is determined using the time at the endpoints of the voyages.

D.2 Validation of AIS Data

We validate our AIS-based voyages by comparing the port entrances observed in the AIS voyage dataset with the U.S. Army Corp of Engineer's Entrance/Clearance (EC) dataset (US ACE 2018). Results are discussed in Klotz and Berazneva (2022). Our pre ECA estimates of fuel consumption within the ECA appear to be reasonable. Although we are not aware of other AIS-based inventories that report these statistics, our totals are generally in line with modeling exercises conducted when the OGV Fuel rule was being evaluated (CARB 2008). Our daily within-ECA fuel consumption estimate of 508 tons is much lower but in general agreement with the estimate of CARB (2008) of 2,100 tons, after adjusting for slower vessel speeds (-700 tons), within port and at berth fuel consumption (-600 tons), and incomplete voyages that are dropped from our analysis (-80 tons).

D.2.1 Origins/Destinations for Entrance/Exits

The Entrance/Clearance dataset contains the date, IMO number, and origin/destination port for vessels entering/exiting US ports that are carrying foreign cargo. We match the Entrance/Clearance data to our voyage data by IMO number, US port, direction (entrance vs exit) and date.[3] Using this procedure, we are able to obtain origin/destination ports for more than 80% of container ship entrances/exits to California ports. We further define origin/destination ports based on AIS data for entrance/exit voyages to/from Alaskan or Hawaiian ports.

The Entrance/Clearance data provides detailed origin/destination port information (e.g., Yokohama, Japan). Since the precise location of the origin/destination port is unlikely to have a substantial impact on within-study area outcomes and because we observe many origin/destination ports infrequently, we group origin/destination ports to broadly capture

[3]In the voyage dataset, we have the date and time at which a voyage reaches or definition of the port. After constructing all matches within IMO, port and direction, we take the closest temporal match provided it is within 48 hours. We allow for matches within a relatively wide time window to account for vessels traveling from the choke points that we use to define ports and their berths and because the Entrance/Clearance data only reports dates of entry and not times.

the direction of travel to/from U.S. west coast ports. The most detailed groups are for the major Pacific Rim shipping hubs. Specifically, we group ports within Alaska, Hawaii, the west coast of Canada, Japan, South Korea, Taiwan, Eastern Russia, and three regions of China — south of Taiwan including Hong Kong, Taiwan, and north to the Yellow Sea (e.g., Ning Bo and Shanghai), and Yellow Sea ports (e.g.,Tianjin and Dailin). The remaining groups are more aggregated and include all ports within Oceania, all ports in Middle Eastern countries and Asian countries not listed above, and all ports that would require voyages to/from the south. This final group includes ports in Mexico, Central and South America, and any ports that require travel through the Panama Canal – Caribbean, the east coast of the U.S. and Canada, Europe (including Russia's western ports), and Africa.

Voyages matched to the Entrance/Clearance data under represent voyages with only domestic cargo. However, we show that voyages not observed in the Entrance/Clearance dataset are generally similar in terms of observed behavior (Figure A.5) and vessel characteristics (Table A.2) pre ECA.

D.3 Recovering Vessel IDs

For 2010 to 2014, the vessel identifiers (IMO and MMSI numbers) in the AIS data are scrambled. Using the raw AIS data from 2009 and after 2015 we use a matching algorithm to recover vessel identifiers. We can track vessels within our two analysis windows using the AIS identifiers, so vessel fixed effects in our main specifications never rely on the results of this matching procedure.

Vessels without IMO numbers reported are matched to vessels we observe with IMO numbers reported, based on the numbers contained in the scrambled and unscrambled MMSI and vessel characteristics. The scrambled MMSI numbers for vessels without IMO numbers are just a reordering of the true MMSI numbers, so the scrambled MMSI and true MMSI will contain the exact same counts of each digit between 0 and 9. The MMSI is a 9 digit number, with the first 3 digits representing a country code (Maritime Identification Digit or MID) and the last 6 identifying a vessel. The set of true MMSI that are consistent with a scrambled

MMSI is actually quite small because the country code was not scrambled and for many MMSI the last 3 digits are zeros. To recover the missing IMO numbers, we first create a dataset of vessels with unique combinations of MMSI numbers, country code, length, width, and vessel type. This dataset includes IMO numbers for those vessels observed in 2009 or 2015 and later. We then match vessels with IMO numbers to those without IMO numbers using a nearest neighbor algorithm. The distance between vessels is based on observed length and width, because these values appear to have been slightly modified (1-2 m) in the scrambled data, and we match exactly on MID, the counts of each digit between 0 and 9 in the last 6 digits of the MMSI, and vessel type. We reject any matches that are more than 5 m different in total size and those that match to more than one vessel. This process recovers IMO numbers for roughly two-thirds of observed cargo ships and just under half of observed tankers, which account for around 70% of total observed vessel tracks.

D.4 Filling Missing Characteristics

Our database on vessel characteristics contains missing values, but the number of missing values is small for most technical characteristics. For example, only 1.1% of container ships are missing draft information, and only 5% are missing service speed. One variable that is more sparse is fuel consumption at service speed, which is missing for 20% of container ships. However, vessel characteristics are closely related because they are based on engineering relationships. For example, the R^2 in a linear regression of fuel consumption on length, beam, draft, built year, main engine power, deadweight, service speed, fuel consumption at service speed is 0.977. This suggests that filling missing values using imputation is a reasonable approach.

We use iterative imputation to fill missing values for key vessel characteristics. This algorithm iterates through each vessel characteristic and predicts the missing values of the selected characteristic based on the other characteristics, where the missing values for these other characteristics have filled using the most recent prediction. After cycling through all characteristics, the process is repeated a set number of times to refine the predictions. The

characteristics that enter this algorithm are length, beam, draft, built year, main engine power, deadweight, service speed, fuel consumption at service speed, and auxiliary engine load. See `https://scikit-learn.org/stable/auto_examples/impute/plot_iterative_imputer_variants_comparison.html`.

D.5 Estimating Fuel Consumption

We calculate fuel consumption from vessels' main and auxiliary engines for each voyage using a well-established approach in the literature (Liu et al. 2016; Molina and McDonald 2019). Fuel consumption (F) used for propulsion by main engine is a function of vessel characteristics (α_i), as well as vessel speed (S) and distance (D) of vessel i at time t across all segments s of a voyage it:

$$F_{it} = \alpha_i \sum_s S_{its}^2 D_{its}. \tag{3}$$

Here, $\alpha_i = \frac{f_i}{S_i^3}$ with f_i being fuel consumption at design speed in tons of fuel per hour and S_i being design speed for vessel i. The quadratic relationship between fuel consumption and speed captures the engine's load factor (i.e., the fraction of total engine power required to achieve a particular speed) and is derived from the propeller law. Fuel consumption by auxiliary engine used to generate electricity is a product of hours of operation, vessel type and class-specific auxiliary engine load, and a fuel oil consumption factor. We use auxiliary engine loads and consumption factors from IMO (2015).

D.6 Emission Factors

Auxiliary engine loads and fuel oil consumption factor are from IMO (2015). We use "at sea" loads because our voyages mostly capture vessel movements well outside of port and a fuel oil consumption factor (grams fuel per kWh) for medium-speed auxiliary engines.

Emission factors are also from IMO (2015). NO_x emission factors for main and auxiliary engines depend on vessel age. IMO implemented tiered NO_x emission standards that depend on when the vessel was built. Tier I standards apply to vessels built in 2000 and before 2011, while Tier II standards apply to vessels built in 2011 or later. The NO_x emission factors (tNO_x per ton fuel) we use are as follows:

- Pre 2000 vessels: 0.093 main; 0.065 auxiliary
- Tier I vessels: 0.090 main; 0.057 auxiliary
- Tier II vessels: 0.078 main; 0.049 auxiliary

We use the emission factor of 0.00308 ton VOC per ton fuel combusted for both main and auxiliary engines.

We account for three GHGs: CO_2, CH_4, and N_2O. The emission factors for CO_2, CH_4, and N_2O are 3.11, 0.00006, and 0.00016 tons per ton fuel, respectively. After converting based on 100-year global warming potentials (34 for CH_4 and 298 for N_2O), aggregate emission factor is 3.16 tCO_2e/t. Nearly 99% of CO_2e is due to CO_2.

The slightly higher energy content of some low-sulfur fuels (distillates) implies that ECAs could mechanically lower emissions of local pollutants and GHGs because the same engine power can be obtained with fewer physical units of fuel (IMO 2015). We present results without this adjustment for energy content for three reasons. First, our fuel consumption estimates are based on vessel-specific data on fuel consumption, and we do not have equivalent data for fuel consumption when using distillate fuels. Second, our goal is to isolate behavioral responses to the ECA; accounting for energy differences complicates interpretation of our results (e.g., isolating the contributions of avoidance, speed adjustments, and energy differences). Third, adjusting energy contents requires making assumptions about the types of fuels being used, which is especially complicated when analyzing the North American ECA because vessels could be using distillate or low-sulfur residual fuels.

