Local Standards, Behavioral Adjustments, and Welfare: Evaluating California's Ocean-Going Vessel Fuel Rule

Richard Klotz Julia Berazneva

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Abstract

We examine how adjustments along unregulated margins affect welfare outcomes of a local fuel standard established by California's Ocean-Going Vessel Fuel Rule, which targets particulate matter pollution from maritime transport by requiring the use of low-sulfur fuel in California's coastal waters. Using sharp within-route temporal discontinuities in voyage-level data on vessel movements we show that vessels respond to the higher fuel prices imposed by the standard by shifting activity to unregulated waters and reducing speeds in the regulated area. We combine the data on vessel movements with simple physical relationships and location-specific marginal damages to quantify the welfare consequences of these adjustments. We find that behavioral adjustments erode roughly $4.8 million per month in emission benefits but lower compliance costs by $2 million per month, both of which are sizable fractions of the aggregate net benefits of the policy.

Keywords: local environmental policy, behavioral adjustments, local air pollution, emission control areas.

JEL codes: D62, L51, Q51, Q52, Q53, Q58, R41.

Klotz: Department of Economics, Colgate University (rklotz@colgate.edu). Berazneva: Department of Economics, Middlebury College (jberazneva@middlebury.edu). This paper has benefited from comments on earlier drafts by Peter H. Matthews, Matthew Gibson, Corey Lang, seminar participants at Colgate University, Middlebury College, Penn State University, AERE Summer Conference, AAEA Annual Meetings, Colorado University Environmental and Resource Economics Workshop, and Heartland Environmental and Resource Economics Workshop.

Economic theory generally favors policy instruments that directly target externalities (Green and Sheshinski 1976). In practice, however, regulators must often choose from policies that indirectly target externalities by regulating a related margin or outcome. Many studies have shown that a weakness of such policies is that regulated agents can adjust behavior on unregulated margins, e.g., substituting inputs or changing input intensity (Davis (2008) or West et al. (2017)) or adjusting location (Henderson (1996) or Levinson (1996)), in ways that affect welfare outcomes (Ito and Sallee 2018). Yet, how behavioral adjustments on unregulated margins affect net benefits is not always clear. The flexibility to reduce exposure to the policy allows regulated agents to decrease compliance costs, but behavioral adjustments may also alter realized benefits. Focusing solely on costs or benefits may, therefore, overstate the social importance of these behavioral responses and cloud insights into how policy can be improved. However, isolating the welfare impacts of behavioral adjustments on unregulated margins is empirically challenging because it requires establishing a credible counterfactual in which regulated agents comply with the policy but make no other behavioral changes.

Policies that indirectly target externalities are used in a variety of contexts and have long played an important role in efforts to reduce the substantial health impacts of local air pollution (e.g., fine particulate matter ($PM_{2.5}$), carbon monoxide, and ozone).[1] Examples include various emission and technology standards on fossil fuel combustion technologies, sulfur and volatile organic compound limits on onroad and nonroad fuels, subsidies and grants for lower emission technologies, and, more recently, local standards for mobile sources such as low emission zones. While a number of empirical studies have focused on how behavioral responses on unregulated margins affect the benefits or costs of policies, we know of no other study that directly estimates the welfare impacts of behavioral adjustments in the context of local air pollution policy.

In this paper, we estimate how behavioral adjustments along unregulated margins affect the welfare outcomes of an emission control area (ECA). ECAs are increasingly common environmental policies that target air pollution from maritime transport by imposing fuel and/or technology standards in designated waters. Ocean-going vessels (OGVs) – the large cargo and tanker ships engaged in maritime transport – are major contributors to local air pollution and the resulting human health impacts in coastal regions (Corbett et al. 2007; Liu et al. 2016), largely due to the high-sulfur content of the fuels that vessels consume.[2]

[1] Other indirect policies include subsidies and standards for energy efficiency or renewable energy technologies meant to reduce greenhouse gas emissions or investments in high-occupancy vehicle or toll lanes targeting traffic congestion.

[2] Between 2012 and 2020, the global sulfur limit on maritime fuels was 3.5% sulfur by weight (IMO 2020), which vastly exceeds the U.S. sulfur limit for onroad fuels of 0.0015%.

Due to relatively lax global regulation, numerous efforts at the multinational, national, and subnational levels have targeted $PM_{2.5}$ from OGVs using ECAs that impose fuel sulfur limits.

The specific ECA we study was established by California's Ocean-Going Vessel Fuel Rule in 2009 (CARB 2011). The "California ECA" covers waters within 24 nautical miles (nm) of the California coast and, thus, vessel traffic at some of the most important ports in the U.S. – Los Angeles and Long Beach (LA/LB), and the ports in the San Francisco Bay. Compliance with the ECA involves switching to lower-sulfur, but substantially more expensive, fuels when traveling within the ECA (i.e., the regulated margin).[3] Vessel operators can lower compliance costs during a voyage primarily by adjusting the course taken between ports (e.g., avoid the ECA) and speed, which are unregulated margins.[4] Any associated increase in fuel consumption outside the ECA, where vessels can continue using high-sulfur fuels, leads to an emission spillover that undercuts the environmental benefits of the sulfur limit. However, the reductions in fuel use within the ECA and the shift in emissions away from coastal populations reinforce the environmental benefits.

Our analysis uses one-minute scale data on the movements of regulated vessels off the U.S. west coast from Automatic Identification System (AIS) transponders, which are required safety equipment on the majority of OGVs. For each year in our sample, we process around 250 million AIS records into roughly 20,000 voyages (origin-destination pairs). Each voyage is represented by distance traveled, the location of travel, and a speed profile, which are the primary margins through which vessels can respond to the ECA. We also obtain predictions of voyage-level fuel costs and mortality damages associated with changes in $PM_{2.5}$ levels due to emissions of primary $PM_{2.5}$ and sulfur dioxide (SO_2) using standard physical relationships and location-specific marginal damages from integrated assessment models. We then use sharp temporal discontinuities at the establishment of the California ECA in within-route or within-vessel-by-route outcomes, which rule out potential changes in the composition of voyages across routes or vessels within routes, to estimate the policy's impacts.

We find that changes in vessel behavior in response to the ECA lead to sharp and sizable reductions in distance traveled, speed, and fuel consumption within the ECA. Container

[3] Vessels can switch fuels while traveling as most OGVs have multiple fuel tanks and are powered by simple two-stroke engines that can operate on residual and distillate fuels interchangeably. Enforcement reports indicate that compliance with the California ECA has been nearly universal (CARB 2018). The drastic changes in behavior we observe in response to the ECA provide further evidence of high levels of compliance.

[4] It is possible that the ECA induces changes in ports and transport modes used and the composition of the vessel fleet. Our focus, however, is on within-voyage changes in behavior, which appear to be the primary behavioral adjustments in this context. Since ECAs only directly regulate fuel sulfur content, we treat other margins as unregulated. One can conceptualize adjustments along any margin as a channel through which a maritime regulation could lower pollution damages. However, regulatory documents suggest that these margins were not intentionally targeted for the California ECA.

ships, which contribute roughly 80% of pre policy fuel use within the ECA, cut distance traveled in the ECA by 24-44% and speeds by 8-13%. These adjustments lead to reductions in predicted fuel use of 52% on routes between California and other west coast ports and by 36% on routes to/from more distant ports. Fuel use outside the ECA tends to increase by more than the reductions within the ECA because vessels compensate for the within-ECA adjustments by traveling greater distances and, in some cases, speeding up outside the ECA.

In order to isolate how these behavioral adjustments alter the costs and benefits of the ECA, we estimate changes in predicted fuel cost and pollution damage outcomes under the assumption that OGVs use the higher-cost low-sulfur fuel within the ECA both pre and post policy. In this analysis, the pre policy values provide a counterfactual in which vessels comply with the fuel standard but make no other behavioral adjustments, so that the estimated changes reflect only behavioral responses. We find that behavioral adjustments by container ships cut away \$3,600-\$17,000 (10-25%) per voyage of the potential reductions in air pollution damages due to the ECA, largely due to a considerable pollution spillover. The impacts of behavior on pollution damages are modest relative to the impacts on emission levels because some fuel consumption shifts to lower marginal damage areas. But, these same adjustments generate fuel cost savings of \$1,800-\$5,000 per voyage. While behavioral adjustments are clearly welfare reducing – for every \$1 reduction in compliance costs due to behavioral adjustments, pollution damages increase by \$2.6 – we emphasize the relative magnitude of the fuel cost savings. Focusing solely on pollution damages would overstate the social importance of behavioral adjustments along unregulated margins by 40%. Behavioral adjustments by other cargo and tanker vessels have a small impact on realized net benefits because preexisting traffic patterns limit avoidance possibilities.

Heterogeneity across routes reveals that avoidance opportunities drive large differences in the impacts of behavior on welfare. For container ships, avoidance opportunities are greater on more exposed routes (in terms of distance within the ECA pre policy). For container ships the ratio of increased damages to fuel cost savings on the most exposed routes exceed 3, while these ratios are closer to 1 on the less exposed routes. Speed responses, which are more evident for container ships than other vessel types, play a smaller role in determining welfare outcomes of the ECA. The systematic speed reductions within the ECA generate fuel cost savings, but have a limited impact on pollution damages as these adjustments occur when vessels use low-sulfur fuel. Substantial differences in outcomes for vessels that avoid the ECA versus those that do not on the LA/LB–San Francisco Bay route further emphasize the importance of avoidance in determining welfare outcomes of the ECA.

Aggregating across all routes and vessel types, and assuming our estimates of the impacts of behavioral responses extend for several years, we show that behavioral adjustments eliminate about $77 million of the roughly $1 billion in potential net benefits – reductions in pollution damage less fuel cost increases – during the 29 months the original California ECA boundary was in place. While these estimates do not capture all possible costs/benefits associated with behavioral changes induced by the ECA, we find that the magnitude of some other channels — increased travel time, changes in correlated pollutants, and port/mode shifts — are likely to be small relative to the air pollution benefits.[5]

This paper makes two primary contributions to the economics literature on environmental policy. First, we isolate how behavioral adjustments along multiple unregulated margins can reinforce or undercut the realized costs and benefits of an ECA. In doing so, our work contributes to a broad and long-standing literature evaluating the behavioral responses to indirect environmental regulations.[6] Like most studies attempting to quantify the welfare impacts of behavioral adjustments, we face tradeoffs between our ability to isolate the impacts of changes in behavior, the assumptions required, and data availability. Structural approaches (e.g., Fowlie (2009)) can directly link behavior changes to welfare outcomes, often with limited data requirements, but require potentially strong assumptions to predict regulated agent behavior. Empirical studies that exploit data on final outcomes (e.g., Davis (2008), Auffhammer and Kellogg (2011)) can deduce the impact of behavior from changes, or variation in changes, in these final outcomes, without strong assumptions regarding behavior but do not necessarily provide precise measures of the welfare implications. Empirical studies that obtain data on behavior typically estimate changes along unregulated margins and then map these changes into final outcomes using supplemental back-of-the-envelope calculations (e.g., Ito and Sallee (2018)). We also have data on behavior, but obtain transparent estimates of the welfare implications of behavioral adjustments by predicting final outcomes from this data using standard physical relationships and spatially explicit integrated assessment models. In our context, the advantages of this approach are that, without making strong assumptions regarding the behavior of regulated agents, it can account for adjustments along multiple margins – including spatial adjustments – that are potentially non-linearly related, it cleanly establishes the appropriate counterfactual, and it yields direct measures of the impacts of behavioral adjustments.

By isolating the impacts of behavioral adjustments on both compliance costs and environmental benefits we point to welfare-improving modifications to the California ECA.

[5]In a companion paper (Klotz and Berazneva 2020), we analyze the impacts of ECAs on correlated pollutants and find modest increases in CO_2 damages and offsetting reductions in damages from correlated local pollutants.

[6]The consequences of behavioral responses to environmental regulations have been studied in a wide variety of contexts. Examples include climate policy (Fell and Maniloff 2018), fuel economy standards (Jacobsen and van Benthem 2015; West et al. 2017; Ito and Sallee 2018), promotions for the adoption of green technology (Bento et al. 2014), and road pricing (Gibson and Carnovale 2015).

Our results imply that alternative policies aimed at reducing avoidance (e.g., reimbursements for low-sulfur fuels) could increase the net benefits of the ECA, especially if targeted at particular routes and vessel types. We also find that changes to the ECA boundary in 2011, which raised the cost of avoidance by expanding the ECA in southern California and encouraged travel through the Santa Barbara Channel, induced behavioral adjustments that reinforced the potential net benefits of the boundary change for some routes.

Second, we show that avoidance can undercut the net benefits of a local standard and that the extent of avoidance and its consequences depend on geography. Economists have long studied spatial adjustments to environmental policies, including those in the transportation sector (e.g., Gibson and Carnovale (2015)). Evidence for policies targeting mobile sources of local air pollution, like ECAs, is relatively limited. Two examples are Wolff (2014) and Gehrsitz (2017) who study low emission zones, which restrict high-polluting vehicles from entering designated areas of cities, and find limited pollution spillovers to unregulated areas. We find that behavioral responses to the California ECA greatly erode the reductions in emissions generated by the policy, but that the associated damages are modest since the emission increases occur in relatively low marginal damage areas. Our results suggest that the design of local standards should be at least partially based on the distribution of marginal damages and avoidance opportunities.

Another contribution of this work is to provide the first systematic evaluation of changes in OGV behavior in response to an ECA.[7] This aspect of our paper contributes to a growing economics literature on vessel behavior (Brancaccio et al. 2019; Molina and McDonald 2019). Evaluating how OGVs respond to environmental regulations is an important exercise as regulators continue to target pollution from maritime transport.[8] Most previous studies of the costs and benefits of maritime environmental policy have relied on engineering or inventory approaches (Winebrake et al. 2009; Sofiev et al. 2018) that cannot separate the impact of the policy from other background trends and may not capture, what we find to be, important consequences of changes in vessel behavior.

The paper proceeds as follows. In Section 1 we present details on the maritime transportation sector and ECAs. We then describe the construction of our data set in Section 2 and show graphical evidence in support of our analysis in Section 3. We describe our empirical strategy in Section 4 and results in Section 5. Section 6 discusses policy

[7]Earlier work has provided graphical evidence of changes in vessel traffic (Moore et al. 2018) or analyzed a single behavioral adjustment (Adland et al. 2017). We quantify a range of behavioral adjustments focusing on within-route variation induced by the ECA.

[8]ECAs with sulfur limits have been established in the North and Baltic Seas, along the North American and Chinese coasts, and off the California coast, and have been proposed for Australia, Norway, Japan, and the Mediterranean Sea. In 2020, the global sulfur limit for maritime fuel was lowered from 3.5% to 0.5% (IMO 2020).

implications and concludes.