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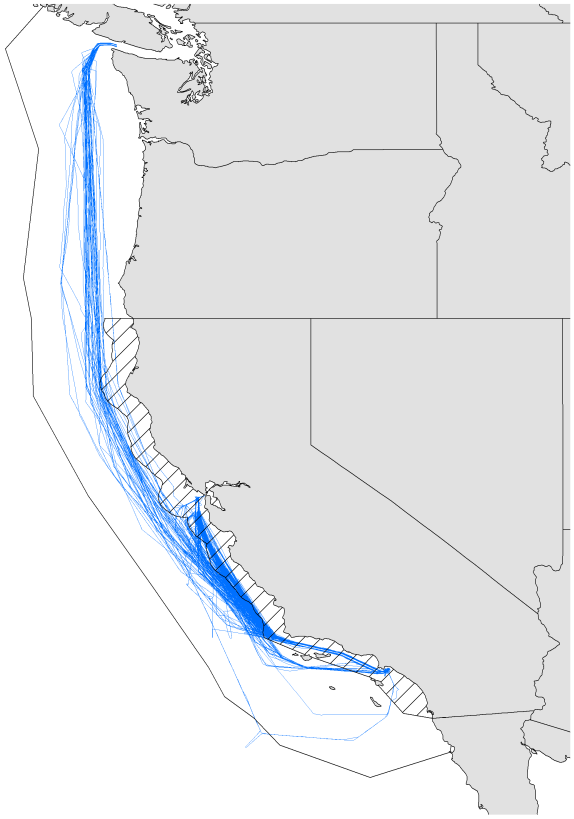
Supplemental Figures and Tables



Notes: Figure depicts all container ship voyages between LA/LB and other west coast ports prior to the establishment of the California ECA.

Figure A.1: Graphical Depiction of Voyages

	No. Cal	So. Cal
Exit	.95	.21
	(.22)	(.41)
Length (m)	301	306
	(29)	(36)
Main Engine Power (kW)	54,165	57,074
	(13,574)	(13,728)
TEU	6,390	6,890
	(2,141)	(2,193)
US Flagged	.019	.043
	(.14)	(.2)
N	4408	6050

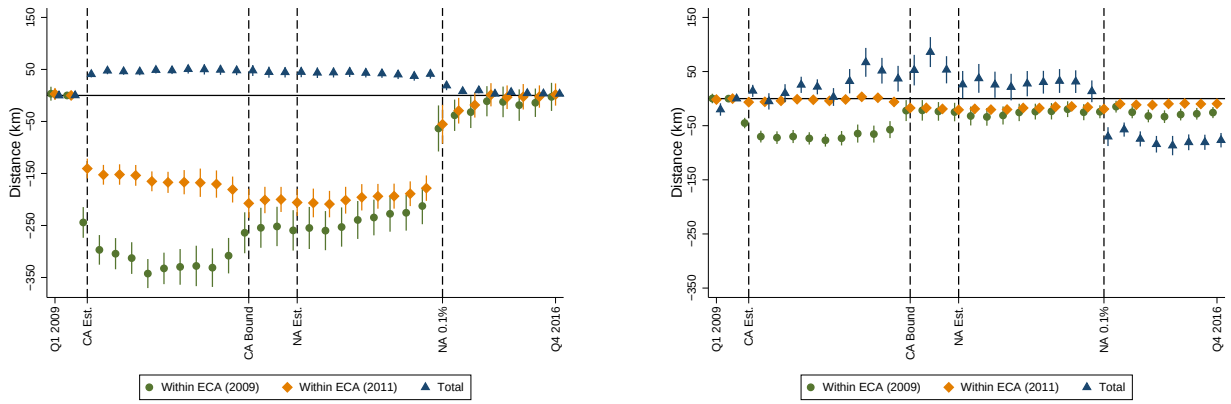
(a) Full Sample

	No. Cal	So. Cal
Exit	1	.17
	(.067)	(.38)
Length (m)	306	308
	(31)	(34)
Main Engine Power (kW)	55,608	58,186
	(13,272)	(12,918)
TEU	6,819	7,105
	(2,381)	(2,193)
US Flagged	.0068	.035
	(.082)	(.18)
N	444	1434

(b) NA ECA Crossings

Notes: Vessel and voyage characteristics on California–Asia routes in full sample (a) and those observed crossing North American ECA (b). Exit row reports the fraction of voyages leaving west coast ports.

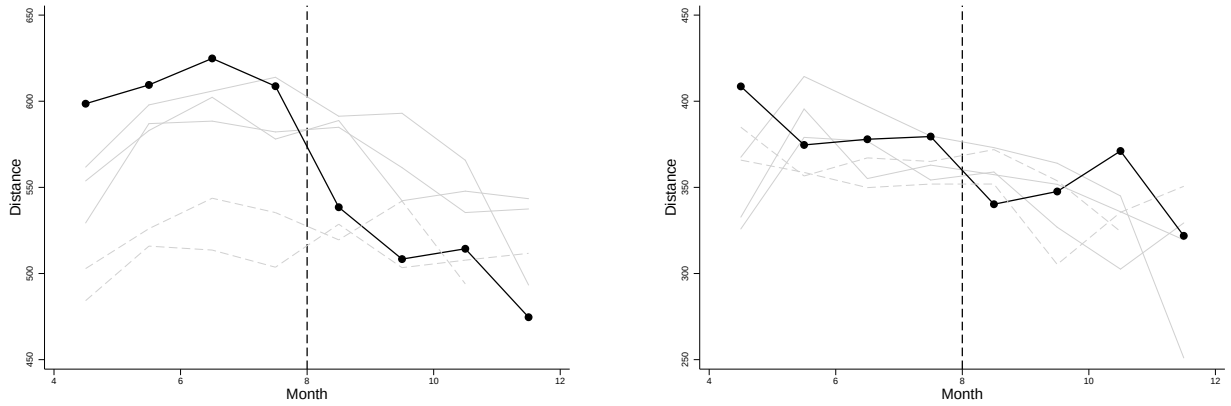
Table A.1: Characteristics of Vessels Crossing North American ECA



(a) Port-to-Port (b) Enter/Exits

Notes: Points are quarterly averages of outcome variables after partialling out route fixed effects and fuel prices. The first quarter prior to the implementation of the California ECA is omitted, so that the coefficients are differences from this quarter. Lines represent 95% confidence intervals, clustered by vessel, which are relevant for pairwise comparisons to the omitted quarter. For entrance/exit voyages routes are defined according to origin/destination and changes reflect only adjustments within the study area.

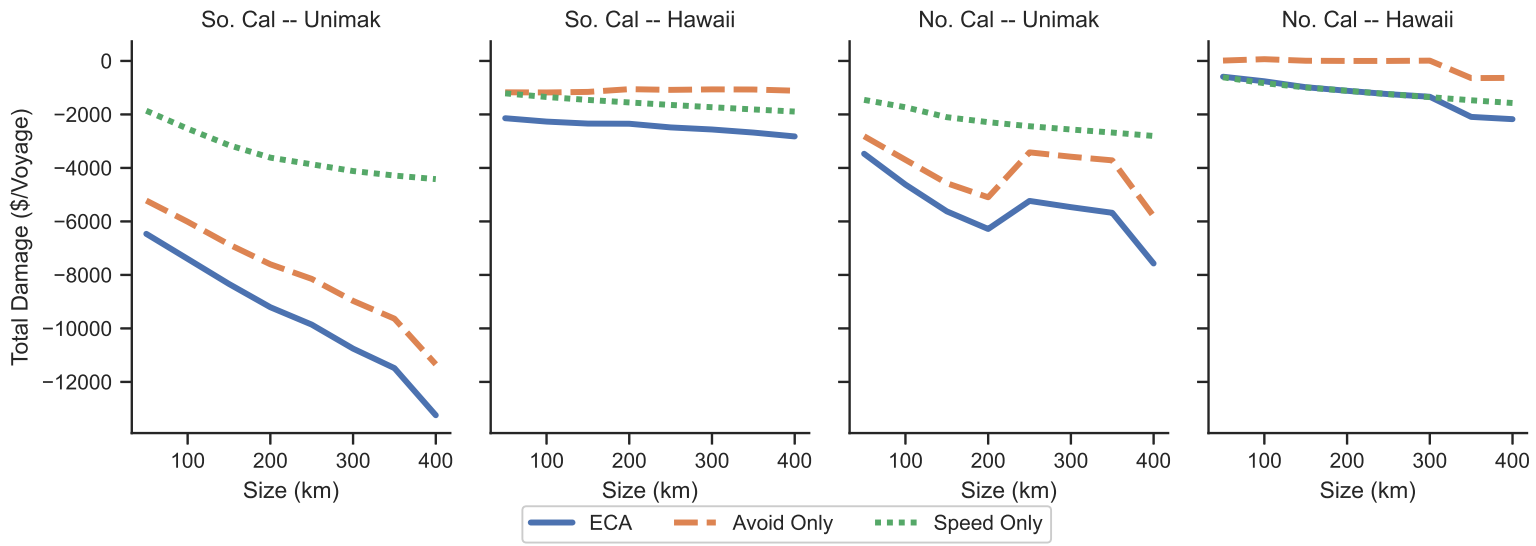
Figure A.2: Impacts of ECAs on Distance Traveled