1 Background and Policy Context

Maritime transport is a critical component of the global economy, carrying more than four-fifths of world merchandise by volume (UNCTAD 2017). Due to the sector's reliance on petroleum fuels, it is, however, a major source of particulate matter that negatively impacts air quality and public health in coastal regions (Corbett et al. 2007). Some estimates suggest that, globally, emissions from ships lead to 400,000 premature deaths from lung cancer and cardiovascular disease and about 14 million cases of childhood asthma annually (Sofiev et al. 2018). The majority of these health impacts are due to $PM_{2.5}$ (Liu et al. 2016).

A large fraction of the $PM_{2.5}$ generated by OGVs is related to the sulfur content of the fuels that vessels use. Residual fuel oils, which are the heavier fractions of crude oil that remain after the extraction of gasoline and distillate fuels in the refining process, are the highest sulfur options. Between 2012 and 2020, residual fuel oil has had a maximum sulfur content of 3.5%, but averaged 2.5% globally (IMO 2015). On the other end of the spectrum there are distillate fuel oils. Although common designations are required to contain less than 1.5% sulfur, sulfur levels for distillate fuel oils are closer to 0.1% in practice (CARB 2008).

Most large OGVs are powered by simple two-stroke engines that can burn residual and distillate fuels interchangeably. Switching between fuels is a delicate, but relatively straightforward, procedure. Since most vessels have multiple fuel tanks, they are able to switch fuels while on route (American Bureau of Shipping 2010). However, distillate fuels are far more expensive than residual fuels. Between 2009 and 2012, the price of distillate fuel oil greatly exceeded the price of residual fuel (see Figure A.1 in Appendix). As fuel costs are a significant portion (20-60%) of the total operating costs (Stopford 2003), vessel operators opt for the higher-sulfur residual fuels when possible.

The global vessel fleet can be broadly broken down into three types: container ships, other cargo ships, and tankers. Container ships carry high-value containerized cargo and generally provide liner service, or regularly scheduled service between ports. Other cargo vessels and tankers mainly carry large consignments of a single raw material (e.g., iron ore, coal, grain, crude oil) and travel on flexible routes or even one-off voyages (Stopford 2003). As a result, container ships are much more likely to appear repeatedly on the same route than other cargo vessels and tankers. Due to the nature of goods transported and service provided, container ships are larger, more powerful, travel faster, and consume more fuel per kilometer than other cargo ships and tankers.

1.1 California's Ocean-Going Vessel Fuel Rule

The health impacts of OGVs are an important concern in California, where the population is concentrated in coastal regions close to major ports. The Ports of Los Angeles and Long Beach in southern California form the largest seaport complex in the U.S., while the Ports of San Francisco Bay (primarily Oakland, San Francisco, and Richmond) are major trade hubs in northern California. In 2010, LA/LB and the San Francisco Bay ports accounted for 28% and 4% of the total value of U.S. maritime trade, respectively (US Census Bureau 2010). Hueneme and San Diego, which lack large-scale container capacity, are smaller ports in southern California.

The California ECA was established by California's Ocean-Going Vessel Fuel Rule and came into force on July 1, 2009 (CARB 2011). The OGV Fuel Rule required the vast majority of commercial vessels to use distillate fuels within the ECA boundary, which extends 24 nm off the California coast (Figure 1).[9] Partly motivated by the potential for avoidance to erode environmental benefits, the ECA boundary in southern California was modified in December of 2011. The changes aligned the boundary more closely with the state's "contiguous zone," which covers 24 nm from the shorelines of the Channel Islands, and modified the western entrance to the Santa Barbara Channel to encourage travel within the ECA.

As of 2020, the fuel sulfur requirements of the OGV Fuel Rule are still in effect, despite the establishment in August 2012 of the North American ECA, which extends 200 nm off the U.S. and Canadian coasts. California continues to enforce the OGV Fuel Rule because, unlike the North American ECA, it does not allow compliance through the use of exhaust gas cleaning devices ("scrubbers") and requires the use of distillate fuel.

The ECA is enforced by the California Air Resources Board (CARB), with inspectors boarding vessels at California ports to collect fuel samples and to review records and fuel switching procedures. Fines for failing to switch to compliant fuels start at $45,500 per port visit plus a $10,000 administrative penalty, while other minor violations, such as failing to complete fuel switching prior to entering regulated waters, have lower penalties. Vessel operators, by and large, have complied with the sulfur limits. CARB enforcement reports show that between 2009 and 2017 there was an average of 620 inspections per

[9] A small number of steam-turbine powered vessels, which are unable to operate on distillate fuels, and smaller vessels are exempt from the fuel sulfur limit. For vessels subject to the regulation, the sulfur limit applies to fuels used in main and auxiliary engines and auxiliary boilers. Compliance through the use of exhaust gas cleaning devices ("scrubbers") is not allowed. When the ECA was established, vessels were required to use marine gas oil (MGO) with a maximum of 1.5% sulfur or marine diesel oil (MDO) with a maximum of 0.5% sulfur. The sulfur limits were occasionally tightened so that by January 2014 the maximum sulfur content was 0.1%. The sulfur content of available distillate fuels was far below the stated limits. Since 2007, the global average sulfur content of MGO/MDO was 0.15% or below (IMO 2015) and even in 2007 MGO and MDO with sulfur content below 0.1% was available in many Pacific Rim Ports (CARB 2008).

year and a noncompliance rate, including minor violations, was around 5% (CARB 2018). The non-compliance rate was similarly low in the six months immediately following the implementation of the ECA (CARB 2018).

2 Data

The core data for our analysis is a detailed data set of vessel movements from Automatic Identification System transponders. AIS transponders are required navigation safety devices that transmit the location, speed, and course of a vessel to other nearby vessels. The U.S. Coast Guard collects AIS signals through a network of on-shore receivers. We obtain AIS records from 2009-2016 for the U.S. west coast, Alaska, and Hawaii from MarineCadastre.gov, which cleans the Coast Guard data and releases it at a one-minute scale (BOEM/NOAA 2017). The Coast Guard receivers are designed to collect signals within, at minimum, 50 nm of the U.S. coast, but the receivers pick up more distant signals. Since coverage tends to fall with distance away from the coast, we restrict our study area to a region extending 100 nm (185 km) off the U.S. west coast (Figure 1).

We process the AIS records, roughly 250 million per year, into voyages (origin-destination pairs) using an algorithm that assesses whether temporally consecutive AIS records are part of the same voyage. We then classify voyages to specific routes. A route is defined as a vessel movement between two ports ("port-to-port") or between a port and the study area boundary ("entrance/exit").[10] Since our study area extends well beyond the California ECA, outcomes on entrance/exit routes should capture most of the behavioral responses to the ECA. To explore potential impacts of the ECA on vessel activity outside our study area, we also construct a set of long-distance voyages between west coast ports and Alaska and Hawaii but analyze them as a robustness check, since large portions of these voyages are interpolated. Our voyage data set generally captures the vessel activity reported in the U.S. Army Corps of Engineers' Entrance/Clearance data set (see Appendix Section B.1 for more details on our AIS data procedures and validation).

We drop any voyages that cross land, have a maximum observed speed above 60 kilometers per hour (km/h), are outliers in terms of time or distance, or stop at offshore crude terminals of El Segundo and Rosarito. Unfortunately, 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). Given our empirical specification this is not ideal, but we present a range of evidence that suggests this missing data is of limited concern.[11]

[10]Ports are defined based on traffic choke points at the entrance of the ports, so they may capture traffic to many ports. For example, San Francisco Bay includes Oakland, Richmond, and other ports. Any voyage that enters/exits the Strait of Juan de Fuca, which leads to the ports of Seattle, Vancouver, and Tacoma, among others, is classified as Seattle.

[11]It is important to emphasize that these missing days are purely a data issue and not related to the Great

For vessels with valid identifiers we merge in vessel characteristics from Clarksons Research and Marine Traffic and vessel type- and class-specific auxiliary engine loads from IMO (2015) into the voyages data. Missing values in vessel characteristics are filled with iterative imputation (Appendix Section B.5). We also merge in weekday, ex-wharf (excluding taxes, duties, and wharfage fees) residual and distillate fuel prices in Los Angeles from S&P Global. Fuel prices are increasing over our study period (see Figure A.1 in Appendix). The relative price premium for distillate fuel generally remains constant, although it increases slightly following the implementation of the California ECA.

A key aspect of our data work is that we map rich data on vessel behavior into voyage-level measures of final outcomes (i.e., fuel costs and pollution damages). Our goal is to create proxies for these outcomes that reflect the key margins of adjustments we observe in the AIS data (distance, speed, and location of travel) using simple and transparent assumptions. Alternatively, this could be thought of as a means of combining multidimensional data on vessel behavior into single metrics related to final outcomes that are suitable for empirical analysis. We describe the procedures used to calculate fuel costs and damages below.

2.1 Fuel Consumption

We calculate fuel consumption by main and auxilliary engines based on the AIS data and vessel characteristics using a well-established approach in the literature (Liu et al. 2016; Molina and McDonald 2019) that is generally representative of fuel consumption (Jalkanen et al. 2012). The main engine is typically a slow-speed two-stroke engine that provides propulsion power, while auxiliary engines are medium-speed four-stroke engines that provide electrical power. Main engine fuel consumption (F) for vessel i on voyage t depends on vessel characteristics (α_i), as well as vessel speed (S) and distance traveled (D) across all segments s of a voyage according to:

$$F_{it} = \alpha_i \sum_s S_{its}^2 D_{its}. \tag{1}$$

The quadratic relationship between fuel consumption and speed captures the engine's load factor – or the fraction of total engine power required to achieve a particular speed – which is derived from the propeller law. $\alpha_i = \frac{f_i}{S_i^3}$, where f_i is fuel consumption at design speed in tons of fuel per hour and S_i is design speed. Fuel consumption by auxiliary engines is the product of hours of operation, auxiliary engine load, and a fuel oil consumption factor.

Our fuel calculations abstract from other factors (e.g., hull roughness or wave height) that can influence fuel consumption. Due to data limitations, studies comparing predicted fuel use and observed fuel use are limited. However, the existing studies that validate

Recession. Vessel counts to/from California ports in the Entrance/Clearance data trend smoothly over this period. For example, monthly entrances/exits by container vessels to California ports fall between 320 and 360 from March until December of 2009.

fuel consumption using calculations similar to ours show the error in predicted fuel use to be at most 20% across different vessel categories and time frames (Jalkanen et al. 2009, 2012; Goldsworthy and Goldsworthy 2015). These studies also suggest that much of this error is related to fuel consumption from auxiliary engines. One likely consequence of this measurement error is that our reported standard errors will be smaller than those that would be obtained with actual fuel consumption. Non-classical measurement error in the prediction of fuel consumption (e.g., if error is correlated with vessel behavior) is a possibility, but we think is of limited concern in our setting. Our results suggest that the primary driver of the welfare effects is the drastic shift in distance traveled to outside the ECA, so the implications of non-classical measurement error would have to be large to affect our results. This seems unlikely given that our fuel equation tends to predict fuel consumption with only modest error. We explore this measurement error issue further in our robustness checks.

2.2 Fuel Costs and Local Air Pollution Damages

As discussed above, we calculate fuel costs and local air pollution damages under various assumptions regarding the type of fuel used within and outside the ECA. The type of fuel consumed determines costs and emissions per unit fuel. To ease interpretation and avoid introducing potentially spurious time-series variation we value fuel at the average, tax exclusive, prices across our study window: $503 and $760 for residual and distillate fuels, respectively (in 2011 US $).

We value the mortality damages associated with $PM_{2.5}$ due to OGV emissions of primary $PM_{2.5}$ and SO_2, which contributes to secondary $PM_{2.5}$ formation.[12] Marginal damages from emissions of $PM_{2.5}$ and its precursors vary widely in space due to the chemical and physical relationships between emissions and ambient concentrations, atmospheric conditions (e.g., wind), and proximity to population centers. Therefore, we explicitly account for the location of pollution along a voyage's path when calculating total pollution damages. To do so, we first calculate emissions of $PM_{2.5}$ and SO_2 for each segment of a voyage using emission factors from IMO (2015).[13] Then we obtain damages for each segment by multiplying emissions by pollutant-specific estimates of marginal damages ($ per ton of pollutant) that depend on the segment's location. Finally, we sum damages across pollutants and segments to obtain the local pollution damages generated by each voyage.

Our main results use marginal damage estimates (in 2011 US $) for ground-level emissions

[12] We focus on mortality damages because these are the largest source of benefits from air pollution reductions (US EPA 2011). Accounting for costs associated with morbidity, expenditures on defensive behaviors, and non-health related impacts of $PM_{2.5}$ and SO_2 emissions (e.g., visibility) would likely increase the benefits of pollution reductions.

[13] We assume residual and distillate fuels have sulfur content of 2.7% and 0.1%, respectively, and use separate emission factors for main and auxiliary engines (Appendix Section B.6).

from the InMAP Source-Receptor Matrix (ISRM) integrated assessment model (Goodkind et al. 2019a). ISRM provides annual average estimates of marginal damages associated with one unit of pollution for a grid of source locations. These marginal damage estimates are calculated by combining transfer coefficients derived from the Intervention Model for Air Pollution (InMAP) – which describe how emissions at a source location affect pollution concentrations at every location in the grid, standard concentration-response functions for mortality, and estimates of the value of a statistical life.[14] The grid underlying ISRM extends roughly 400 km off the coast, which allows us to spatially join the gridded marginal damage estimates to each segment of each voyage. We also use an offshore extension of the AP2 model (Muller 2014) to value the local pollution damages as a robustness check.[15]

ISRM's marginal damages for SO_2 and $PM_{2.5}$ exhibit steep spatial gradients (Figure A.2 in Appendix). Marginal damages for both pollutants are extremely high around the population centers of Los Angeles and San Francisco, but decay rapidly with distance to these locations. In Figure A.3 in Appendix we plot how marginal damages of $PM_{2.5}$ change across the average container ship voyage from LA/LB to San Francisco. Prior to the establishment of the ECA, the first 50 km of the voyage takes place in areas where marginal damages exceed 200,000 $/t. Between 200 and 250 km into the voyage, marginal damages are below 50,000 $/t because vessels are farther off the coast and the population centers.

2.3 Summary Statistics

Table A.1 in Appendix breaks down the 48,640 voyages we observe visiting west coast ports between January 1, 2009 and August 1, 2012, when the North American ECA comes into force, across ports, routes, and vessel types. Across all vessel types, 71% of voyages are on entrance/exit routes (those between west coast ports and the study area boundary). More than 50% of all voyages connect to southern California ports of LA/LB, San Diego, and Hueneme (panel (ii)). Southern California port-to-port voyages are primarily to/from San Francisco Bay and Seattle, while entrance/exit voyages are split between southern (towards the Panama Canal) and western (towards other Pacific Rim Ports) routes. The primary routes to/from northern California are to/from Seattle and western entrances/exits.