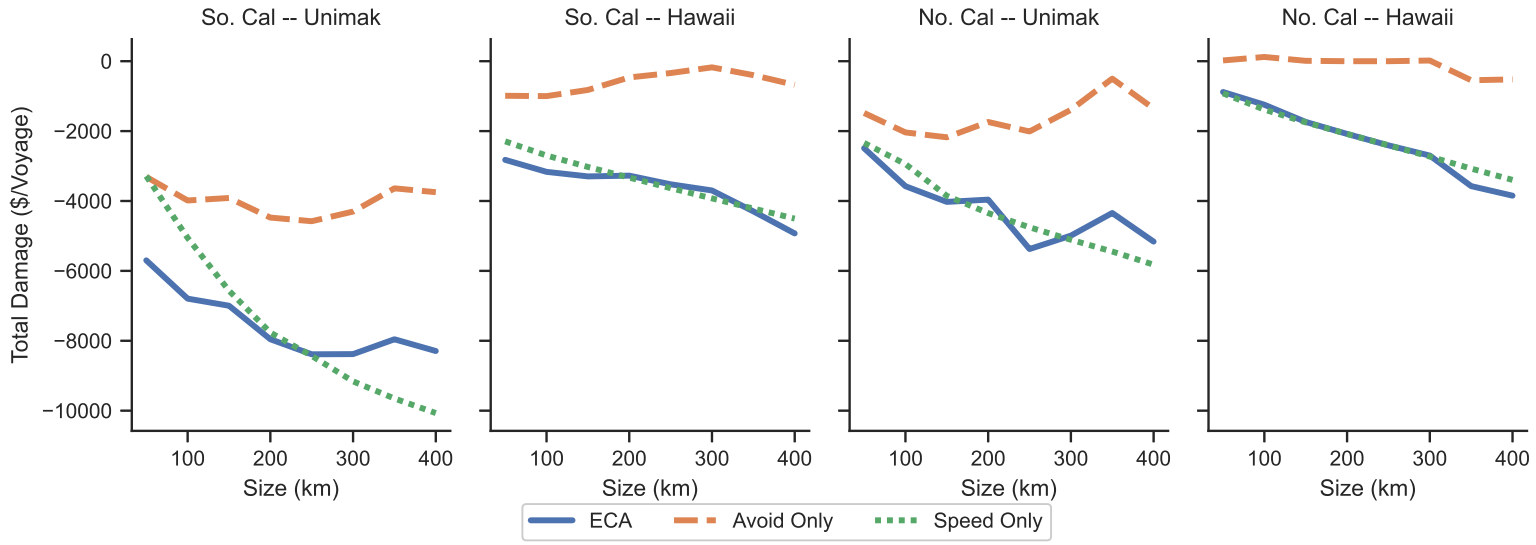
(a) Southern California (b) Northern California

Notes: Lines reflect average distance traveled within study area by month (x-axis) and year for voyages to/from ports in Asia. Solid black line denotes 2012. Dashed vertical line represents month North American ECA is established in 2012. Solid light gray lines represent years prior to ECA (2009-2011), while dashed gray lines represent years after the ECA is implemented but prior to sulfur limit falling to 0.1% (2013-2014).

Figure A.3: Seasonality in California–Asia Routes



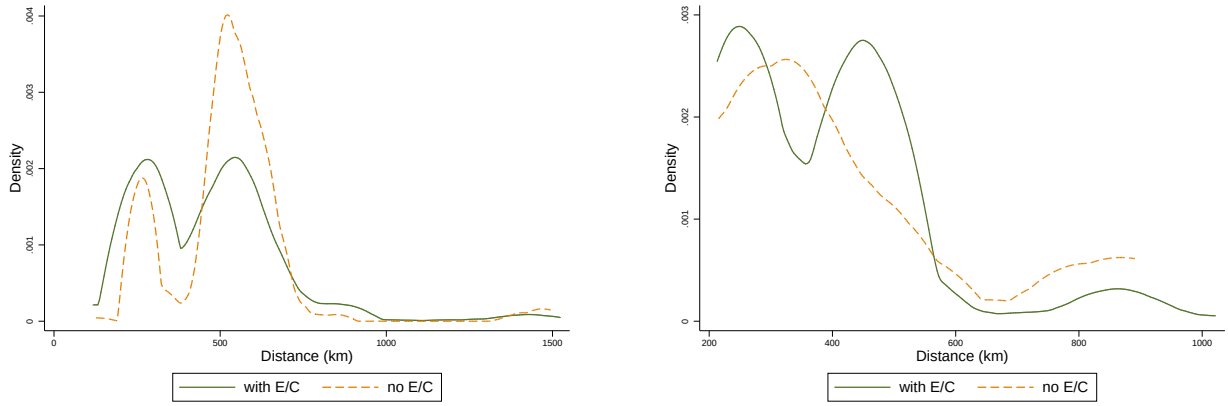
(a) SCC = $50



(b) SCC = $200

Notes: Simulated outcomes on four representative routes. Curves reflect net correlated pollution damages under ECAs from 100km to 400km off the coast. The 400km ECA is essentially comparable to the North American ECA. "Avoid Only" and "Speed Only" curves are outcomes when the other behavioral channel is locked down. Simulations do not account for adjustments due to the California ECA or the North American ECA around Hawaii.

Figure A.4: Impacts of Alternative Policies

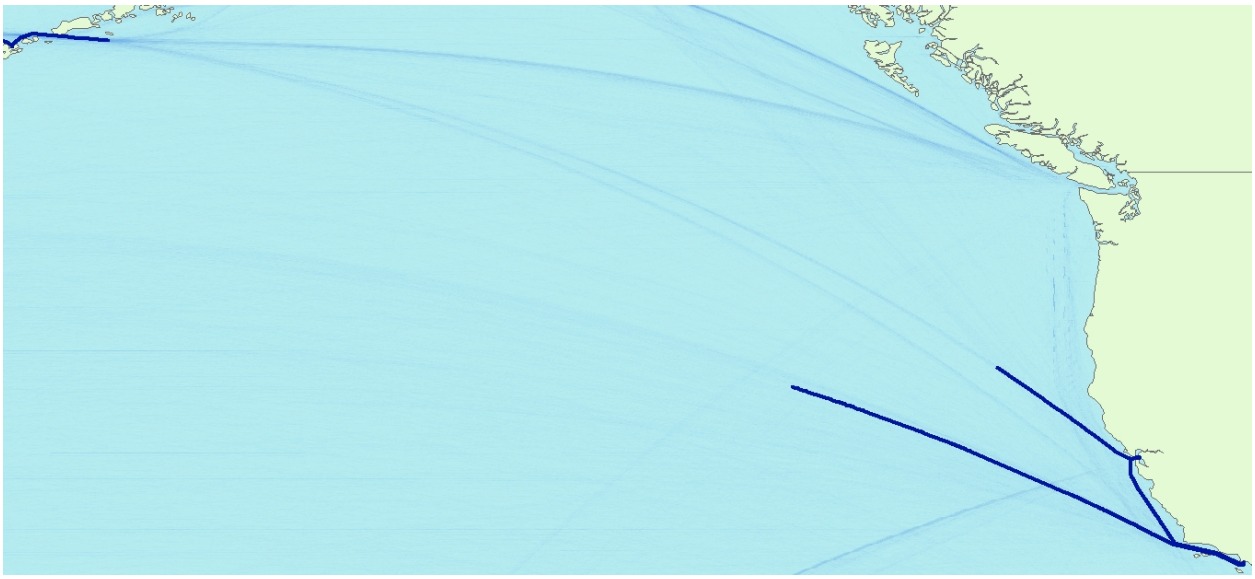


(a) So. California

(b) No. California

Notes: Distributions of pre California ECA distance traveled for entrance/exit voyages that are not matched to the Entrance/Clearance data ("no E/C") and those that are ("with E/C").

Figure A.5: Comparing Distance Distributions by Entrance/Clearance Match



Notes: Figure provides a graphical representation of our interpolation procedure for vessels traveling from Alaska and Hawaii. The thick blue lines represent observed movements for a single vessel in the AIS data. We observe this vessel moving eastward through the Unimak Pass (upper left), entering the San Francisco Bay from the north before continuing on to LA/LB. Our procedure would interpolate between these voyages if the time and distance between these voyages implied a reasonable vessel speed. The voyage from LA/LB westward into the Pacific would be included in our dataset only between LA/LB and the 100 nm study area boundary. The shaded dark blue background reports vessel traffic densities for 2008 (Halpern et al. 2015) to illustrate typical vessel patterns and show that interpolation along the Great Circle route is reasonable.

Figure A.6: Example of Interpolated Voyage

	no E/C	with E/C
Length (m)	279	268
	(38.8)	(48.4)
Main Engine Power (kW)	46,103	42,271
	(17,299)	(19,067)
Speed (km/h)	31.8	32.2
	(5.36)	(5.9)
Fuel Consumption (t/km)	.101	.0943
	(.0328)	(.035)
TEU	5,155	4,729
	(1,867)	(2,101)
US Flagged	.111	.0742
	(.314)	(.262)
N	280	984

Notes: Average vessel characteristics for pre California ECA voyages that are not matched to the Entrance/Clearance data ("no E/C") and those that are ("with E/C").

Table A.2: Vessel Characteristics by Entrance/Clearance Match

		Voyages per Month				
	Total	Pre ECA	CA, 2009	CA, 2011	CA + NA (1%)	CA + NA (0.1%)
(i) All California Ports						
Total Voyages	84,624	811	939	903	916	853
Has IMO	72,313	809	747	673	741	853
Has Vessel Chars.	72,102	786	744	673	741	853
Container	42,926	500	471	407	451	453
Port-to-Port	12,719	157	147	119	129	130
Entrance/Exit	24,338	256	257	219	253	282
Has Orig/Dest	17,930	187	192	154	177	219
(ii) Containers, Southern California Ports						
Total Voyages	21,838	258	241	196	209	256
LA/LB	21,159	254	235	193	202	244
Port-to-Port	10,277	134	119	94	100	108
to/from SF Bay	9,667	123	113	93	97	97
to/from Seattle	402	11	6.4	1.1	1.1	5.1
Entrance/Exit	11,561	124	121	102	109	148
to/from China	4,297	45	41	38	43	57
to/from Japan	1,245	18	17	12	11	12
to/from S. Korea	1,333	9.6	15	11	11	19
to/from Oceania	312	3.6	2.9	3.4	3	4.2
to/from South	3,739	41	41	30	35	48
(iii) Containers, Northern California Ports						
Total Voyages	8,811	86	98	77	97	92
Port-to-Port	2,442	23	27	25	29	22
to/from Seattle	2,309	22	25	24	27	22
Entrance/Exit	6,369	63	70	52	68	70
to/from China	1,794	21	23	13	16	19
to/from Japan	1,820	21	22	16	18	19
to/from S. Korea	1,073	8	11	9.5	12	13
to/from Oceania	450	3.6	4.8	4.3	4.6	5.4
to/from South	369	3.2	3.3	2.8	2.5	6.8
(iii) Containers, Interpolated						
Total Voyages	5,869	87	67	69	69	41
So. Cal. – Honolulu	1,383	15	15	15	15	14
So. Cal. – Unimak	775	9	9	11	9.5	5
No. Cal. – Honolulu	1,154	14	13	11	13	11
No. Cal. – Unimak	2,556	50	30	32	33	11

Notes: "Has IMO" row reports the number of voyages for which we have a valid IMO number and "Has Vessel Char." row reports number of voyages that we can obtain vessel characteristics. "Has Orig/Dest" row reports the number of entrance/exit voyages that we can match to the Entrance/Clearance dataset.

Table A.3: Voyage Counts by Route and Policy Period

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Fuel in CA ECA (t)	(4) Distance (km)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) So. Cal – Port-to-Port (n=1,053, vessels=262)							
CA ECA (2009)	-253.5***	-4.271***	-28.25***	42.53***	3.798*	-1,476***	-32.57***
	(21.74)	(0.681)	(2.661)	(5.311)	(1.931)	(411.3)	(4.926)
R-squared	0.832	0.678	0.822	0.995	0.946	0.906	0.767
Mean (t=0)	571.7	31.23	54.37	762.8	71.46	18261	261.4
% change	-44.34	-13.67	-51.97	5.576	5.314	-8.082	-12.46
CO_2 Damage (SCC=50 $/t)					600.1		
CO_2 Damage (SCC=200 $/t)					2400		
(ii) No. Cal – Port-to-Port (n=186, vessels=50)							
CA ECA (2009)	-151.2***	-4.814***	-14.39**	19.84**	-4.143	-2,421**	-14.86***
	(48.12)	(1.678)	(5.921)	(7.811)	(5.245)	(1,157)	(5.218)
R-squared	0.792	0.709	0.696	0.951	0.969	0.961	0.801
Mean (t=0)	255.8	33.24	18.45	1299	102.5	19917	196.1
% change	-59.10	-14.48	-77.99	1.527	-4.044	-12.15	-7.578
CO_2 Damage (SCC=50 $/t)					-654.6		
CO_2 Damage (SCC=200 $/t)					-2618		
(iii) So. Cal – Ent/Exit West (n=526, vessels=156)							
CA ECA (2009)	-85.05***	-3.372***	-9.446***	17.31	4.503	-606.8	-20.74***
	(18.39)	(1.225)	(2.494)	(11.22)	(2.750)	(528.3)	(5.068)
R-squared	0.864	0.738	0.837	0.976	0.948	0.944	0.691
Mean (t=0)	263.1	27.25	23.05	571.2	57.44	10446	181.2
% change	-32.33	-12.37	-40.99	3.031	7.839	-5.809	-11.45
(iv) So. Cal – Ent/Exit South (n=388, vessels=83)							
CA ECA (2009)	-8.827*	0.555	-0.141	4.208*	0.465	472.8	16.51
	(4.439)	(1.369)	(0.683)	(2.495)	(0.725)	(403.1)	(13.90)
R-squared	0.899	0.415	0.800	0.967	0.918	0.706	0.539
Mean (t=0)	108.4	21.86	5.331	243.3	15.93	3438	217.6
% change	-8.145	2.539	-2.643	1.730	2.919	13.75	7.585
(v) No. Cal – Ent/Exit (n=472, vessels=145)							
CA ECA (2009)	-7.956	-3.170***	-1.800**	1.898	-0.540	-515.3	-10.67
	(7.595)	(0.699)	(0.850)	(16.36)	(2.288)	(562.3)	(8.864)
R-squared	0.686	0.710	0.782	0.875	0.874	0.896	0.685
Mean (t=0)	117.2	34.74	10.31	351.5	36.26	11150	312.6
% change	-6.786	-9.124	-17.46	0.540	-1.489	-4.622	-3.415

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel by route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. We drop infrequently traveled routes, which we define as routes with less than 5 voyages both pre and post cutoff.

Table A.4: Impact of California ECA on Correlated Pollutants by Route

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Fuel in CA ECA (t)	(4) Distance (km)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) So. Cal – Port-to-Port (n=914, vessels=197)							
CA ECA (2011)	-29.46***	-0.887**	-3.957***	-4.037	0.242	778.2**	11.30***
	(6.234)	(0.423)	(0.865)	(4.469)	(2.053)	(351.8)	(3.337)
R-squared	0.726	0.502	0.733	0.584	0.785	0.797	0.625
Mean (t=0)	374.3	28.02	28.41	759.2	68.42	14328	215.6
% change	-7.869	-3.167	-13.93	-0.532	0.353	5.431	5.242
CO_2 Damage (SCC=50 $/t)					38.16		
CO_2 Damage (SCC=200 $/t)					152.7		
(ii) No. Cal – Port-to-Port (n=202, vessels=52)							
CA ECA (2011)	-2.040	-0.207	0.0298	25.35*	-4.084	-1,069	-8.303***
	(5.426)	(1.052)	(0.821)	(14.77)	(6.479)	(1,160)	(2.987)
R-squared	0.811	0.667	0.804	0.933	0.926	0.918	0.857
Mean (t=0)	117.3	28.23	7.725	1307	127.5	22607	182.7
% change	-1.739	-0.732	0.386	1.939	-3.203	-4.730	-4.545
CO_2 Damage (SCC=50 $/t)					-645.2		
CO_2 Damage (SCC=200 $/t)					-2581		
(iii) So. Cal – Ent/Exit West (n=642, vessels=154)							
CA ECA (2011)	-19.03***	-2.808***	-4.442***	-4.489	-2.948	59.58	11.00***
	(5.394)	(0.549)	(1.002)	(8.596)	(1.900)	(328.8)	(3.922)
R-squared	0.858	0.658	0.836	0.927	0.885	0.853	0.697
Mean (t=0)	256.1	26.72	20.23	517.7	47.54	7193	158.5
% change	-7.429	-10.51	-21.96	-0.867	-6.200	0.828	6.944
(iv) So. Cal – Ent/Exit South (n=276, vessels=59)							
CA ECA (2011)	-15.79**	1.348	-0.779	-0.714	0.752	193.1	1.906
	(7.597)	(0.884)	(0.680)	(1.690)	(0.874)	(436.4)	(17.15)
R-squared	0.900	0.327	0.771	0.980	0.820	0.585	0.416
Mean (t=0)	106	19.76	5.683	243.4	15.56	3748	234.5
% change	-14.90	6.821	-13.70	-0.293	4.830	5.153	0.813
(v) No. Cal – Ent/Exit (n=434, vessels=130)							
CA ECA (2011)	-0.369	0.894	0.246	31.42**	4.942***	1,018***	-15.90*
	(3.040)	(0.662)	(0.309)	(14.66)	(1.644)	(377.9)	(8.628)
R-squared	0.663	0.707	0.824	0.829	0.842	0.864	0.609
Mean (t=0)	99.83	27.37	6.485	320.3	24.93	7598	313.7
% change	-0.369	3.268	3.789	9.808	19.83	13.40	-5.067

Notes: Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.5: Impact of California ECA Boundary Change on Correlated Pollutants