Comparing across vessel types, the vast majority of the voyages are by container or other cargo ships, while tankers comprise a smaller share. Container ships are much more likely to move between the largest U.S. ports because they provide liner service and require container

[14] ISRM captures the transport of pollution at a fine spatial resolution, especially near populated areas, showing important local spatial gradients in marginal damages (Goodkind et al. 2019b).

[15] The extension of AP2 extrapolates AP2's county-to-county area-source transfer coefficients to offshore locations using a regression of the transfer coefficients on the distance and bearing of a source to each county. We use ISRM in our main results because it does not involve extrapolation, which may average out important spatial heterogeneity.

handling capacity. Other vessel types that are more likely to make a single stop at a west coast port and to call at smaller ports (e.g., San Diego).

Figure 2 shows monthly fuel consumption within the ECA original boundary by vessel type. Excluding the months affected by the trade collapse in early 2009 caused by the Great Recession, total fuel consumption within the ECA is just over 15,000 metric tons (tons) per month prior to the establishment of the ECA.[16] Container ships, which make up about 50% of voyages to California ports, are responsible for a disproportional share (well over 80%) of fuel use within the ECA, mainly due to the differences in traffic patterns and fuel economy.[17]

Within-ECA fuel consumption by container ships falls drastically (roughly 50%) the month the ECA is established, indicating that container ships undertake considerable behavioral adjustments in response to the ECA. Fuel use continues to decline for around six months after the establishment of the ECA, although this is partially due to seasonality. Changes in within-ECA fuel use are less pronounced for other cargo vessels and tankers.

3 Graphical Evidence

In order to further demonstrate the detail of our data, motivate our empirical strategy, and provide intuition for our results, we present a range of graphical evidence that shows dramatic changes in vessel behavior when the ECA comes into place. We focus on container ships, which are the biggest contributors to within-ECA fuel consumption.

3.1 Avoidance of the ECA

Avoidance is clearly evident in maps of voyages. Each map in Figure 3 displays container ship voyages on a particular route (rows) prior to the ECA establishment, when the original boundary of the ECA is in place, and when the modified ECA boundary is in place (columns).

Prior to the ECA, most container vessels on the LA/LB–San Francisco Bay route (first map in first row) minimize distance traveled by remaining close to the coast and within the ECA boundary for most of the voyage. Most vessels travel through the Santa Barbara Channel, which lies between the southern California coast and the Channel Islands. With the establishment of the ECA (second map in the first row) the bulk of vessels travels outside the ECA except when leaving or approaching a port, thereby adding distance traveled and shifting fuel consumption away from the coast. However, some vessels continue to use the established shipping lanes in the Santa Barbara Channel, which suggests heterogeneous responses to the policy. When the ECA boundary expands around the Channel Islands

[16] Our estimates are comparable to previous fuel estimates when differences in vessel speeds and methodology are accounted for (see Appendix B.1).

[17] In Table A.2 in Appendix, we show that mean fuel consumption per kilometer for other cargo vessels and tankers are 30% and 60% lower than for container ships, respectively, due to differences in vessel characteristics (size and power) and operating behavior (speed).

(third map in the first row) in 2011, some traffic returns to the channel and new traffic patterns form through notches in the ECA boundary. Similar patterns are observed for vessels entering/exiting the ports of Los Angeles and Long Beach (second row). Avoidance opportunities are more limited for vessels entering or exiting the ports of San Francisco Bay (third row) because, even pre policy, many vessels on this route pass straight through the ECA. When the ECA is established, however, vessels take even more direct routes.

These spatial adjustments lower marginal damages. Figure A.3 in Appendix shows that the implementation of the ECA causes an average container vessel on the LA/LB and San Francisco route to travel in lower marginal damage areas from around 50 km until 250 km into the voyage. The reductions in marginal damages are especially large (upwards of $100,000) at between 50-100 km into the voyage, but for most of the voyage the spatial adjustments have a relatively small impact on marginal damages.

Analogous maps for other cargo vessels and tankers (Figures A.4 and A.5 in Appendix) show that these vessels are less exposed to the ECA than container ships because they travel farther off the coast, and therefore respond less dramatically to the ECA. This is particularly evident for tankers because many tanker operators voluntarily agreed to travel 50 km off the coast for environmental and safety reasons after the Exxon Valdez oil spill (Doyle 2000).

3.2 Speed Profiles

Figure 4 shows that container ships conserve distillate fuels by lowering speeds within the ECA. Solid lines, measured on the left y-axis, show average speed (across all vessels) in 25-km distance bins along each route. Dashed lines, measured on the right y-axis, show the share of vessels that are within the ECA boundaries in each bin.

Prior to the ECA, container ships traveling from LA/LB to the San Francisco Bay accelerate quickly after leaving LA/LB and maintain a cruising speed of 35 km/h starting around 125 km into the trip (solid line with circle markers in subfigure (a)). There is no discernible change in speed when most vessels exit the ECA around 300 km into the trip (when the dashed line with circle markers drops from close to one to around 0.4). The speed profile is almost unchanged when the ECA is established in 2009 (solid line with diamond markers) as many vessels now exit the ECA 100 km into the journey during the initial acceleration. However, when vessels must travel longer distances within the ECA due to the 2011 boundary change, one can see depressed speeds inside the ECA (solid line with triangle markers). After an initial acceleration, vessels travel at just under 30 km/h for nearly 150 km and achieve cruising speed only after exiting the ECA. Similar speed adjustments are evident for vessels exiting LA/LB to the west (subfigure (b)).[18] Depressed speeds within the

[18]Reductions in cruising speeds over time, which are marked by the flat portion of the speed profile on the right side of the subfigures (a) and (b), reflect the global trends towards slower vessel speeds. Cruising

ECA and the secondary acceleration can be seen for vessels connecting to the San Francisco Bay (subfigures (c) and (d)), because avoidance opportunities are limited on these routes.

This speed profile analysis illustrates the difficulties in isolating behavioral speed changes within the ECA and any related impacts on fuel use in a voyage-level analysis. When distance inside the ECA falls, average speed within the ECA can fall mechanically as vessels travel less distance at cruising speed within the ECA or exit the ECA while still accelerating. On routes where avoidance is feasible, it is not possible to separate this mechanical effect from the behavioral response to the ECA. We, therefore, supplement our voyage-level analysis with a speed-bin analysis to provide insights about behavioral speed adjustments.[19]

3.3 Time-Series Discontinuities

The behavioral adjustments shown above occur sharply with the policy change. Figure 5 depicts monthly measures of distance, speed, and fuel use for container ships from the start of our sample until the North American ECA comes into place, after removing any time-invariant route-specific factors. Left and right columns show results for port-to-port and entrance/exit routes, respectively.

Immediately following the implementation of the ECA, distance traveled within the ECA boundary falls by over 200 km per voyage on port-to-port routes (subfigure (a)) and, given limited avoidance opportunities, by about 50 km on entrance/exit routes (subfigure (b)). Total distance traveled increases by about 40 km on port-to-port routes but changes very little on entrance/exit routes, implying that the increase in distance traveled outside the ECA is at least as large as the reduction in travel within the ECA.

Speeds within the ECA also fall sharply and by 2-4 km/h when the ECA is implemented (circle green markers in panels (c) and (d)). Similar sharp reductions in speeds are less evident outside the ECA (diamond orange markers).[20] The final row of panels shows that changes in predicted fuel use follow the patterns depicted in the distance and speed figures.

An important takeaway of these figures is that, while our empirical strategy uses initial responses to identify the effects of the ECA, these adjustments are clearly persistent and representative of longer-term responses. The initial responses to the ECA are maintained until, at least, the 2011 boundary changes when vessels readjust routes and speeds.[21]

speeds fall more drastically on entrance/exit routes as vessels travel longer distances on these routes.

[19]This issue also hinders a boundary discontinuity analysis, which could confound vessels crossing the ECA during the initial acceleration with behavioral speed adjustments on routes with avoidance.

[20]Speed outside the ECA is shown here to emphasize the highly localized changes in speed. Our analysis never relies on comparisons of speeds inside and outside the ECA because speeds outside the ECA may also respond to the policy.

[21]Distance and fuel use within the original boundary rise for both types of routes as vessels seek to avoid the updated boundaries. Decreases in speeds are evident leading up to the boundary change due to increased adoption of slow steaming starting in mid-2010 (see Figure A.7 in Appendix), which some analysts tie to excess capacity of the vessel fleet generated by the Great Recession (IMO 2015).

Reductions in distance, speed, and fuel use within the ECA, if anything, continue to fall in the months after the ECA is established. One caveat here is that our short-run estimates will not reflect background trends towards slower speeds that are evident, primarily, on entrance/exit routes. It is also worth noting that pre establishment trends are limited for both types of routes, especially for distance and fuel, which helps mitigate concerns about the missing data in the month prior to the establishment of the ECA.

4 Empirical Strategy

Given the sharp changes in vessel behavior associated with the implementation of the ECA, we estimate the impacts of the policy using a regression discontinuity design with time as the running variable. With this approach the impact of the ECA is identified as any discontinuous change in the outcome variable that occurs at the time of the policy change. As long as time-varying unobservables (e.g., other maritime policies, global economic conditions, or vessel speed trends) vary smoothly across the policy change, this approach will identify causal impacts of the ECA.

Our main specification is:

$$y_{irt} = \beta ECA_t + \delta_{rt} t + \gamma X_{irt} + \lambda_{ir} + \epsilon_{irt}, \tag{2}$$

where y_{irt} is an outcome for vessel i on route r starting on date t (t is rescaled so that it equals 0 on the date of the policy change). ECA_t is an indicator variable equal to one when the ECA is active, so β is the coefficient of interest. $\delta_{rt} t$ are linear time trends, which we allow to vary by route and pre and post policy, λ_{ir} are vessel-by-route fixed effects, X_{irt} are other control variables, and ϵ_{irt} is all remaining unexplained voyage-level variation. The outcomes we analyze include observed distance and speed, as well as predicted voyage-level fuel consumption and cost, and pollution levels and damages. We analyze port-to-port and entrance/exit samples separately since we observe only partial voyages for the entrance/exit routes and further split these samples by vessel type due to important differences in behavior across types.

We estimate (2) using standard fixed-effects regressions, but we restrict the sample to a small window around the implementation of the ECA (e.g., 150 days on each side).[22] Alternative estimation strategies for regression discontinuities in time (e.g., global polynomials and augmented local linear) are not appropriate in our setting.[23] Since factors

[22]In the context of the regression discontinuity literature, this can be thought of as a local linear approach using a rectangular kernel.

[23]A number of papers in environmental economics use a longer time window and account for time trends using high-order polynomials (e.g., Auffhammer and Kellogg (2011)), but recent literature has called into question the use of higher-order polynomials in regression discontinuity designs (Hausman and Rapson 2018;

that affect vessel behavior (e.g., vessel management or maintenance) may be correlated across voyages for a particular vessel, we cluster standard errors by vessel.

In order to verify the validity of our empirical strategy, we conduct several robustness checks, including those suggested by Hausman and Rapson (2018) that are relevant in our context. They include showing that our estimates are insensitive to bandwidth and various other specification choices; conducting placebo tests for routes unaffected by the ECA and "fake" policy dates; and showing, qualitatively, that a small number of exempt vessels (those with steam turbine engines) do not respond to the ECA.[24]

The inclusion of vessel-by-route fixed effects adjusts for baseline differences in individual-vessel outcomes along each route. Therefore, identification depends on time-series comparisons of outcomes for a particular vessel on a particular route. These fixed effects also prevent bias from changes in the composition of vessels operating on particular routes over time. When small sample sizes limit our use of vessel-by-route fixed effects, we use route fixed effects and control for vessel characteristics.[25] In our primary specifications we control for marine fuel prices because vessel behavior, particularly speed, may respond to prices and there are notable changes in fuel prices during our study window, but show that results are not sensitive to dropping fuel prices.

The identifying assumption underlying our empirical strategy is reasonable. Ocean-going vessels are part of sophisticated global logistic networks optimized to reduce costs relative to some standards of service. While vessel behavior is affected by global economic trends, vessel behavior within a particular route is unlikely to change suddenly unless induced by a policy or some other external event (e.g., a port strike or piracy). This is particularly true for distance traveled. Vessels on any route should, on average, travel on the path of minimum fuel cost, because adding distance when moving between fixed geographic points increases fuel costs with no added benefit. Fuel consumption will exhibit time trends depending on vessel speeds, but these should be smooth if based on broader economic trends.

Gelman and Imbens 2019). Hausman and Rapson (2018) suggest the augmented local linear approach where fixed effects and other control variables are partialled out using the full (or broader) sample in a first stage, then a local linear estimator is applied to the residuals in a second stage. This approach may not be applicable if there are differences in the time-series patterns of observations across units because the first stage does not purge these differences.

[24]It is possible that voyages on unexposed routes could serve as a control group in a difference-in-difference analysis. However, this approach could only recover estimates for changes in voyage-level outcomes (e.g., total distance or total fuel), and not the composition of activity inside and outside the ECA, which is the primary driver of our results. For this reason, and because we only observe a single unexposed route between west coast ports, key variables (e.g., speed and fuel consumption) seem to trend differently on exposed and unexposed routes, and we have a relatively short pre policy window to identify trends, we do not attempt this type of difference-in-difference approach.

[25]These are year built, deadweight, length, beam, draft, power, and indicator variables for U.S. flag and detailed vessel type (e.g., the type of vessel within the other cargo category).

A limitation of the regression discontinuity approach is that it recovers a local treatment effect, which could be interpreted as a short-run effect in a time-series setting. However, this concern seems to be relatively minor in our setting. Figure 5 suggests that the short-run impacts of the policy, particularly those related to distance and for port-to-port routes, are generally representative of the impacts for several years.[26] We also note that our estimated impacts of the policy are conditional on vessels' route choices. We expect these estimates to capture the bulk of welfare changes because, as we show later, adjustments on other margins, such as changes in the vessel fleet or the diversion of vessel traffic to other west coast ports, are likely minimal.

4.1 Identifying Impacts of Behavior Changes

Figure 6 illustrates our strategy to isolate the impacts of behavioral adjustments on unregulated margins. Outcomes, y, for any voyage depend on a vector of behaviors (speed profile, distance, location of travel), $\boldsymbol{\theta_i}$, and what fuel is used within the ECA (residual or distillate). The overall impact of the ECA (illustrated in the discontinuity in the solid black line) is identified by the change in outcomes associated with switching from residual to distillate fuels within the ECA and behavioral changes ($\boldsymbol{\theta_0}$ to $\boldsymbol{\theta_1}$). To isolate the impacts of behavioral adjustments, we need to compare post policy outcomes, $y(\boldsymbol{\theta_1}, distillate)$, to a counterfactual where vessels switched fuels but did not change behavior, $y(\boldsymbol{\theta_0}, distillate)$ or the dashed black line. We do this by estimating changes in outcomes calculated under the assumption that vessels use distillate fuel within the ECA both pre and post policy change, so that the pre ECA values provide the appropriate counterfactual. For comparison, the counterfactual impact had vessels switched fuel without changing any other behavior is the difference between the dashed and solid lines pre policy change.