	(1) Distance in CA ECA (km)	(2) Speed in CA ECA (km/h)	(3) Fuel in CA ECA (t)	(4) Distance (km)	(5) Fuel (t)	(6) NOx+VOC Damage ($)	(7) NOx+VOC Damage ($/t)
(i) Returners (n=379, vessels=69)							
CA ECA (2011)	3.115	-1.044*	-2.516**	-35.89***	-7.142**	1,129**	38.90***
	(8.197)	(0.556)	(1.155)	(5.489)	(2.751)	(511.0)	(4.203)
R-squared	0.457	0.549	0.637	0.570	0.725	0.714	0.788
Mean (t=0)	359.7	28.23	29.46	763.5	73.82	15270	211.3
% change	0.866	-3.699	-8.542	-4.701	-9.676	7.394	18.41
$ CO_2 Damage (SCC=50 $/t)					-1129		
$ CO_2 Damage (SCC=200 $/t)					-4514		
(ii) Avoiders (n=386, vessels=81)							
CA ECA (2011)	-46.27***	-1.464**	-5.953***	18.01***	1.287	78.97	-1.201
	(7.643)	(0.607)	(1.278)	(4.417)	(3.204)	(516.6)	(2.927)
R-squared	0.752	0.480	0.794	0.591	0.822	0.824	0.568
Mean (t=0)	359.4	27.87	27.94	761	70.90	14197	205.7
% change	-12.87	-5.253	-21.30	2.367	1.815	0.556	-0.584
$ CO_2 Damage (SCC=50 $/t)					203.3		
$ CO_2 Damage (SCC=200 $/t)					813.2		

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. Bandwidth is 150 days. Sample includes container ships on the LA/LB–San Francisco Route. We restrict our sample to vessels that were not utilizing the channel prior to the boundary change, then classify vessels based on whether they use the channel or not post boundary change ("returners" and "avoiders"). We then restrict our sample further to include only vessels that were observed both pre and post policy.

Table A.6: Heterogeneity Due to Avoidance, CA ECA Boundary Change

	(1)	(2)	(3)	(4)
Dist in ECA (km)	-253.5***	-221.2***	-9.020	-6.067
	(21.74)	(41.07)	(10.05)	(12.03)
Speed in ECA (km/h)	-4.271***	-5.449***	-0.0995	-0.0291
	(0.681)	(1.335)	(0.368)	(0.423)
Fuel in ECA (t)	-28.25***	-25.52***	-0.564	-0.433
	(2.661)	(5.521)	(1.043)	(1.035)
Distance (km)	42.53***	37.83***	4.046	5.108
	(5.311)	(9.563)	(2.479)	(3.230)
Fuel (t)	3.798*	2.163	1.605	0.454
	(1.931)	(4.376)	(1.388)	(2.080)
NOx+VOC Damages ($)	-1,476***	-827.5	234.1	9.839
	(411.3)	(973.9)	(281.9)	(395.5)
Observations	1,053	516	1,118	667
Bandwidth	150	90	150	90
Vessels	262	170	235	183
Cut			+1 year	+1 year

(a) Southern California

	(1)	(2)	(3)	(4)
Dist in ECA (km)	-151.2***	-102.2	21.09	40.11
	(48.12)	(103.3)	(26.87)	(38.51)
Speed in ECA (km/h)	-4.814***	-7.545**	-0.140	-1.328
	(1.678)	(2.950)	(1.102)	(1.350)
Fuel in ECA (t)	-14.39**	-11.21	0.803	1.458
	(5.921)	(9.247)	(2.070)	(2.729)
Distance (km)	19.84**	21.45***	1.378	5.395
	(7.811)	(7.444)	(4.057)	(9.401)
Fuel (t)	-4.143	-10.32	-2.057	-6.780
	(5.245)	(9.904)	(5.551)	(5.298)
NOx+VOC Damages ($)	-2,421**	-4,173*	-698.7	-1,812
	(1,157)	(2,041)	(1,151)	(1,248)
Observations	186	80	155	93
Bandwidth	150	90	150	90
Vessels	50	30	37	30
Cut			+1 year	+1 year

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices and route specific linear time trends with different slopes on either side of the cutoff. Bandwidths row reports number of days pre and post policy that are included in estimation sample. Cut row reports how policy cutoff is shifted for placebo tests. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.7: Bandwidth and Placebo Checks for Port-to-Port Routes, Establishment of CA ECA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dist in ECA (km)	-85.05***	-67.89**	6.757	4.444	-53.45***	-60.97*	8.428	5.423
	(18.39)	(32.37)	(5.324)	(6.788)	(17.12)	(32.61)	(5.640)	(6.783)
Speed in ECA (km/h)	-3.372***	-0.894	0.273	0.295	-2.229**	-2.213	-0.0527	-0.136
	(1.225)	(1.990)	(0.563)	(0.724)	(0.992)	(1.794)	(0.534)	(0.713)
Fuel in ECA (t)	-9.446***	-6.496	0.868**	0.737	-6.756***	-9.129**	0.947**	1.067
	(2.494)	(4.374)	(0.413)	(0.604)	(2.144)	(4.260)	(0.451)	(0.730)
Distance (km)	17.31	31.15**	2.624	2.219	34.51*	-10.57	-0.289	-19.68
	(11.22)	(15.30)	(7.286)	(6.844)	(19.56)	(29.44)	(13.34)	(14.06)
Fuel (t)	4.503	10.51*	0.863	1.498	6.340**	4.042	0.728	-0.0192
	(2.750)	(5.605)	(1.839)	(2.071)	(3.098)	(5.008)	(2.444)	(2.531)
NOx+VOC Damages ($)	-606.8	1,089	571.8*	690.3	-94.84	-465.6	470.8	584.6
	(528.3)	(1,095)	(326.6)	(481.5)	(502.6)	(939.5)	(395.9)	(549.0)
Observations	526	245	628	432	604	269	658	434
Routes	Bound	Bound	Bound	Bound	E/C	E/C	E/C	E/C
Bandwidth	150	90	150	90	150	90	150	90
Vessels	156	95	155	131	177	101	157	126
Cut			+1 year	+1 year			+1 year	+1 year

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Dist in ECA (km)	-7.956	6.765	-0.366	0.0709	-12.58	-20.92**	1.760	-0.231
	(7.595)	(10.71)	(1.475)	(1.688)	(8.267)	(9.238)	(1.463)	(1.602)
Speed in ECA (km/h)	-3.170***	-0.681	1.193**	0.390	-3.257***	-0.773	1.135**	0.433
	(0.699)	(1.439)	(0.524)	(0.663)	(0.666)	(1.203)	(0.493)	(0.617)
Fuel in ECA (t)	-1.800**	0.367	0.364	0.0671	-2.152**	-2.122	0.567**	0.0828
	(0.850)	(1.692)	(0.249)	(0.289)	(0.909)	(1.310)	(0.246)	(0.277)
Distance (km)	1.898	-10.12	7.025	-14.33	26.39	-70.03**	26.32**	-10.08
	(16.36)	(25.64)	(9.267)	(11.89)	(18.79)	(30.43)	(12.06)	(12.23)
Fuel (t)	-0.540	-0.848	1.654	-2.150	2.509	-6.423	3.235**	-1.841
	(2.288)	(3.996)	(1.383)	(1.723)	(2.442)	(4.042)	(1.554)	(1.712)
NOx+VOC Damages ($)	-515.3	-630.8	359.4	-648.9	-115.7	-2,587**	859.9**	-533.8
	(562.3)	(1,081)	(357.1)	(430.4)	(629.1)	(1,050)	(402.5)	(458.9)
Observations	472	287	567	384	508	295	611	405
Routes	Bound	Bound	Bound	Bound	E/C	E/C	E/C	E/C
Bandwidth	150	90	150	90	150	90	150	90
Vessels	145	110	152	130	149	111	162	136
Cut			+1 year	+1 year			+1 year	+1 year

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices and route specific linear time trends with different slopes on either side of the cutoff. Bandwidths row reports number of days pre and post policy that are included in estimation sample. Cut row reports how policy cutoff is shifted for placebo regressions. All samples excludes southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff. Southern California sample excludes results southern entrances and exits.

Table A.8: Bandwidth and Placebo Checks for Entrance/Exit Routes, Establishment of CA ECA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-253.5***	-241.1***	-253.7***	-241.7***	-248.8***	-247.9***	-253.0***	-220.6***	-210.4***
	(21.74)	(21.79)	(21.58)	(21.72)	(21.19)	(20.97)	(21.61)	(21.31)	(21.20)
Speed in ECA (km/h)	-4.271***	-4.073***	-4.299***	-4.129***	-4.350***	-3.806***	-4.258***	-3.310***	-3.358***
	(0.681)	(0.656)	(0.703)	(0.678)	(0.663)	(0.642)	(0.677)	(0.680)	(0.661)
Fuel in ECA (t)	-28.25***	-27.57***	-28.44***	-27.82***	-29.11***	-26.19***	-28.16***	-24.89***	-24.10***
	(2.661)	(2.611)	(2.732)	(2.666)	(2.658)	(2.452)	(2.606)	(2.439)	(2.374)
Distance (km)	42.53***	41.17***	43.27***	42.04***	42.13***	43.68***	42.43***	39.91***	38.57***
	(5.311)	(5.146)	(5.494)	(5.166)	(5.097)	(4.938)	(5.290)	(4.570)	(4.464)
Fuel (t)	3.798*	1.967	3.998**	2.186	2.191	3.536**	3.786*	3.887*	1.022
	(1.931)	(1.933)	(2.016)	(1.980)	(1.961)	(1.697)	(1.933)	(2.195)	(2.670)
NOx+VOC Damages ($)	-1,476***	-1,668***	-1,464***	-1,654***	-1,755***	-1,417***	-1,470***	-1,243***	-1,778***
	(411.3)	(392.9)	(418.1)	(396.9)	(390.1)	(375.1)	(410.2)	(394.8)	(455.4)
Observations	1,053	1,053	1,053	1,053	1,053	1,053	1,053	1,053	1,147
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	262	262	262	262	262	262	262	262	349

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-151.2***	-158.5***	-150.6***	-159.3***	-159.0***	-157.6***	-151.9***	-106.7**	-98.99**
	(48.12)	(46.57)	(47.54)	(45.22)	(45.35)	(45.20)	(47.62)	(47.12)	(42.70)
Speed in ECA (km/h)	-4.814***	-4.454***	-4.753***	-4.444***	-4.430***	-4.924***	-4.754***	-4.020***	-4.135***
	(1.678)	(1.625)	(1.655)	(1.612)	(1.597)	(1.577)	(1.717)	(1.472)	(1.366)
Fuel in ECA (t)	-14.39**	-14.45**	-14.23**	-14.42**	-14.42**	-14.50**	-14.46**	-10.71**	-10.27**
	(5.921)	(5.836)	(5.868)	(5.766)	(5.763)	(5.624)	(5.902)	(5.034)	(4.483)
Distance (km)	19.84**	10.02	21.07***	10.82	10.72	23.36***	19.04**	17.71**	17.22**
	(7.811)	(8.048)	(6.606)	(7.472)	(7.429)	(8.399)	(8.227)	(8.197)	(7.812)
Fuel (t)	-4.143	-2.903	-3.919	-2.784	-2.584	-7.788	-3.759	-7.314	-6.545
	(5.245)	(4.284)	(5.220)	(4.270)	(4.218)	(4.843)	(5.383)	(5.292)	(5.306)
NOx+VOC Damages ($)	-2,421**	-2,096**	-2,387**	-2,076**	-2,058**	-2,899***	-2,351*	-2,450**	-2,399**
	(1,157)	(986.8)	(1,154)	(988.8)	(979.3)	(1,065)	(1,208)	(1,109)	(1,103)
Observations	186	186	186	186	186	186	186	186	204
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	50	50	50	50	50	50	50	50	68

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All time trends have different slopes on either side of the cutoff. Vessel controls are: year built, dead weight, length, draft, beam, main engine power and an indicator for US flagged. Main sample are those used in our main results (column (1)), which requires multiple observations of a vessel on a route. Full sample includes all observations. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.9: Specification Checks for Port-to-Port Routes, Establishment of CA ECA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-85.05***	-73.08***	-62.68***	-60.75***	-62.35***	-82.09***	-87.55***	-85.80***	-71.93***
	(18.39)	(16.61)	(20.29)	(18.16)	(18.43)	(16.07)	(17.99)	(13.02)	(11.94)
Speed in ECA (km/h)	-3.372***	-3.079***	-2.419**	-2.655***	-2.690***	-3.791***	-3.662***	-4.728***	-4.822***
	(1.225)	(1.001)	(1.171)	(1.004)	(1.003)	(1.186)	(1.177)	(1.007)	(0.775)
Fuel in ECA (t)	-9.446***	-9.139***	-7.412***	-8.131***	-8.269***	-9.562***	-9.819***	-9.983***	-9.936***
	(2.494)	(2.183)	(2.758)	(2.394)	(2.391)	(2.271)	(2.425)	(1.812)	(1.547)
Distance (km)	17.31	27.51***	15.73	28.18***	27.92***	16.99*	17.32	15.62*	11.99
	(11.22)	(10.21)	(11.00)	(10.44)	(10.44)	(9.915)	(11.41)	(8.774)	(7.847)
Fuel (t)	4.503	3.961	4.064	3.905	3.953	3.038	4.465	0.854	-1.712
	(2.750)	(2.695)	(2.596)	(2.563)	(2.544)	(2.735)	(2.756)	(2.492)	(2.082)
NOx+VOC Damages ($)	-606.8	-551.5	-448.7	-498.2	-491.3	-887.0*	-699.1	-1,241**	-1,568***
	(528.3)	(496.8)	(504.5)	(483.5)	(477.2)	(531.2)	(511.9)	(481.0)	(393.3)
Observations	526	526	526	526	526	526	526	526	770
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	156	156	156	156	156	156	156	156	295

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-7.956	-15.92***	-16.82**	-20.71***	-20.57***	-12.62*	-8.019	-15.94**	-19.59***
	(7.595)	(5.665)	(8.088)	(6.329)	(6.347)	(7.597)	(7.624)	(7.895)	(7.186)
Speed in ECA (km/h)	-3.170***	-2.383***	-2.994***	-2.346***	-2.275***	-2.848***	-3.155***	-2.471***	-1.838***
	(0.699)	(0.559)	(0.697)	(0.569)	(0.578)	(0.631)	(0.704)	(0.663)	(0.587)
Fuel in ECA (t)	-1.800**	-2.285***	-2.813***	-2.870***	-2.841***	-2.306***	-1.813**	-2.889***	-2.973***
	(0.850)	(0.621)	(0.881)	(0.686)	(0.690)	(0.806)	(0.849)	(0.901)	(0.814)
Distance (km)	1.898	-8.947	-5.813	-12.45	-12.46	-16.42	1.497	-8.739	-21.15*
	(16.36)	(12.45)	(15.78)	(12.63)	(12.61)	(13.97)	(16.36)	(13.44)	(12.19)
Fuel (t)	-0.540	-0.678	-1.449	-1.204	-1.142	-2.881	-0.577	-2.016	-2.561
	(2.288)	(1.843)	(2.139)	(1.804)	(1.811)	(1.921)	(2.285)	(1.912)	(1.727)
NOx+VOC Damages ($)	-515.3	-349.6	-878.0	-564.9	-532.9	-982.5*	-526.3	-1,001*	-1,088**
	(562.3)	(427.4)	(543.8)	(437.8)	(441.2)	(510.7)	(560.6)	(537.3)	(464.0)
Observations	472	472	472	472	472	472	472	472	624
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	145	145	145	145	145	145	145	145	250

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All time trends have different slopes on either side of the cutoff. Vessel controls are: year built, dead weight, length, draft, beam, main engine power and an indicator for US flagged. Main sample are those used in our main results (column (1)), which requires multiple observations of a vessel on a route. Full sample includes all observations. All samples exclude southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.10: Specification Checks for Entrance/Exit Routes, Establishment of CA ECA

VARIABLES	(1) Study Area	(2) 200km	(3) 250km	(4) 300km	(5) Study Area	(6) 200km	(7) 250km	(8) 300km
CA (1.5%), 2009	-606.8	-346.8	-469.9	94.95	-428.0	-215.1	-96.34	94.95
	(528.3)	(545.8)	(600.8)	(687.9)	(605.4)	(622.9)	(653.7)	(687.9)
Observations	526	519	436	351	351	351	351	351
R-squared	0.944	0.942	0.945	0.915	0.895	0.900	0.908	0.915
Sample	Full	Full	Full	Full	All Bounds	All Bounds	All Bounds	All Bounds
Vessels	156	155	136	115	115	115	115	115

(a) Southern California

VARIABLES	(1) Study Area	(2) 200km	(3) 250km	(4) 300km	(5) Study Area	(6) 200km	(7) 250km	(8) 300km
CA (1.5%), 2009	-510.2	-279.8	-353.9	118.1	-73.32	9.947	7.943	118.1
	(566.0)	(549.4)	(705.1)	(754.7)	(764.1)	(739.3)	(750.6)	(754.7)
Observations	465	434	360	283	283	283	283	283
R-squared	0.896	0.913	0.922	0.944	0.935	0.940	0.942	0.944
Sample	Full	Full	Full	Full	All Bounds	All Bounds	All Bounds	All Bounds
Vessels	144	137	122	100	100	100	100	100

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel by route fixed effects, fuel prices, and route specific linear time trends with different slopes on either side of the cutoff. Columns report estimated changes in local pollution when damages are calculated within the 100 nm study area, and 200 km, 250 km, 300 24nkm from the US west coast. Bandwidth is 150 days. Full samples include any voyage that terminates outside the designated boundary. "All Boundary" samples include only voyages that terminate outside the widest boundary. All samples excludes southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff. Southern California sample excludes southern entrances and exits.

Table A.11: Effect of Size of Study Area on Local Pollution Damage Estimates, Implementation of California ECA

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag
CA (1.5%), 2009	0.776	1,875	2.058	-0.0645	1,657	-0.0129
	(0.671)	(2,491)	(5.064)	(0.184)	(2,092)	(0.0200)
Observations	1,351	1,351	1,351	1,351	1,351	1,351
R-squared	0.058	0.079	0.101	0.083	0.093	0.023
Vessels	352	352	352	352	352	352
Mean (t=0)	1999	56968	264.3	12.73	39744	0.118
% change	0.0388	3.292	0.779	-0.507	4.170	-10.92

(a) Port-to-Port

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag
CA (1.5%), 2009	0.985	5,634**	7.426	0.139	3,023	-0.0132
	(0.631)	(2,529)	(4.787)	(0.163)	(1,855)	(0.0207)
Observations	1,840	1,840	1,840	1,840	1,840	1,840
R-squared	0.166	0.384	0.397	0.416	0.344	0.389
Vessels	433	433	433	433	433	433
Mean (t=0)	1999	53858	258.7	12.42	37717	0.117
% change	0.0493	10.46	2.870	1.119	8.014	-11.28

(b) Entrance/Exits

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. We drop infrequently traveled routes, which we define as routes with less than 5 voyages both pre and post cutoff.