The changes depicted in Figure 6 represent pollution damages. The net impact of fuel switching and behavioral changes lead to overall reductions in pollution damages (impact of the ECA on damages is negative) due to the considerable benefits of switching fuels in high marginal damage areas. But, behavioral changes that drive a spillover in pollution to outside the ECA dampen the net reduction in pollution damages (impact of behavior changes on damages is positive).

5 Results

5.1 Aggregate Effects

We report estimated impacts of the establishment of the California ECA using our primary specification in Table 1. The columns reflect different measures of vessel behavior,

[26]We also explore the extent to which fleet efficiency improvements could mitigate the impacts of behavioral adjustments in Section 5.4.

emissions by vessels, fuel costs, and pollution damages, while the panels report separate analyses for port-to-port and entrance/exit routes by vessel type. For each outcome, we report the predicted mean value for both the date of the policy change ($t = 0$) and one month prior ($t = -30$), which allows us to infer the potential impacts of extrapolating across the month prior to the implementation of the ECA. We supplement the main results with equivalent specifications applied to an additional set of outcome variables in Table A.3.

5.1.1 Container Ships

Results for container ships on port-to-port routes are in panel (i). Estimates in columns (1) and (2) show that distance and average speeds within the ECA boundary fall dramatically upon implementation of the ECA. Average distance within the ECA falls by 245 km per voyage while speeds fall by 4 km/h.[27] The distance and speed effects are statistically significant and sizable (45% and 13% reductions relative to the predicted mean outcome just prior to the implementation of the ECA ($t = 0$)).[28] Predicted fuel consumption within the ECA (column (3)) falls by 26.5 tons per voyage. The relative reduction in fuel consumption within the ECA is larger than the relative reduction in distance due to the reductions in speed. To provide a metric for the changes outside the ECA that correspond to the within-ECA changes, we report the "spillover ratio" – the change outside the ECA divided by reduction within the ECA – for fuel use and distance.[29] The spillover ratios for distance and fuel consumption are both above one, implying that the compensating increases outside the ECA are larger than the within-ECA reductions.

The impacts of these behavioral adjustments on fuel costs, pollution, and pollution damages are reported in columns (4) through (6). In these regressions the dependent variables are outcomes calculated under the assumption that vessels use low-sulfur fuel within the ECA both pre and post policy change. The coefficients on the policy indicator now reflect changes in the outcome relative to a counterfactual in which vessels complied with the sulfur limit inside the ECA but maintained all other pre ECA behavior. We find vessels saved around $5,300 per voyage (relative to the costs had they only switched fuel) by making distance and speed adjustments. The increase in fuel costs would have been around $12,800 per voyage had vessels maintained pre policy behavior, so adjustments in behavior reduced the increase in fuel costs by about 41% (reported in final two rows of each panel). The limited geographic coverage of the ECA and the ability to adjust speed provide vessels with

[27]As mentioned above, some of the reductions in speed within the ECA are mechanically related to avoidance. We disentangle the mechanical and behavioral speed adjustments in Sections 5.2 and 5.3.1.

[28]Given the changes in distance and speed, we also check the average impacts of the ECA on travel time. We find minor impacts for container vessels of around one hour or less (Table A.3). We discuss the welfare consequences of these changes in travel time below.

[29]Estimated changes in total distance and total fuel consumption used to construct the spillover ratios are reported in Table A.3 in Appendix.

considerable flexibility to reduce exposure to the policy.

The private savings due to the behavioral adjustments come with large environmental costs. Adjustments in behavior eliminate 60% (0.187 tons) of the per voyage $PM_{2.5}$ reductions that would have been achieved through fuel switching, largely because fuel consumption shifts to outside the regulated area, and therefore to higher-sulfur fuels.[30] The associated increase in damages per voyage is $17,000, or 24%. The impact of vessel behavior on pollution damages is modest relative to the impact of behavior on emissions. This is because vessels cannot avoid the ECA in the high marginal damage areas surrounding the ports, so the spillover of fuel use from within the ECA to outside the ECA occurs in areas with relatively low marginal damages. Changes in behavior within the ECA contribute little to the total reduction in $PM_{2.5}$ because vessels make these adjustments when using distillate fuels (column (5) in Table A.3). While behavioral adjustments are clearly welfare reducing, the fuel cost savings are relatively important. For every dollar in additional pollution damages generated by behavioral adjustments, compliance costs fall by around $0.3. Put differently, focusing solely on pollution damages would overstate the social importance of behavioral adjustments by 40%.

The differences between the two predicted pre policy means ($t = 0$ and $t = -30$) are negligible for all outcomes, which implies weak pre ECA time trends and that extrapolation across the period with missing data prior to the ECA has a limited impact on estimated discontinuities.[31]

Panel (ii) in Tables 1 and A.3 report impacts of the ECA on container ships on entrance/exit routes. As we do not observe complete voyages for this sample, our analysis of total outcomes only captures responses within the study area. With this caveat, the ECA has more muted impacts on vessel behavior on entrance/exit routes than port-to-port routes as entrance/exit routes are, on average, less exposed to the ECA (based on pre ECA distance within the ECA). Vessels on the entrance/exit routes reduce distance, speed, and fuel use within the ECA by 24%, 8%, and 36%, respectively. These behavioral adjustments have a smaller impact on fuel costs (-41%) and damages (10%), but are still welfare reducing.

5.1.2 Validation and Falsification Tests

Before proceeding, we verify the validity of our empirical approach using a range of robustness checks. We emphasize the bandwidth analysis and falsification tests which are the checks suggested by Hausman and Rapson (2018) that are relevant in our context.

Although estimates using local linear methods can be sensitive to bandwidth choices, we

[30] Results for SO_2 are qualitatively similar.

[31] As a further robustness check, we show that dropping this month from our time index does not drastically change our results (Tables A.6 and A.7).

find that the choice of bandwidth is inconsequential in our setting. In Table A.5 in Appendix we show that estimates for all outcomes are remarkably consistent across bandwidth choices from 90 days to a full year. For example, point estimates for the impacts of behavioral adjustments on damages only range from \$14,993 to \$17,950 per voyage for container ships on port-to-port routes.

Our results are also insensitive to various specification choices (Tables A.6 and A.7 in Appendix). We obtain similar results if we drop the 30 days prior to the policy change from the time index, drop the fuel price controls, use a homogeneous linear trend instead of route specific trends, restrict our analysis to vessels we observe both pre and post policy, replace vessel fixed effects with shipping company (operator) fixed effects, or use route fixed effects with vessel controls. These results are discussed in detail in Appendix Section A.

Next, we conduct a series of placebo tests that lend support for our empirical specification. First, we estimate effects using a "fake" policy that is implemented 365 days after the establishment of the ECA. Results in Table A.5 show that these placebo checks recover small, and mostly statistically insignificant, effects across all outcomes and bandwidth choices. Second, we find that estimated impacts of the ECA on unexposed entrance/exit routes from Pacific Northwest ports show no change in distance traveled and only a slight increase in speed that leads to small in magnitude increases in fuel costs and damages (Table A.4 in Appendix). These null results mitigate concerns about changes in shipping markets or the U.S. economy that affected all west coast ports. Third, we show qualitative evidence that container ships exempt from the OGV Fuel Rule do not adjust behavior in response to the ECA, which implies that our results are not driven by contemporaneous changes in traffic patterns or other maritime policies that might affect all vessels calling at California ports. Figure A.6 shows that exempt container ships do not lower speed within the ECA boundaries or avoid the ECA on routes where avoidance is possible.[32]

5.1.3 Other Vessel Types

Panels (iii)–(vi) of Tables 1 and A.3 present estimated impacts of the establishment of the California ECA for other cargo vessels and tankers. The estimates are noisier partially due to smaller sample sizes (and our inability to include vessel-by-route fixed effects) and partially due to the diverse nature of these vessels. Overall, we find that behavioral adjustments by other cargo vessels and tankers have a limited impact on welfare outcomes of the ECA due to the lack of avoidance opportunities. While other cargo and tankers avoid the ECA to the extent possible, these adjustments have limited consequences because, pre policy, these vessels consume less fuel within the ECA due to differences in fuel economy and travel

[32] The number of exempt vessels is small and are concentrated on particular routes. We observe a total of only 8 exempt container ships (and fewer for the other vessel types). These vessels tend to service Hawaii.

patterns – other cargo vessels and tankers tend to operate on less exposed routes and, on any particular route, travel farther off the coast.[33] Speed changes have a minor influence on fuel use for other cargo vessels because these vessels travel at lower speeds and are relatively fuel efficient. For tankers, fuel consumption within the ECA falls proportionally more than distance due to decreased time spent within the ECA perhaps because vessels spend less time queuing around ports, which reduces auxiliary engine fuel use.

5.2 Heterogeneity Across Routes

Routes are differentially affected by the ECA due to the location of ports, coastal geography, and the design of the ECA boundary. Table A.8 reports results after splitting the sample of container vessels by northern and southern California ports and, for entrance/exit routes, by the direction of entrance or exit. Comparing results across routes illustrates that welfare consequences of behavioral changes can range from extremely negative to almost neutral depending on avoidance opportunities. Vessels on southern California routes that have the option to avoid the Santa Barbara Channel – port-to-port and western entrances/exits – generate more than \$3 in damages for each dollar saved in fuel costs due to behavioral adjustments. Vessels on the other less exposed routes can only avoid the ECA by traveling straight through the ECA, and as a result each dollar of fuel cost savings leads to \$1.2 or less increase in pollution damages. Geography also plays a role in determining the damages associated with changes in emissions due to behavioral adjustments. Increased emissions due to behavioral adjustments lead to proportionally stronger increases in damages on port-to-port routes in northern California than southern California. This indicates that changes in the location of fuel combustion due to avoidance occur in areas with a relatively flatter marginal damage gradient in northern California.

The route-specific results also help isolate the impacts of speed adjustments. The strong reductions in speeds within the ECA on routes with limited avoidance opportunities indicate that speed reductions within the ECA are due to vessels changing behavior and are not just mechanically related to avoidance (i.e., traveling less distance at cruising speed within the ECA). The speed reductions within the ECA generate sizable fuel cost savings but have a limited impact on pollution damages because these adjustments occur when vessels are using distillate fuel. For example, on northern California port-to-port routes, fuel use within the ECA falls by 14.2 tons due to avoidance and speed reductions (Table A.8). Had average speed inside the ECA not changed, fuel use would have fallen by roughly the same percentage as distance inside the ECA (58%) or 12.1 tons. Fuel saving due to speed (2.1 tons) reduces

[33] To see that other cargo vessels and tankers are avoiding to the extent possible note that post ECA distance traveled within the ECA is roughly comparable for all vessel types, even without accounting for differences in route composition. For example, post ECA average distance within the ECA on entrance/exit routes is 150 km for container ships, 137 km for other cargo vessels, and 125 km for tankers.

fuel costs by around \$1,600, which is important relative to the total change in fuel costs and the total fuel cost savings due to behavioral adjustments. However, this fuel saving only lowers within-ECA $PM_{2.5}$ emissions by 0.0021 tons, which contributes little to reductions in damages.

5.3 Consequences of Avoidance

The implications of avoidance are somewhat masked by the average effects because not all vessels avoid the ECA. We provide suggestive evidence of the full impacts of avoidance on the busiest southern California route – LA/LB–San Francisco Bay – where the use of the Santa Barbara Channel is a strong indicator of avoidance. Prior to the ECA, nearly 95% of voyages went through the Santa Barbara Channel. Use of the channel fell to 53% immediately after implementation of the ECA and then further to 15% after six months. We classify voyages as remaining in or avoiding the channel ("remainers" and "avoiders") after the establishment of the ECA, then estimate equation (2) separately for each subsample, so that estimates are based on pre-post comparisons within a particular group.[34] Our focus here is on heterogeneity of effects as opposed to across group comparisons since the choice to avoid is clearly endogenous. Even though nearly all vessels eventually avoid the channel, early adopters may be different from later or never adopters. There are, however, only small, yet statistically significant, average differences in vessel characteristics between groups.[35]

Estimated impacts of the ECA on avoiders and remainers are reported in Table 2. Behavioral adjustments by avoiders (panel (i)) eliminate almost \$37,000 in environmental benefits while saving vessels around \$6,500 in fuel costs. Avoidance leads to sharp increases in total distance and total fuel consumption (spillover ratios are well above 1). Strikingly, behavioral adjustments eliminate nearly all of the reductions in $PM_{2.5}$ that would have occurred had behavior not changed. The reduction in damages for avoiders, therefore, results mainly from shifting emissions from high to low marginal damage areas, not emission reductions. Behavioral adjustments by remainers (panel (ii)) reduce fuel costs by slightly more than the associated increase in pollution damages, implying that the flexibility afforded by the ECA to this subset of vessels does not reduce net benefits.

The slow decline in use of the Santa Barbara Channel after the initial drop and the heterogeneous effects across avoiders and remainers partially explain the slow transition in fuel consumption that we observed in Figure 5. As more vessels avoid the channel in the longer run, behavioral adjustments from container ships on this route eliminate more of the

[34] Specifically, we restrict our sample to vessels that used the channel prior to the ECA, then classify voyages according to whether they use or do not use the channel post policy. We then restrict the sample further to include only vessels that we observe both pre and post policy.

[35] Avoiders tend to be older, smaller, more likely to be U.S. flagged, and travel more frequently on this route (see Table A.11 in Appendix).

potential net benefits of the ECA.

5.3.1 Heterogeneity in Speed Response

Comparing the relative sizes of distance and fuel spillover ratios across avoiders and remainers implies disparate speed responses to the ECA and that avoidance interacts with speed adjustments to amplify the pollution spillover.[36] To further isolate adjustments in vessels' speed, we estimate changes in distance traveled within discrete speed bins. In this analysis we include vessel-by-route-by-bin fixed effects so that changes in distance traveled in each speed bin are identified from within-vessel variation.[37] We present results graphically in Figure 7. The orange markers and lines represent the estimated changes in distance traveled within each speed bin and 95% confidence intervals, while the green bars show the pre policy distance traveled in each speed bin.