Table A.12: Impacts of ECAs on Vessel Composition, Implementation of California ECA

	(1)	(2)	(3)	(4)	(5)	(6)
Dist in ECA (km)	12.68	22.39*	10.53***	9.145**	0.868	-4.798
	(12.34)	(12.33)	(3.525)	(3.721)	(6.781)	(6.170)
Speed in ECA (km/h)	0.102	1.445**	0.254	-0.218	0.0422	0.783
	(0.528)	(0.683)	(0.362)	(0.504)	(0.559)	(0.658)
Distance (km)	-3.302	-6.774	-0.774	0.462	5.371*	5.777
	(4.323)	(5.942)	(2.612)	(2.910)	(2.819)	(3.543)
Speed out of ECA (km/h)	0.549	-0.492	-0.425	-1.116	0.201	1.277
	(0.957)	(1.223)	(0.556)	(0.713)	(0.895)	(1.150)
Fuel (t)	-0.971	-1.274	-1.710	-3.979**	1.802	3.916
	(2.370)	(2.935)	(1.548)	(1.895)	(2.248)	(2.792)
NOx+VOC Damages ($)	229.2	312.6	-312.9	-640.2*	244.3	468.3
	(553.6)	(613.2)	(278.3)	(382.5)	(482.7)	(554.9)
Observations	973	596	1,070	680	1,013	614
Bandwidth	150	90	150	90	150	90
Vessels	201	167	201	184	221	183
Cut			-1 year	-1 year	+1 year	+1 year

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)
Dist in ECA (km)	21.47	61.73	8.623	6.759	2.104	8.429**
	(14.99)	(46.61)	(7.297)	(7.645)	(3.926)	(3.922)
Speed in ECA (km/h)	1.105	6.763**	0.468	0.292	2.111	2.688
	(2.888)	(3.054)	(0.728)	(0.877)	(1.465)	(1.745)
Distance (km)	-7.658	-12.08	-6.811	-10.50	2.174	2.466
	(6.876)	(7.649)	(7.461)	(11.92)	(3.295)	(5.523)
Speed out of ECA (km/h)	-2.369	-0.916	0.156	-1.270	0.824	2.192
	(1.984)	(2.166)	(0.594)	(0.940)	(1.471)	(1.842)
Fuel (t)	-6.719	6.135	0.912	-7.821	2.188	10.18
	(10.27)	(12.81)	(3.325)	(5.059)	(7.814)	(9.349)
NOx+VOC Damages ($)	-489.2	3,658	335.7	-985.1	824.4	2,663
	(2,262)	(2,266)	(551.8)	(897.1)	(1,455)	(1,676)
Observations	168	101	236	146	208	121
Bandwidth	150	90	150	90	150	90
Vessels	41	32	48	41	48	35
Cut			-1 year	-1 year	+1 year	+1 year

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices and route specific linear time trends with different slopes on either side of the cutoff. Bandwidths row reports number of days pre and post policy that are included in estimation sample. Cut row reports how policy cutoff is shifted for placebo tests. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.13: Bandwidth and Placebo Checks for Port-to-Port Routes, Establishment of NA ECA

	(1)	(2)	(3)	(4)	(5)	(6)
Dist in ECA (km)	1.585	-0.259	4.346*	4.660*	-1.053	-1.306
	(6.351)	(8.368)	(2.252)	(2.489)	(4.361)	(5.620)
Speed in ECA (km/h)	-0.308	0.477	0.701*	-0.174	0.103	-0.484
	(0.681)	(0.960)	(0.376)	(0.452)	(0.501)	(0.641)
Distance (km)	-118.1***	-65.54***	-22.03**	20.94*	-4.911	29.02***
	(20.86)	(21.34)	(9.571)	(12.33)	(10.78)	(10.23)
Speed out of ECA (km/h)	-1.476*	-1.686	-0.292	-0.861	-0.00314	-0.480
	(0.819)	(1.133)	(0.604)	(0.692)	(0.648)	(0.820)
Fuel (t)	-16.32***	-11.15***	-3.553**	-0.314	-1.356	1.524
	(3.042)	(3.472)	(1.453)	(1.878)	(1.932)	(1.599)
NOx+VOC Damages ($)	-1,781***	-1,277**	-462.2**	86.23	-165.4	389.6
	(430.9)	(514.5)	(190.7)	(233.2)	(265.5)	(258.3)
Observations	720	479	787	526	757	477
Routes	E/C	E/C	E/C	E/C	E/C	E/C
Bandwidth	150	90	150	90	150	90
Vessels	149	129	162	140	178	134
Cut			-1 year	-1 year	+1 year	+1 year

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)
Dist in ECA (km)	0.182	-1.447	-0.849	-0.185	-1.206	1.504
	(2.552)	(2.276)	(1.040)	(1.485)	(3.914)	(4.104)
Speed in ECA (km/h)	-0.529	-0.547	-0.0698	0.261	0.146	-1.327*
	(0.946)	(1.108)	(0.465)	(0.484)	(0.583)	(0.781)
Distance (km)	-47.03**	-48.20*	-21.83**	8.846	-21.79	17.55
	(20.49)	(26.78)	(8.501)	(8.558)	(13.36)	(13.18)
Speed out of ECA (km/h)	-1.455	-1.925*	0.188	0.258	0.272	-0.114
	(1.007)	(1.138)	(0.551)	(0.585)	(0.609)	(0.787)
Fuel (t)	-7.141***	-8.065***	-1.838	1.137	-1.423	2.315
	(2.115)	(2.835)	(1.156)	(0.993)	(1.434)	(1.655)
NOx+VOC Damages ($)	-1,321**	-1,297	-504.7	191.1	-288.1	108.8
	(589.9)	(788.6)	(314.3)	(273.6)	(363.7)	(447.4)
Observations	501	354	553	380	607	344
Routes	E/C	E/C	E/C	E/C	E/C	E/C
Bandwidth	150	90	150	90	150	90
Vessels	139	119	124	115	164	116
Cut			-1 year	-1 year	+1 year	+1 year

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel-by-route fixed effects, fuel prices and route specific linear time trends with different slopes on either side of the cutoff. Bandwidths row reports number of days pre and post policy that are included in estimation sample. Cut row reports how policy cutoff is shifted for placebo tests. All samples exclude southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.14: Bandwidth and Placebo Checks for Entrance/Exit Routes, Establishment of NA ECA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	12.68	11.09	12.68	11.09	-0.230	5.316	12.58	7.954	6.180
	(12.34)	(13.01)	(12.34)	(13.01)	(3.180)	(7.368)	(12.33)	(7.143)	(7.193)
Speed in ECA (km/h)	0.102	0.581	0.102	0.581	0.0129	-0.571	0.0824	-0.656	-0.796*
	(0.528)	(0.493)	(0.528)	(0.493)	(0.237)	(0.412)	(0.525)	(0.460)	(0.460)
Distance (km)	-3.302	-6.449	-3.302	-6.449	-1.988	-4.924	-3.253	-5.021	-4.441
	(4.323)	(4.042)	(4.323)	(4.042)	(1.749)	(3.014)	(4.324)	(3.702)	(3.684)
Speed out of ECA (km/h)	0.549	0.454	0.549	0.454	-0.258	-0.889	0.534	-1.173*	-1.239*
	(0.957)	(0.841)	(0.957)	(0.841)	(0.383)	(0.636)	(0.958)	(0.646)	(0.640)
Fuel (t)	-0.971	-0.948	-0.971	-0.948	-1.164	-3.889**	-1.028	-4.170**	-4.226**
	(2.370)	(2.194)	(2.370)	(2.194)	(0.851)	(1.527)	(2.378)	(1.728)	(1.704)
NOx+VOC Damages ($)	229.2	-21.43	229.2	-21.43	-12.50	-566.4*	219.4	-525.2	-569.0
	(553.6)	(490.8)	(553.6)	(490.8)	(193.7)	(332.9)	(557.7)	(372.6)	(366.9)
Observations	973	973	973	973	973	973	973	973	1,000
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	201	201	201	201	201	201	201	201	228