Avoiders (subfigure (a)) swap distance traveled at speeds between 30 and 34 km/h for distance at speeds between 20 and 28 km/h and increase distance at speeds above 35 km/h. This pattern is consistent with vessels slowing down within and speeding up outside the ECA, possibly to compensate for the longer distance traveled.[38] The speed increases by avoiders are an important contributor to the pollution spillover. All speed adjustments, including any reductions within the ECA, contribute 40% of the increase in total fuel use or about 4.4 tons, which offset around 7% of the reduction in within-ECA pollution. For remainers (subfigure (b)), there is increased travel at slower speeds but no evidence of additional travel at higher speeds. These results point to a fundamental inefficiency in how ECAs affect vessel speeds. Vessels slow down to conserve the cleaner fuel but speed up when using the dirty fuel. A policy that priced pollution at its marginal damage would induce speed reductions with either fuel, but all else equal, should lead to greater speed reductions when vessels are using the dirty fuel.

5.4 Other Analyses and Robustness Checks

5.4.1 Impacts of the 2011 Boundary Change

Given that the establishment of the ECA clearly distorts vessel behavior in ways that affect the potential welfare outcomes of the policy, changes to the ECA boundary to limit avoidance could generate behavioral adjustments with modest or even favorable welfare

[36] The stronger spillover ratio for fuel relative to distance for avoiders implies speed increases outside the ECA.

[37] Formally, we estimate $d_{irtb} = \sum_b \alpha_b ECA \times \mathbb{1}\left[s_{irtd} = b\right] + \lambda_{irb} + \epsilon_{irtb}$ where d_{irtb} is the distance voyage irt spent in speed bin b, λ_{irb} is a set of vessel-by-route-by-bin fixed effects, and $\mathbb{1}\left[s_{irtd} = b\right]$ is an indicator for whether a particular observation falls within speed bin b. α_b are the coefficients of interest, which measure the change in distance traveled in each speed bin. As in the voyage-level analysis, we restrict the sample to be within 150 days from the policy change and cluster standard errors by vessel.

[38] It is notable that the change in speed distribution clearly does not follow the pattern we would expect if vessels increased distance at cruising speeds, which is illustrated by the blue bars in the figure.

implications. In Table A.9 in Appendix we show that, on average, adjustments in behavior in response to the ECA boundary change in 2011, which was partially designed to reduce avoidance of the Santa Barbara Channel, have limited impacts on the welfare outcomes.[39] We find that the boundary change affects distance, speed, and fuel consumption in the ECA only for routes from southern California ports, but that the fuel costs and pollution damage changes associated with these behavioral adjustments are mostly small and comparable in magnitude. Since vessel behavior is already distorted by the original ECA boundaries, the potential net benefits of expanding the boundary are not greatly eroded by changes in behavior. In fact, for southern California entrances and exits to the west, the fuel cost savings appear to dominate the increased pollution damages. Estimated impacts for routes unaffected by the boundary change – northern California and other west coast routes – are mostly small and statistically insignificant.

To further explore the possibility of potentially favorable behavioral adjustments, we estimate separate effects for container ships that avoid the broader ECA boundary and those that return to the Santa Barbara Channel on the LA/LB–San Francisco Bay route.[40] Our results imply that by reducing avoidance the net benefits of the boundary change were partially reinforced by behavioral adjustments. Behavioral adjustments by vessels that return to the Santa Barbara Channel reduce the potential increase in fuel costs by roughly $4,000 per voyage, which are largely driven by speed reductions (Figure A.8). These fuel cost savings come with a negative, but negligible, impact on pollution damages. While behavioral adjustments actually reinforce the emission reductions achieved by the expansion of the ECA boundary by around a third, these reductions lead to limited reductions in damages because the emissions occur in higher marginal damage areas. Behavior changes by vessels that continue to avoid the updated boundary slightly lower realized increases in fuel costs, but at the expense of increased damages that are more that three times larger than the fuel cost savings.

5.4.2 Impacts on Activity Outside the Study Area

A concern with analyzing the incomplete entrance/exit voyages is that vessels may adjust behavior outside the study area. Large changes outside the study area are, however, unlikely since the ECA has a limited impact on total distance traveled inside the study area. Using a sample of entrance/exit voyages for which we can interpolate full voyages to the Unimak Pass in Alaska and Honolulu, Hawaii (where we have AIS records), we are able to provide

[39] Since the ECA is in place prior to the boundary change, estimating Equation (2) recovers changes in behavior, and the impacts of these changes, due to the boundary change relative to the distorted behavior due to the original ECA boundary.

[40] This analysis is similar to the one presented in Section 5.3 and is discussed in Appendix Section A.

some insight on the magnitude of adjustments outside the study area.[41]

Mean distances reported in Table A.12 in Appendix show that container ships traveling to/from the Unimak Pass increase distance outside the study area by 40 km for northern California ports and 60 km for southern California ports. Routes to/from Honolulu travel no additional distance outside the study area. Back-of-the-envelope calculations suggest that for the Unimak routes, fuel consumption outside the study area increases by 3.8 and 5.8 tons for southern and northern California routes, respectively, which adds $1,500 and $2,200 in fuel costs and, at most, $1,200 and $1,800 in damages. Factoring in activity outside the study area will reduce the fuel costs savings and add to the damages associated with behavioral adjustments, but the increases in damages will still easily dominate.

5.4.3 Predicted Fuel Consumption, Marginal Damages, and Emission Factors

In Tables A.13 and A.14 in Appendix we assess the sensitivity of our results to the assumptions used to predict final outcomes from vessel behavior.

We first estimate changes in outcomes for container vessels using alternative assumptions to predict fuel consumption from vessel behavior. We find that our results change little if we derive α_i in Equation (1) from vessel power or use only main engine fuel consumption (which may be measured more reliably than auxiliary engine consumption) (columns 2 and 3 in Table A.13). Our results are also unchanged when we set each vessel's α_i to the mean α by vessel type. Since changing these assumptions implies different correlations between vessel characteristics and behavioral changes, the consistent results provide some evidence that non-classical measurement error in the prediction of fuel consumption is of limited concern.

In order to explore one aspect of the potential longer-term implications of the ECA, we also estimate changes in final outcomes under the assumption that each vessel is at the current efficiency frontier by setting α_i to the 5th percentile α by vessel type (column 5). This analysis implies that the observed behavioral adjustments would still be privately beneficial on average (saving fuel costs by $4,200) and that the adjustments would still have substantial environmental consequences if vessels were at the current efficiency frontier Our results suggest that modest efficiency improvements are not likely to substantially alter the consequences of behavioral changes.[42]

[41] The Unimak Pass is a busy shipping channel through the Aleutian Islands that lies on the Great Circle route between the U.S. west coast and many ports in East Asia. Since Unimak routes are among the most northern possible western routes connecting to California, the angle to/from the west coast ports will be more affected by the ECA than more southern routes. Therefore, it is reasonable to assume that results for the Unimak routes are an upper bound of the potential changes outside the study area for other western entrances/exits.

[42] It is important to note that what we are not capturing here is *how* more efficient vessels would respond to the ECA. We expect the behavioral changes of more efficient ships will be more muted due to different time/fuel tradeoffs. However, given the large differences in fuel costs and what appears to be effectively a discrete choice regarding avoidance (nearly all vessels avoid the Santa Barbara Channel), it seems unlikely

In Table A.14 we report estimated changes in fuel costs and pollution damages for container vessels under different assumptions that link changes in fuel consumption to final outcomes (discussed in Appendix Section A). When vessels are assumed to comply with the OGV Fuel Rule's stated sulfur limit, as opposed to the observed average sulfur content for distillate fuels, the private benefits of behavioral adjustments on port-to-port routes are 40% lower than our central results due to the smaller price premium for distillate fuel, while the impact on pollution damages falls by almost 50%. When we use marginal damages from AP2, which are lower on average and exhibit a flatter spatial gradient than those from ISRM, behavioral adjustments cut a much larger fraction (58%) of reductions in pollution damages because reductions in pollution in coastal areas are less beneficial, while the increases in pollution outside the ECA are relatively more important.

5.5 Overall Welfare Impacts

In Table 3 we compare the welfare consequences of behavioral adjustments to estimates of the aggregate welfare impacts of the California ECA. This analysis helps illustrate the importance of the behavioral adjustments we have identified. We note, however, that our estimates of the aggregate welfare impacts should be interpreted with care because, as discussed above, our estimates are short-run, only capture impacts within the study area, and may not include all potential channels of adjustment to the ECA.[43] We calculate aggregate results by scaling estimates of the impact of the establishment of the ECA by average monthly voyage counts over the period when the ECA is active at the vessel type and port level, then aggregating.[44] We include both port-to-port and entrance/exit routes in the analysis but use estimates from separate regressions for each group.

The first column in Table 3 reports monthly totals aggregated over all ports and vessel types and the next three columns break down the monthly totals by vessel type. On average, 1,067 voyages per month were affected by the establishment of the ECA (first row of numbers). Panel (i) reports the baseline (first row for each outcome) and change relative to the baseline (second row) for distance and fuel use within the ECA, and $PM_{2.5}$ released by vessels. For $PM_{2.5}$ emissions, we also report the change associated with behavioral adjustments. We find that $PM_{2.5}$ emitted by vessels fell by 68 tons per month due to the ECA, but would have fallen an additional 48 tons per month had vessels not changed behavior.

that modest efficiency gains would eliminate behavioral adjustments.

[43]Other channels of adjustment may include changes in the composition of the vessel fleet, reorganization of routes, or diversion of shipping traffic to alternative ports or modes (e.g., trucks or rail). Although we cannot rule out these changes, in the Appendix Section A we discuss evidence that suggests strong adjustments on these other margins is limited.

[44]We include voyages that we drop from our analysis sample due to missing origins or destinations by scaling up voyage counts by port while assuming that the dropped voyages had identical route shares as the voyages in our analysis sample. This adjustment adds around 240 voyages to the monthly totals.

Panel (ii) shows that the ECA reduced pollution damages by $36 million per month, while fuel costs only increased by $2.8 million per month. Overall (but not accounting for within-port fuel costs and pollution damages), the net benefits of the ECA total $33 million per month or $957 million ($903 million in July 2009 dollars if discounted at 5% annually) over the 29 months the original boundary was in place. Net benefits would have been $35.6 million per month had vessels not changed behavior. Vessels are able to save $2.1 million in fuel costs, but in the process generate an additional $4.9 million in pollution damages. In total, the behavioral adjustments eliminate $76.6 million over the period in which the original boundary was in place. That fuel cost savings are around 40% of the pollution damages due to behavioral changes makes clear the importance of analyzing both the costs and benefits of policy-induced behavioral adjustments. The vast majority of the net benefits stem from container ships, despite the reductions in net benefits due to behavioral changes being almost totally associated with these vessels.

In panel (iii) we quantify other welfare impacts of behavioral adjustments that are not captured in our main analysis. We describe these results in Appendix, but highlight two main points here. First, changes in correlated pollutants (CO_2 and NO_x) and time costs due to behavioral adjustments are small relative to the sulfur-related environmental benefits.[45] Second, rough estimates of within-port (i.e., between our defined port entrances and the terminal) fuel costs and reductions in pollution damages may reinforce the aggregate net benefits of the ECA.

6 Policy Implications and Conclusion

In this paper we combine detailed data on vessel movements along the U.S. west coast with standard physical relationships and location-specific marginal damages from integrated assessment models to evaluate how behavioral adjustments along unregulated margins alter the welfare impacts of the ECA established by California's Ocean-Going Vessel Fuel Rule. Although the ECA generates net benefits, we find that the behavioral adjustments vessels undertake in response to the ECA are, on average, welfare reducing: for every $1 in fuel cost savings, pollution damages increase by $2.6.

By isolating how behavioral adjustments affect welfare outcomes, we offer a number of insights into the design of ECAs and, potentially, other local standards. In our context, one option to reduce avoidance and increase the net benefits of the ECA is to raise the cost of avoidance by modifying the ECA boundary. We find that the 2011 changes to the ECA boundary generate generally modest and even welfare-enhancing behavioral

[45] Changes in the location of vessel activity could also impact ecosystem services (e.g., changes in underwater noise or probability of fatal whale-vessel collisions (Moore et al. 2018)); estimating these impacts, however, is out of the scope of this paper.

adjustments. However, expanding the ECA farther will not necessarily increase net benefits due to marginal damages declining with distance to the coast and heterogeneity in routes. Additional boundary expansions may eliminate avoidance on coastal routes, but vessels on entrance/exit routes may incur increased fuel costs to avoid relatively low marginal damage areas.[46]

Another way to reduce avoidance is to complement a zonal fuel sulfur standard with a subsidy that eliminates the price premium for distillate fuels. The crudest version of such a policy would be for California to reimburse vessels for the price premium of fuel used within the ECA. Vessels would then use distillate fuels within the ECA, but would not avoid the regulated area or reduce speeds inside the ECA.[47] Our results suggest that such a policy could be welfare improving if it was targeted at particular vessels and routes. For example, reimbursing container ships roughly $15,000 per voyage on the LA/LB–San Francisco Bay route (at the government cost of about $21,000 assuming the marginal cost of public funds of 1.4) would generate a $37,000 gain in environmental benefits if vessels no longer avoided the Santa Barbara Channel. Even paying container ships to use distillate fuels when traveling between LA/LB and San Francisco would dominate the ECA on this route.[48]

Policies that regulate vessel speeds appear unlikely to generate net benefits of the same magnitude as those targeting fuel sulfur. The strong speed reductions by container vessels that remain in the Santa Barbara Channel would have only reduced damages by $3,500 if vessels did not switch fuels (this result is unreported).

Our analysis suggests there could be considerable gains from the optimal design of local standards that account for geography – particularly its impacts on spatial heterogeneity in marginal damages and avoidance opportunities – and for the behavior of regulated agents. Coastal ECAs like the one we study, the North American ECA, or the ECA along the Chinese coast may be subject to substantial avoidance, especially if there are many coastal voyages. Avoidance is likely a minor concern for ECAs in contained areas (e.g., the North or Baltic Seas, or the inland waters of China) or for ports where most vessels travel straight through the ECA. Even an optimally designed ECA, however, may still induce potentially perverse speed responses. We do not compare the welfare impacts of an ECA to the first-best policy, but given the magnitude of the behavioral changes we identify, the optimal design of

[46] Although not displayed here, our voyage data set suggests that this is exactly the pattern that occurs when the North American ECA, which extends 200 nm from the coast, subsumes the California ECA. We do not analyze this change because it coincides with a labor dispute and port slow down on the west coast.

[47] It is also unlikely that this policy would induce additional travel within the ECA if vessels are fuel minimizing prior to the ECA being established.

[48] It would cost California an average of roughly $22,000 (after accounting for the marginal cost of public funds) per voyage to cover the distillate premium for all fuel use, but the shift to distillate fuels would reduce pollution damages by almost $82,000.

maritime air pollution policies is an important area for future work.

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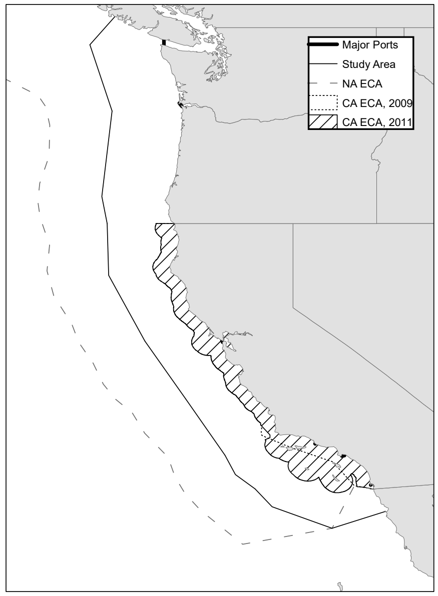
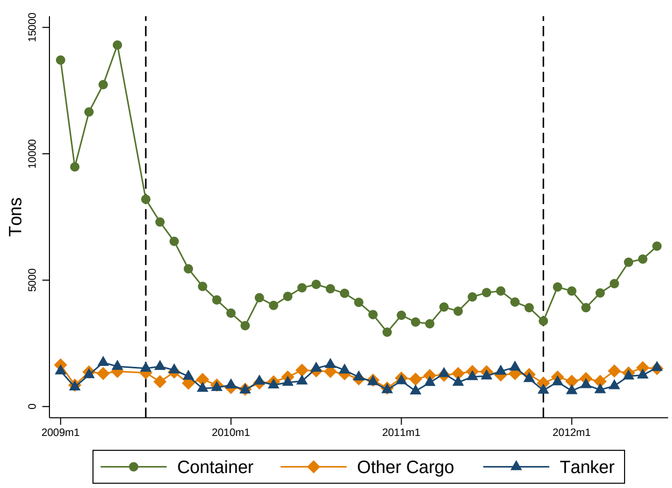


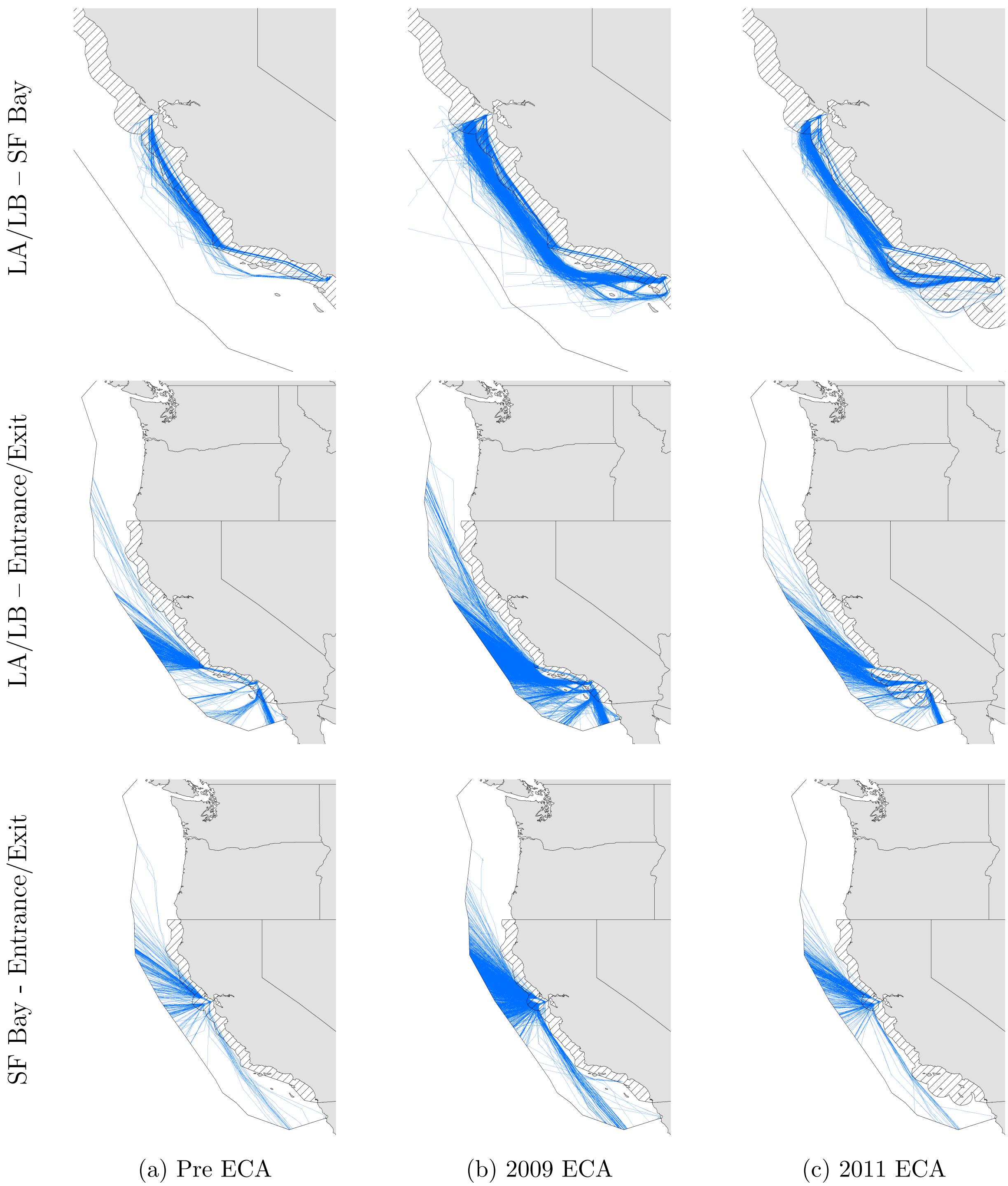
Notes: From north to south the thick dark lines on the coast represent Seattle, Portland, San Francisco Bay, Hueneme, Los Angeles/Long Beach, and San Diego ports. The study area boundary extends approximately 100 nm (185 km) off the coast.

Figure 1: Study Area and the ECA Boundaries



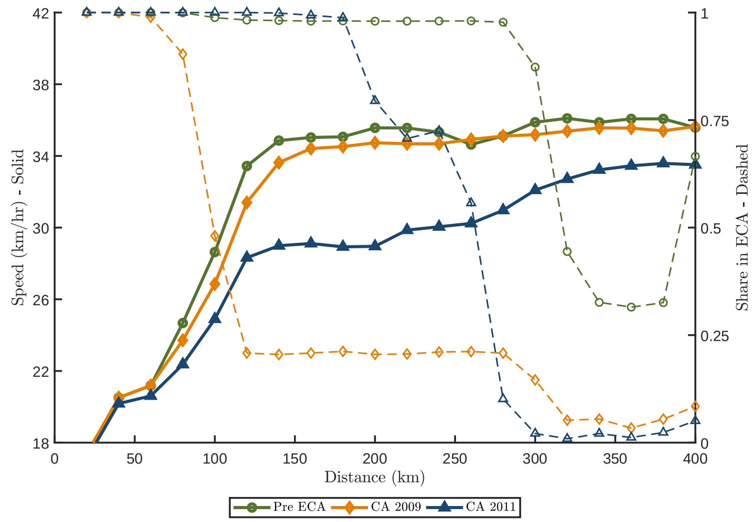
Notes: Reported fuel consumption is within the 2009 ECA boundaries. Dashed horizontal lines denote the establishment of the ECA in 2009 and the ECA boundary change in 2011. Large reduction early in 2009 is due to reduction in voyages resulting from a collapse in trade stemming from the Great Recession. Starting in 2010, we classify cargo vessels with missing vessel characteristics to container or other cargo types based on length and ports visited (because container ships are unlikely to stop at smaller ports).

Figure 2: Fuel Consumption Within ECA Boundaries

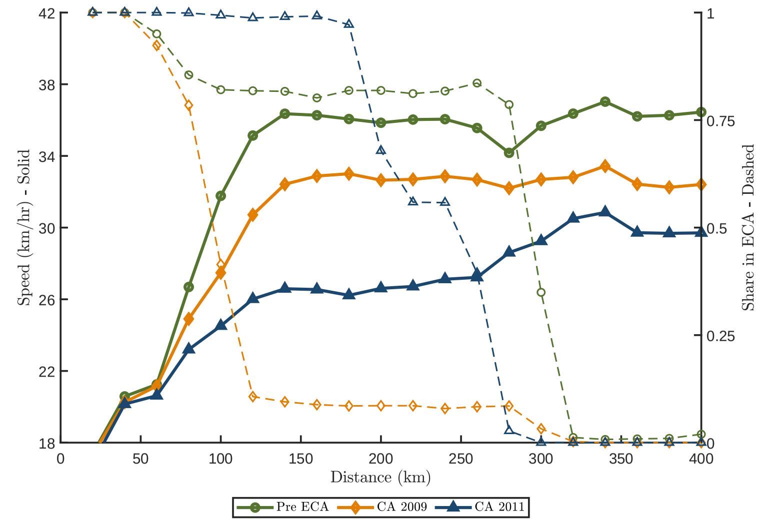


Notes: Solid black line represents the study area boundary. Hashed area depicts the relevant California ECA. For reference, the 2009 California ECA boundary is displayed in the Pre ECA maps. Pre ECA column includes voyages from January 2009 to June 2009; 2009 ECA column includes voyages from July 2009 to December 2011; 2011 ECA column includes voyages from January 2011 to July 2012.

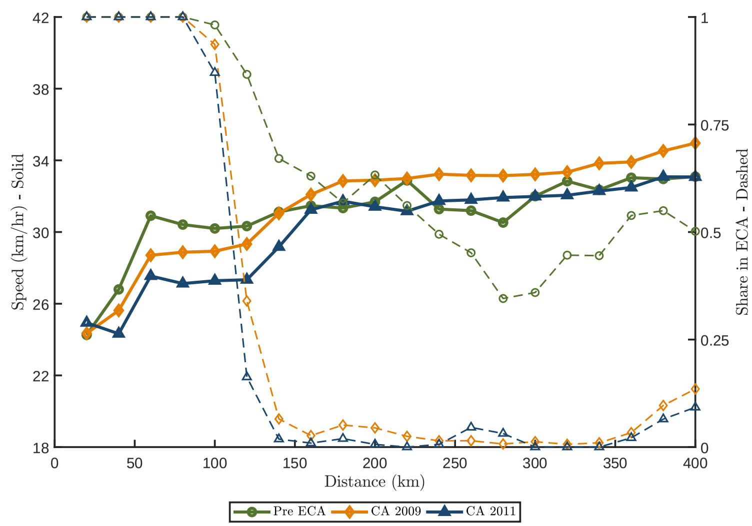
Figure 3: Container Ship Voyages on Major Routes



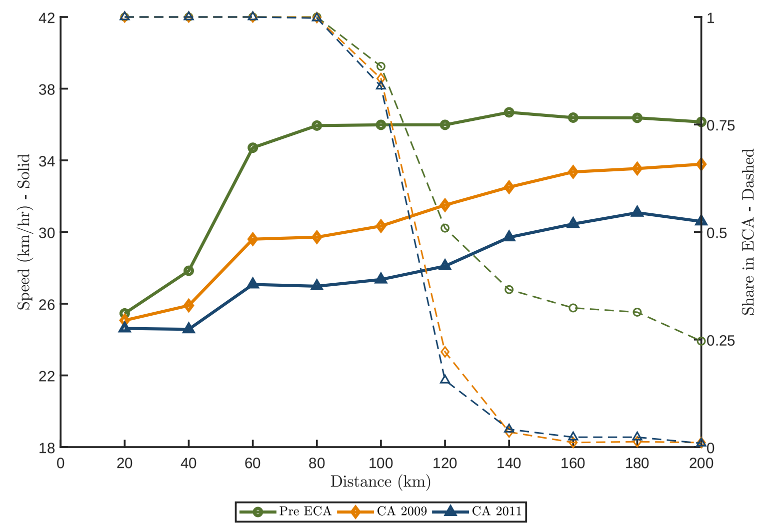
(a) LA/LB – San Francisco Bay



(b) LA/LB – West



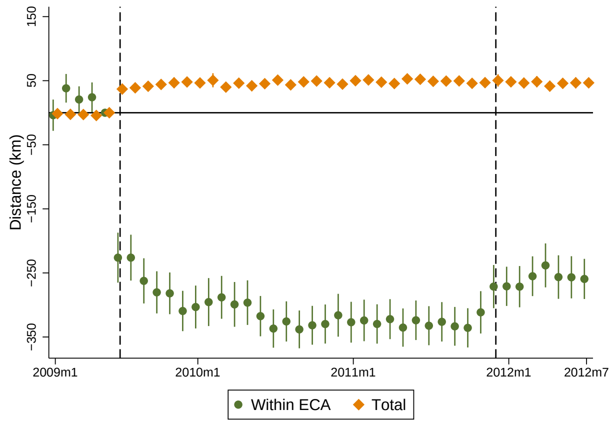
(c) San Francisco Bay – Seattle



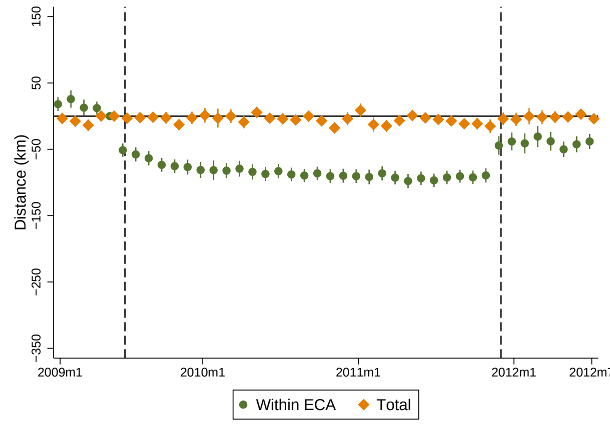
(d) San Francisco Bay – West

Notes: Solid lines represent average speed in distance bins for first 200 or 400 km along route under different policy treatments. Dashed lines represent average share of distance traveled within the ECA boundaries. All vessels moving from the first listed port to the second listed port. Steam-turbine-powered vessels are excluded. Pre ECA share within the ECA boundaries is based on the 2009 boundaries.