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	21.47	45.08	21.47	45.08	-11.48*	39.08	17.29	54.85	54.67
	(14.99)	(39.53)	(14.99)	(39.53)	(6.659)	(38.09)	(15.92)	(43.14)	(42.29)
Speed in ECA (km/h)	1.105	1.062	1.105	1.062	-0.369	-0.519	0.742	0.352	0.249
	(2.888)	(2.458)	(2.888)	(2.458)	(0.693)	(1.347)	(2.564)	(1.295)	(1.280)
Distance (km)	-7.658	-3.281	-7.658	-3.281	-3.098	-2.423	-7.360	-2.641	1.511
	(6.876)	(5.638)	(6.876)	(5.638)	(2.344)	(4.115)	(6.694)	(5.541)	(7.286)
Speed out of ECA (km/h)	-2.369	-1.013	-2.369	-1.013	-1.901***	-2.120**	-2.612	-1.735*	-1.704*
	(1.984)	(1.822)	(1.984)	(1.822)	(0.673)	(0.905)	(1.984)	(0.967)	(0.951)
Fuel (t)	-6.719	3.590	-6.719	3.590	-7.868*	-7.059	-7.508	-8.280	-8.702*
	(10.27)	(9.501)	(10.27)	(9.501)	(3.919)	(4.724)	(9.836)	(5.097)	(5.101)
NOx+VOC Damages ($)	-489.2	814.1	-489.2	814.1	-860.2	-881.5	-710.9	-717.6	-854.8
	(2,262)	(2,088)	(2,262)	(2,088)	(705.7)	(960.3)	(2,130)	(970.0)	(960.2)
Observations	168	168	168	168	168	168	168	168	181
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	41	41	41	41	41	41	41	41	54

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All time trends have different slopes on either side of the cutoff. Vessel controls are: year built, dead weight, length, draft, beam, main engine power and an indicator for US flagged. Main sample are those used in our main results (column (1)), which requires multiple observations of a vessel on a route. Full sample includes all observations. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.15: Specification Checks Port-to-Port Routes, Establishment of NA ECA

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-0.259	4.612	-4.029	2.552	-5.877	0.882	-0.274	-8.546	-7.999
	(8.368)	(7.425)	(8.247)	(7.379)	(4.113)	(5.548)	(8.404)	(6.995)	(6.290)
Speed in ECA (km/h)	0.477	0.355	0.178	0.325	-0.458	0.546	0.439	0.712	0.738
	(0.960)	(0.673)	(0.946)	(0.673)	(0.348)	(0.523)	(0.959)	(0.571)	(0.521)
Distance (km)	-65.54***	-55.92***	-67.74***	-54.76***	-88.73***	-64.44***	-66.24***	-71.20***	-66.31***
	(21.34)	(17.83)	(23.04)	(18.59)	(11.45)	(13.68)	(20.89)	(13.83)	(13.31)
Speed out of ECA (km/h)	-1.686	-0.213	-1.696	-0.211	-0.868*	-0.183	-1.677	-0.471	-0.131
	(1.133)	(0.958)	(1.107)	(0.945)	(0.458)	(0.569)	(1.132)	(0.658)	(0.611)
Fuel (t)	-11.15***	-6.421**	-11.80***	-6.216**	-11.10***	-5.653***	-11.14***	-7.013***	-5.767***
	(3.472)	(2.794)	(3.657)	(2.873)	(1.795)	(1.759)	(3.489)	(2.008)	(1.954)
NOx+VOC Damages ($)	-1,277**	-634.0*	-1,362**	-616.4*	-1,343***	-723.3***	-1,295**	-993.1***	-805.0**
	(514.5)	(358.0)	(557.6)	(372.0)	(259.5)	(270.9)	(504.2)	(353.3)	(343.7)
Observations	479	479	479	479	479	479	479	479	549
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	129	129	129	129	129	129	129	129	180

(a) Southern California

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Dist in ECA (km)	-1.447	-4.061	-1.254	-4.059	-1.420*	-4.242**	-1.470	-4.155**	-3.767**
	(2.276)	(3.018)	(2.002)	(2.930)	(0.795)	(2.071)	(2.302)	(1.811)	(1.769)
Speed in ECA (km/h)	-0.547	-0.143	-0.903	-0.121	0.227	0.594	-0.569	-0.0610	0.139
	(1.108)	(0.952)	(1.173)	(0.904)	(0.460)	(0.586)	(1.099)	(0.658)	(0.642)
Distance (km)	-48.20*	-58.44**	-48.38*	-58.13**	-17.84**	-48.39***	-47.61*	-58.24***	-48.29***
	(26.78)	(22.94)	(26.00)	(23.11)	(8.434)	(13.15)	(26.67)	(11.55)	(11.20)
Speed out of ECA (km/h)	-1.925*	-0.950	-1.683	-0.969	-0.667*	0.00716	-1.969*	-1.008	-0.744
	(1.138)	(1.046)	(1.228)	(1.031)	(0.379)	(0.636)	(1.130)	(0.710)	(0.668)
Fuel (t)	-8.065***	-7.337***	-7.793***	-7.310***	-2.598***	-4.229***	-8.024***	-6.524***	-4.915***
	(2.835)	(2.540)	(2.786)	(2.532)	(0.911)	(1.478)	(2.823)	(1.511)	(1.443)
NOx+VOC Damages ($)	-1,297	-845.3	-1,290	-854.0	-407.7*	-227.0	-1,289	-1,161**	-882.2*
	(788.6)	(701.7)	(786.8)	(689.1)	(244.7)	(389.9)	(785.7)	(500.4)	(462.1)
Observations	354	354	354	354	354	354	354	354	408
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y	Y		
Route FE								Y	Y
Vessel Controls								Y	Y
Trends	Route	Route	Common	Common	None	Route	Route	Route	Route
Trend Break	Y	N	Y	N		Y	Y	Y	Y
Fuel Prices	Y	Y	Y	Y	Y		Y	Y	Y
Weekend							Y		
Sample	Main	Main	Main	Main	Main	Main	Main	Main	Full
Vessels	119	119	119	119	119	119	119	119	163

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All time trends have different slopes on either side of the cutoff. Vessel controls are: year built, dead weight, length, draft, beam, main engine power and an indicator for US flagged. Main sample are those used in our main results (column (1)), which requires multiple observations of a vessel on a route. Full sample includes all observations. All samples exclude southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.16: Specification Checks Entrance/Exit Routes, Establishment of NA ECA

	(1) Study Area	(2) 200km	(3) 250km	(4) 300km	(5) Study Area	(6) 200km	(7) 250km	(8) 300km
NOx+VOC Damage	-1,258**	-1,384**	-1,651**	-1,758**	-1,107**	-1,197**	-1,522**	-1,758**
	(515.9)	(542.4)	(643.3)	(720.0)	(489.5)	(525.9)	(633.3)	(720.0)
Observations	485	481	457	431	431	431	431	431
R-squared	0.820	0.813	0.813	0.834	0.840	0.836	0.834	0.834
Sample	Full	Full	Full	Full	All Bounds	All Bounds	All Bounds	All Bounds
Vessels	129	129	125	123	123	123	123	123

(a) Southern California

VARIABLES	(1) Study Area	(2) 200km	(3) 250km	(4) 300km	(5) Study Area	(6) 200km	(7) 250km	(8) 300km
NOx+VOC Damage	-1,297	-1,078	-1,329	-1,290	-1,196	-1,170	-1,267	-1,290
	(788.6)	(822.3)	(960.2)	(1,106)	(1,062)	(1,042)	(1,079)	(1,106)
Observations	354	323	289	253	253	253	253	253
R-squared	0.872	0.880	0.889	0.902	0.891	0.895	0.900	0.902
Sample	Full	Full	Full	Full	All Bounds	All Bounds	All Bounds	All Bounds
Vessels	119	112	103	95	95	95	95	95

(b) Northern California

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include vessel by route fixed effects, fuel prices, and route specific linear time trends with different slopes on either side of the cutoff. Columns report estimated changes in local pollution when damages are calculated within the 100 nm study area, and 200 km, 250 km, 300 km from the U.S. west coast. Bandwidth is 90 days. Full samples include any voyage that terminates outside the designated boundary. All Bounds samples include only voyages that terminate outside the widest boundary. All samples exclude southern routes. We drop infrequently traveled routes, which we define as observing 5 voyages both pre and post cutoff.

Table A.17: Impact of Size of Study Area on Local Pollution Damage Estimates, Establishment of NA ECA

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag
CA(1%) NA(1%)	0.0431	3,087	3.385	0.129	2,374	-0.0252
	(1.195)	(3,877)	(6.435)	(0.216)	(2,670)	(0.0410)
Observations	1,181	1,181	1,181	1,181	1,181	1,181
R-squared	0.016	0.012	0.003	0.010	0.023	0.003
Vessels	229	229	229	229	229	229
Mean (t=0)	2003	68522	286.5	13.32	47682	0.0913
% change	0.00215	4.505	1.181	0.965	4.980	-27.56

(a) Port-to-Port

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag
CA(1%) NA(1%)	-0.436	-121.3	1.996	0.00900	-1.574	-0.0189
	(0.799)	(3,247)	(5.328)	(0.204)	(2,161)	(0.0239)
Observations	1,199	1,199	1,199	1,199	1,199	1,199
R-squared	0.501	0.649	0.626	0.579	0.647	0.672
Vessels	255	255	255	255	255	255
Mean (t=0)	2003	66707	280.3	13.10	47369	0.0805
% change	-0.0218	-0.182	0.712	0.0687	-0.00332	-23.44

(b) Entrance/Exits

Notes: Standard errors in parentheses are clustered by vessel. *** p<0.01, ** p<0.05, * p<0.1. All regressions include route fixed effects, fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. We drop infrequently traveled routes, which we define as routes with less than 5 voyages both pre and post cutoff.

Table A.18: Impacts of ECAs on Vessel Composition, Implementation of North American ECA