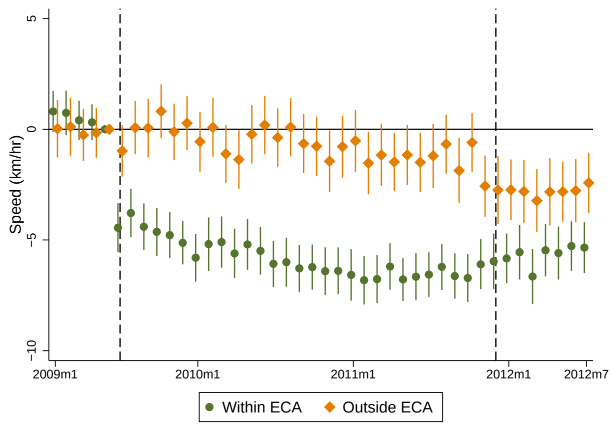
Figure 4: Container Ship Speed Profiles on Major Routes



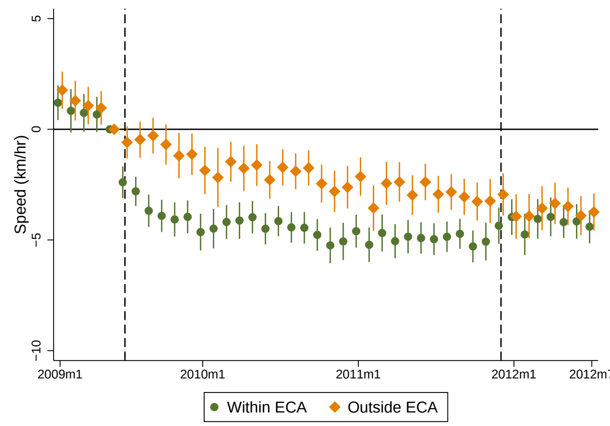
(a) Distance, Port-to-Port



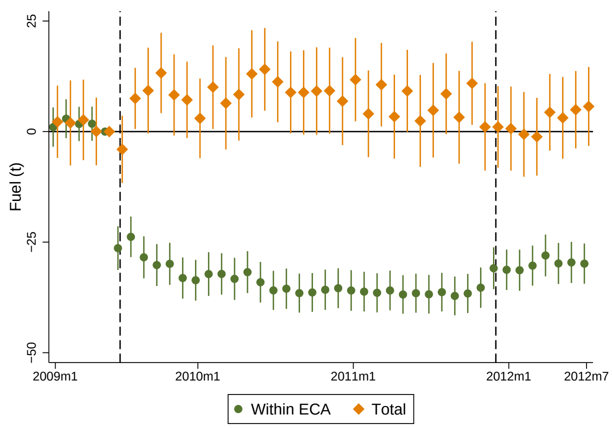
(b) Distance, Entrance/Exit



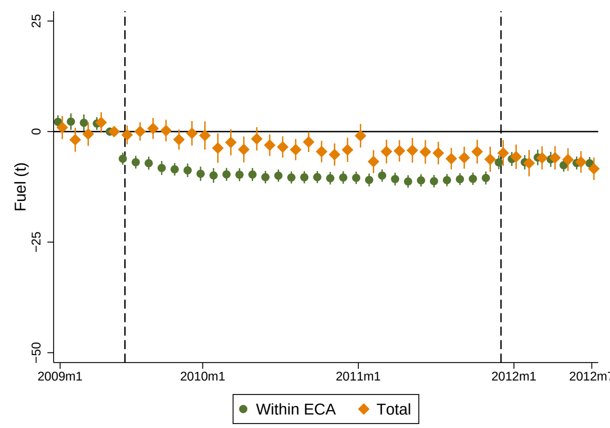
(c) Speed, Port-to-Port



(d) Speed, Entrance/Exit



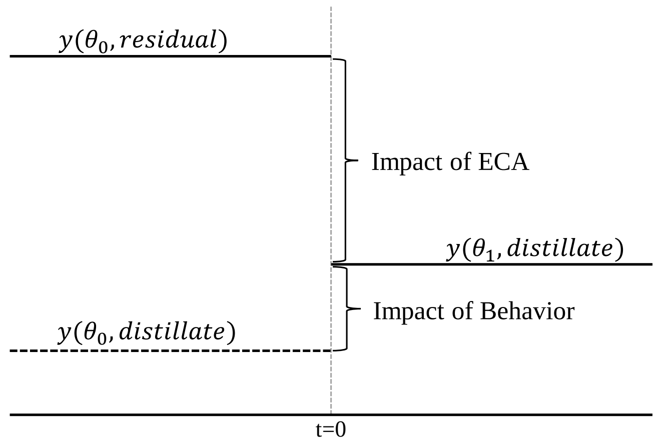
(e) Fuel, Port-to-Port



(f) Fuel, Entrance/Exit

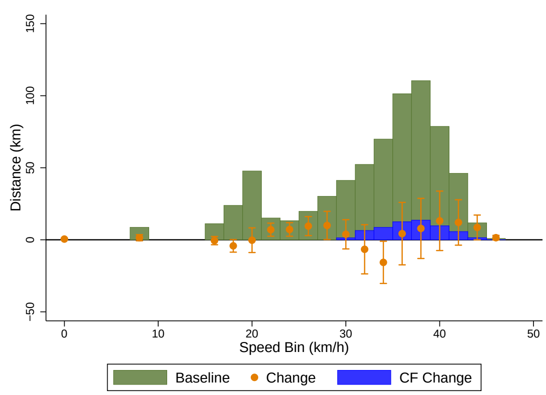
Notes: Points are monthly averages of outcome variables after partialling out route fixed effects. The first month prior to the establishment of the ECA is omitted, so that the coefficients are all differences from this month. Lines represent 95% confidence intervals, clustered by vessel, which are relevant for pairwise comparisons to the omitted month. The dashed vertical lines depict the implementation of the ECA in July of 2009 and the boundary change in December of 2011. Original ECA boundaries are used to calculate within ECA measures.

Figure 5: Effect of the Establishment of the ECA on Container Ship Behavior

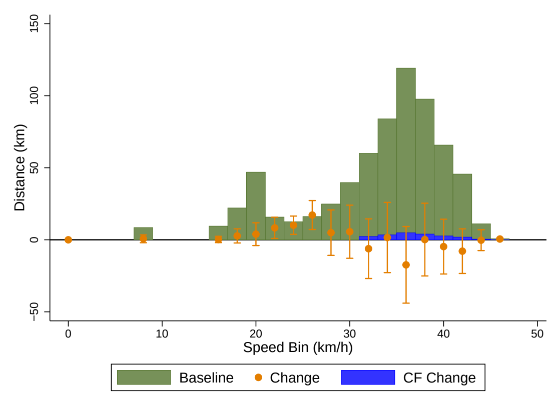


Notes: Y-axis represents time, with policy change occurring at $t = 0$. Outcomes, y, for any voyage depend on a vector of behaviors (speed profile, distance, location of travel), $\boldsymbol{\theta_i}$, and what fuel is used within the ECA (residual or distillate).

Figure 6: Graphical Depiction of the Strategy to Isolate Behavioral Adjustments



(a) Avoiders



(b) Remainers

Notes: Speed bins are between 0-8 km/h, 8-16 km/h, and then in 2 km/h increments between 18 and 48 km/h. Orange points are changes in average distance traveled in each speed bin after policy change. Error bars represent 95% confidence intervals, clustered by vessel. Green bars are average distance traveled in each speed bin in the pre policy period. Blue bars are counterfactual changes in distance assuming that any additional distance been added proportionally to pre policy speed bins after removing the slowest 200 km.

Figure 7: Effect of the Establishment of the ECA on Container Ship Speed Profiles on LA/LB–San Francisco Bay Route

	(1)	(2)	(3)	(4)	(5)	(6)
	ECA Dist (km)	ECA Speed (km/h)	ECA Fuel (t)	Fuel Cost Comply Pre ($)	PM Comply Pre (t)	Damage Comply Pre ($)
(i) Container – Port-to-Port (n=1,259, vessels=270)						
CA ECA (2009)	-245.3***	-4.125***	-26.49***	-5,323***	0.187***	17,385***
	(18.68)	(0.626)	(2.472)	(1,052)	(0.0197)	(1,877)
R-squared	0.852	0.682	0.834	0.947	0.928	0.833
Mean (t=0)	548.5	31.57	51.55	53224	0.250	13675
Mean (t=-30)	549.1	31.63	51.96	54050	0.257	14362
% change	-44.72	-13.07	-51.39	-10	74.86	127.1
Spillover ratio	1.159		1.112			
Δ no behave				12831	-0.310	-71315
% of no behave				-41.49	-60.26	-24.38
(ii) Container – Ent/Exit (n=1,896, vessels=320)						
CA ECA (2009)	-43.04***	-2.316***	-5.439***	-1,842***	0.0276***	3,665***
	(6.407)	(0.621)	(0.827)	(607.3)	(0.00792)	(778.8)
R-squared	0.859	0.744	0.841	0.951	0.933	0.895
Mean (t=0)	178.5	27.74	15.27	25694	0.216	14225
Mean (t=-30)	180.2	27.88	15.76	25944	0.215	14199
% change	-24.11	-8.350	-35.62	-7.168	12.76	25.77
Spillover ratio	1.022		0.839			
Δ no behave				4488	-0.108	-35386
% of no behave				-41.03	-25.51	-10.36
(iii) Other Cargo – Port-to-Port (n=317, vessels=189)						
CA ECA (2009)	-71.19**	-1.382	-3.607**	-2,075	0.00590	2,278
	(31.62)	(1.628)	(1.743)	(2,280)	(0.0305)	(1,833)
R-squared	0.584	0.245	0.471	0.859	0.867	0.818
Mean (t=0)	314.3	21.69	12.04	30581	0.319	15130
Mean (t=-30)	324.1	22.23	12.27	29324	0.298	14561
% change	-22.65	-6.370	-29.95	-6.785	1.852	15.05
Spillover ratio	0.800		0.369			
Δ no behave				2984	-0.0720	-23409
% of no behave				-69.53	-8.201	-9.729
(iv) Other Cargo – Ent/Exit (n=1,014, vessels=478)						
CA ECA (2009)	-21.82***	-1.975**	-0.752*	521.7	0.0149***	1,159***
	(6.481)	(0.779)	(0.397)	(455.7)	(0.00507)	(444.3)
R-squared	0.869	0.198	0.653	0.721	0.695	0.695
Mean (t=0)	157.4	22.64	5.604	8589	0.0672	5845
Mean (t=-30)	156.6	22.50	5.738	8869	0.0699	6005
% change	-13.86	-8.724	-13.41	6.073	22.24	19.82
Spillover ratio	1.416		2.891			
Δ no behave				1537	-0.0371	-15226
% of no behave				33.93	-40.30	-7.610
(v) Tanker – Port-to-Port (n=336, vessels=119)						
CA ECA (2009)	-28.36	0.903	-2.696	-2,348	-0.00625	1,393
	(28.13)	(1.281)	(1.891)	(2,556)	(0.0374)	(1,651)
R-squared	0.478	0.271	0.407	0.839	0.835	0.756
Mean (t=0)	221.6	20.65	11.29	40563	0.466	24493
Mean (t=-30)	219.3	21.33	11.01	40445	0.467	24728
% change	-12.80	4.375	-23.89	-5.790	-1.342	5.688
Spillover ratio						
Δ no behave				3341	-0.0799	-38178
% of no behave				-70.29	7.826	-3.649
(vi) Tanker – Ent/Exit (n=658, vessels=286)						
CA ECA (2009)	-6.679	-0.430	-2.534	-1,820	-0.00127	-576.3
	(8.058)	(1.282)	(1.841)	(1,403)	(0.00982)	(1,074)
R-squared	0.701	0.155	0.254	0.682	0.836	0.631
Mean (t=0)	128	20.67	10.12	17428	0.148	11511
Mean (t=-30)	128.5	20.15	9.407	16700	0.145	11048
% change	-5.217	-2.078	-25.05	-10.44	-0.857	-5.007
Spillover ratio						
Δ no behave				2385	-0.0560	-38352
% of no behave				-76.29	2.270	1.503

Notes: Standard errors in parentheses are clustered by vessel. All regressions include fuel prices and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Container specifications include vessel-by-route fixed effects. Other cargo and tanker specifications include route fixed effects and vessel characteristic controls. Spillover ratio is change in outcome outside the ECA divided by reduction in outcome within the ECA and only reported if the within-ECA change is statistically significant with $p<0.1$. "Δ no behave" row is change in outcome had vessels only adopted lower sulfur fuels and not adjusted on other margins, which is calculated using pre policy observations. "% of no behave" is change in outcome due to behavioral adjustments relative to the no behavior change counterfactual.

Table 1: Estimated Effects of the Establishment of the ECA

	(1)	(2)	(3)	(4)	(5)	(6)
				Fuel Cost	PM	Damage
	ECA Dist	ECA Speed	ECA Fuel	Comply Pre	Comply Pre	Comply Pre
	(km)	(km/h)	(t)	($)	(t)	($)
(i) Avoiders (n=528, vessels=117)						
CA ECA (2009)	-441.8***	-6.703***	-47.18***	-6,492***	0.376***	36,620***
	(11.50)	(0.976)	(2.700)	(1,495)	(0.0233)	(2,226)
R-squared	0.967	0.745	0.893	0.889	0.857	0.867
Mean (t=0)	607.8	31.71	61.12	50374	0.114	8164
% change	-72.68	-21.14	-77.19	-12.89	330.7	448.6
Spillover ratio	1.157		1.238			
Δ no behave				15611	-0.378	-84105
% of no behave				-41.59	-99.58	-43.54
(ii) Remainers (n=335, vessels=87)						
CA ECA (2009)	-117.4***	-2.245***	-16.78***	-6,576***	0.0722***	6,128***
	(21.53)	(0.757)	(3.358)	(1,915)	(0.0192)	(1,370)
R-squared	0.752	0.571	0.854	0.895	0.680	0.711
Mean (t=0)	606.6	32.22	61.27	53114	0.152	11378
% change	-19.35	-6.968	-27.38	-12.38	47.51	53.86
Spillover ratio	1.193		0.733			
Δ no behave				16095	-0.390	-86273
% of no behave				-40.86	-18.53	-7.103

Notes: Standard errors in parentheses are clustered by vessel. Bandwidth is 150 days. Sample includes container ships on the LA/LB–San Francisco Route. We restrict sample to 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 observed both pre and post policy. Spillover ratio is change in outcome outside the ECA divided by reduction in outcome within the ECA and only reported if the within-ECA change is statistically significant with $p<0.1$. "Δ no behave" row is change in outcome had vessels only adopted lower sulfur fuels and not adjusted on other margins, which is calculated using pre policy observations. "% of no behave" is change in outcome due to behavioral adjustments relative to the no behavior change counterfactual.

Table 2: Heterogeneity due to Avoidance in the Effects of the Establishment of the ECA on Container Ships

	Total	Vessel Type		
		Container	Other Cargo	Tanker
Voyages	1067	550	284	233
(i) Vessel Behavior and Emissions				
Distance Within ECA (1000 km)	258.31	163.50	58.53	36.28
Δ due to ECA	-72.50	-60.18	-9.63	-2.70
Fuel Within ECA (1000 t)	19.31	14.80	2.11	2.41
Δ due to ECA	-7.79	-6.74	-0.40	-0.64
PM (t)	353.29	221.20	52.21	79.87
Δ due to ECA	-68.22	-44.53	-7.99	-15.69
Δ due to Behavior	47.95	42.95	4.34	0.66
(ii) Welfare				
Pollution Damage (million \$)	55.07	32.85	7.30	14.92
Δ due to ECA	-35.56	-20.16	-4.33	-11.07
Δ due to Behavior	4.86	4.39	0.43	0.04
Fuel Costs (million \$)	25.08	15.95	3.67	5.46
Δ due to ECA	2.79	1.95	0.53	0.30
Δ due to Behavior	-2.05	-1.68	0.02	-0.40
Net Benefits of ECA	32.77	18.21	3.80	10.77
Net Benefits of ECA, No Behavior	35.58	20.92	4.25	10.41
Net Benefits of Behavior Change	-2.80	-2.71	-0.45	0.36
(iii) Other Welfare Impacts				
CO_2 and NOx Damages (million \$)	18.80	11.99	2.65	4.16
Δ due to ECA	-0.91	-0.61	0.12	-0.43
Time Costs (million \$)	13.58	5.14	3.76	4.68
Δ due to ECA	-0.01	0.08	0.49	-0.58
Within Port Pollution Damage (million \$)	41.73	28.88	3.80	9.06
Δ due to ECA	-39.14	-27.01	-3.45	-8.67
Within Port Fuel Costs (million \$)	2.43	1.41	0.31	0.71
Δ due to ECA	2.32	1.24	0.25	0.83

Notes: All values are monthly totals calculated based on estimates from separate regressions by port (northern California and southern California), vessel type, and route type (port-to-port and entrance/exit). Voyage counts are monthly averages for the period when the ECA is in place with the original boundaries. We include voyages that we drop from our analysis sample due to missing origins or destinations by scaling up voyage counts by port while assuming that the dropped voyages had identical route shares as the voyages in our analysis sample.

Table 3: Monthly Total Welfare Impacts of the ECA

Supplemental Appendix for "Local Standards, Behavioral Adjustments, and Welfare: Evaluating California's Ocean-Going Vessel Fuel Rule"

Richard Klotz and Julia Berazneva

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A Additional Results

A.1 Specification and Sample Choices

Results in Tables A.6 and A.7 illustrate the robustness of our estimates to various specifications. We analyze the establishment of the ECA and report estimates for port-to-port routes in Table A.6 and entrance/exits in Table A.7. Column (1) is our preferred specification. Focusing on the port-to-port sample columns (2)-(5) show, respectively, that we obtain similar results if we drop the 30 days prior to the policy change from the time index, drop the fuel price controls, use a homogeneous linear trend instead of route trends, or restrict our analysis to vessels we observe both pre and post policy.[1]

Although the cost increases imposed by the ECA are relatively small, shipping companies – which manage fleets of vessels – could respond by adjusting the types of vessels that operate on exposed routes. If operators shift vessels better able to adjust to the ECA to exposed routes, this could alter the fuel cost impacts of behavioral adjustments. To allow for this potential margin of adjustment we estimate models with operator-by-route fixed effects. A major caveat of this analysis is that data on operators in our vessel characteristics data set is limited in that 1) it only contains current operator (i.e., as of August 2019 when we accessed the data) and 2) it is considerably more incomplete than other fields. We find that estimates with operator-by-route fixed effects, column (7), are extremely similar to those with vessel-by-route fixed effects, whether we use the full sample or a sample of voyages with operator information, column (6).

Columns (8) and (9) explore specifications that include route fixed effects, which allow for shifts in composition of vessels on particular routes to contribute to the treatment effect. Again, the estimated impacts on fuel costs tend to be similar but slightly larger than with vessel-by-route fixed effects. It is also worth pointing out that the estimation with route fixed effects and vessel controls yields nearly identical results to our full specification, which provides some support for the specification we use for other cargo vessels and tankers.

Estimates for the entrance/exit sample are generally robust across specifications, but slightly more sensitive to the inclusion of route trends and sample restrictions (columns (4) and (5)) because this sample has less well defined routes.

A.2 Impacts of 2011 Boundary Change

Tables A.9 displays results for the impact of the 2011 ECA boundary changes. We find that the boundary changes affect distance, speed and fuel consumption in the ECA only for routes from southern California ports, but that the fuel costs and pollution damage changes associated with these behavioral adjustments tend to be small and comparable in magnitude. Since vessel behavior is already distorted, the potential net-benefits of expanding the boundary are not greatly eroded

[1] To adjust the time index we add 30 to all pre ECA values of the time index (so $t = -30$ is set to $t = 0$, etc.). Comparisons between this column and the baseline specification illustrate the impacts of extrapolation over the month prior to the implementation of the ECA.

by changes in behavior. We note that there are strong background trends in fuel consumption due to the adoption of slow steaming during this period.

Average effects of the boundary change mix responses by vessels that return to the Santa Barbara Channel with those that travel farther to avoid the broader boundary. We explore this heterogeneity for container ships on the LA/LB–San Francisco Bay route as we did in Section 5.3. Prior to the boundary change in 2011 only 10% of voyages use the channel, but the usage jumps to 44% upon the boundary change and to 60% after six months. We classify vessels that return to the channel as "returners" and those continuing to avoid the channel as "avoiders."[2] We present regression results for these subsamples in Table A.10 and changes in speed profiles in Figure A.8.

A.3 Marginal Damage and Emission Factors

In Table A.14 we report estimated changes in fuel costs and pollution damages for container vessels on port-to-port (panel (i)) and entrance/exit (panel (ii)) routes under various assumptions used to link behavior to final outcomes. Our central results are reported in columns (1) and (3). In the columns labeled "(1%)" we report changes in costs and damages assuming that vessels use fuels with 1% sulfur content – the average of OGV Rule's MGO and MDO sulfur limits in 2009 – within the ECA, as opposed to the observed average sulfur content for distillate fuel, which is assumed in our central results. The distillate fuel price and emission factors for this scenario are calculated assuming that vessels use a mixture of distillate and residual fuels that achieves the 1% sulfur limit. Under this assumption, the private benefits of behavioral adjustments are slightly lower than our central results due to the smaller price premium for distillate fuel. On the benefits side, behavioral adjustments still reduce environmental benefits by about 25% on port-to-port routes, but the level of the reduction is considerably smaller.

We report changes in damages using marginal damages from AP2 in column (5). Marginal damages from AP2 are lower on average and exhibit a shallower spatial gradient than those from ISRM. As a result, behavioral adjustments wipe out a much larger fraction (57%) of reductions in pollution damages. Under AP2 marginal damages, reductions in pollution in coastal areas are less beneficial, while the increases in pollution outside the ECA are relatively more damaging. Due to the large costs of the pollution spillover with AP2 marginal damages, fuel cost increases actually exceed the benefits from pollution damages on port-to-port routes. Largely due to avoidance, the overall welfare impact of the California ECA depends critically on the spatial gradient of marginal damages.

A.4 Impacts on Activity Outside the Study Area

Here we provide additional evidence that suggests adjustments outside the study area have limited effects on costs or benefits of the ECA by studying a subset of entrance/exit voyages for which we can interpolate full voyages to origins/destinations in Alaska and Hawaii. Our interpolation procedure (Section B.1) mainly adds voyages to/from the Port of Honolulu and the Unimak Pass, a major vessel traffic choke point through the Aleutian Islands in Alaska. With this set of interpolated voyages, we construct measures of total distance traveled, distance traveled within the study area, and distance traveled outside the study area. We restrict our analysis to interpolated voyages for which we have AIS records crossing the study area boundary so that our results are less dependent on the interpolated portion of the voyage.

Pre and post ECA averages of the three distance measures by route are reported in Table A.12. A major caveat is that sample is small, so the means are imprecisely estimated and we cannot reject that most differences are zero. Vessels connecting to Hawaii do not change total distance

[2] Again, selection bias is an important caveat when comparing returners and avoiders. Vessels that return are older and more likely to be U.S. flagged (Table A.11), but differences in characteristics are small on average.

or distance within the study area, because pre policy traffic patterns on these routes pass directly through the ECA. Notable changes are evident for vessels traveling through the Unimak Pass. For vessels moving between southern California ports and the Unimak Pass, total distance increases around 20 km due to the 150 km reduction in distance within the ECA. The changing angle at which vessels enter/exit LA/LB causes distance within the study area to fall by about 40 km. Taken together, distance traveled outside the study area increases by around 60 km per voyage. Similar, although smaller effects are evident on the northern California to Unimak route.Fuel consumption outside the study area increases by 5.8 and 3.8 tons for southern and northern California routes, respectively, which adds $2,200 and $1,500 in fuel costs and, at most, $1,800 and $1,200 in damages.

For these calculations we assume that vessels consume 0.096 tons of fuel per kilometer, which is the pre ECA mean. We construct upper bound estimates for changes in pollution damages by using marginal damages from the approximate location where the voyages cross the study area, 5,000 and 7,500 $/t for SO_2 and PM, which is likely the highest marginal damage could be for the remaining portion of the voyage.

A.4.1 Other Margins of Adjustment

Here we provide evidence that suggests responses along margins of adjustment not captured in our within-route changes are likely to be minimal. First, there is little evidence that shipping companies are changing the characteristics of vessels operating on exposed routes (e.g., shifting to more fuel efficient vessels). We find that estimates using operator-by-route fixed effects and route fixed effects are very similar to our central estimates (Tables A.6 and A.7 in Appendix).[3] Moreover, we find no evidence of within-route changes in the vessel characteristics in response to the ECA (Table A.15 in Appendix), which further rules out operators adjusting which vessels to service California ports.

Diversion of vessel traffic to other west coast ports or other modes is also unlikely. The average container vessel visiting a California port carries 5,300 twenty-foot equivalent (teu) containers. If this average vessel was operating on the highly exposed triangle route – Asia to LA to San Francisco to Asia, increased fuel costs would be, at maximum, 4 $/teu on a full vessel.[4] These cost increases are quite small relative to the 850 $/teu average freight rate on Pacific routes between 2009 and 2011 (UNCTAD 2017). Moreover, previous studies argue that charges in California ports have to increase by 30-40 $/teu before any significant diversion to other ports will take place (Corbett et al. 2006; Leachman 2010).

A.5 Other Welfare Impacts

In panel (iii) of Table 3 we quantify other potential welfare impacts of the ECA that are not captured in our main analysis.

First, we measure changes in damages from two correlated pollutants – CO_2 and NO_x – related to fossil fuel combustion, which may change due to the ECA's impact on the quantity and location of fuel consumption.[5] We explore the channels underlying the changes in correlated pollutants in a related paper (Klotz and Berazneva 2020) and find that reductions in damages from NO_x emissions due to the shift of fuel consumption away from population centers dominates increased CO_2 damages related to increased fuel use. Second, we value the time costs associated with the

[3]We do not want to place too much weight on the operator fixed effect analysis because, as discussed in Appendix, our data on operators is limited along a number of dimensions.

[4]The estimated increases in fuel costs are $4,500 for the entrance to LA, $9,000 for LA to San Francisco, then $4,200 for the exit from San Francisco. This is likely an upper bound estimate per container given that vessels could also pick up containers at each stop.

[5]Damages from secondary conversion of NO_x to $PM_{2.5}$ are valued using ISRM; damages from CO_2 are assumed to be 50 $/t CO_2.

behavioral adjustments vessels undertake in response to the ECA. Assuming a value of time of \$500 per hour for all vessel types, we find that time costs on average decrease by \$0.01 million.[6] Time costs would be small relative to pollution damage benefits even without the time cost savings associated with tankers.

Third, we report rough estimates for changes in within-port fuel costs and pollution damages for the vessel movements that start/end at our defined port entrance and terminate within the port (Table A.16)[7] and find that the ECA would generate additional \$36.8 million in net benefits. This result only reinforces our finding that the ECA generates net benefits because vessels cannot avoid the regulated area in the highest marginal damage areas.

Finally, in panel (iv) we report pollution damage outcomes using marginal damages from AP2 to illustrate that welfare gains generated by the ECA hinge critically on the spatial gradient of marginal damages. Using the lower and more spatially homogenous marginal damages from AP2, we find that the impact of behavior on pollution damages is relatively more important. In fact, due to behavioral adjustments, the ECA is no longer welfare improving even if within port impacts are considered.

B Data Procedures

B.1 Track Creation from AIS Data

B.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 data set 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.[8] Dropping the records with low SOG eliminates the creation of very complicated geometries generated by ships that are moored or otherwise stationary.

B.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.

[6] We use an upper bound estimate of the value of time from the literature. Using revealed preference methods Ahl et al. (2017) place the value of time at \$425 for container ships, \$315 for bulk carriers, and \$400 for tankers visiting California ports.

[7] We consider this to be a rough estimate since within-port fuel use is predominately from auxiliary engines and we have no way of determining whether the auxiliary engines are operating for the entire port visit or whether their use falls in response to the ECA. In our main analysis, we define voyages to start/end at the entrance of port and therefore do not capture movement between the entrance and the terminal (e.g., between the entrance of the San Francisco Bay and the container terminal at the Port of Oakland).

[8] 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.

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 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 data set 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.9 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.

B.1.3 Route Classification

Our route classifications are based on lines that define the entrances and exits from major ports and U.S. waters (Figure 1). 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.

B.2 Validation of AIS Voyages

We validate our AIS-based voyages by comparing the port entrances observed in the AIS voyage data set with the U.S. Army Corp of Engineer's Entrance/Clearance (EC) data set (US ACE 2018). The EC data set includes records of vessels entering or clearing U.S. ports, including the date, origin or destination port (domestic or foreign), and the vessel's IMO number. A limitation of the EC data set is that it only includes vessels carrying foreign cargo. We merge entrances from the EC data set to our AIS voyages for the years when the AIS data contain IMO codes (2009, 2015, and 2016). An EC record is matched to a voyage if the IMO codes match and if the entrance date in the EC data is within 24 hours of the voyage's end time in the AIS data.

Table A.17 tabulates voyage counts by routes implied by the EC data and the AIS data for entrances to LA/LB (panel (a)) and SF Bay (panel (b)). The first six rows of numbers tabulate voyages by origin in the EC data and the first three columns of numbers tabulate origins corresponding to the AIS data. The counts in the cells formed by these rows and columns report the number of entrances in the EC data that are classified to a particular route in the AIS data. For example, the first cell in panel (a) reports that only 8 entrances to San Francisco from other California ports in the EC data are classified as entrances to San Francisco from the study area boundary in the AIS data.

In the final row we tabulate voyages that only appear in the AIS data ("AISonly"), which are presumably movements of vessels that are not carrying foreign goods. The number of voyages that are classified to the exact route implied by the EC are tabulated in the "Correct" column. Note that it is only possible for us to determine routes between west coast ports using the AIS data, so this count is a subset of the "California" and "Other WC" columns. The "N/A" column tabulates voyages that we cannot classify to a route (e.g., the voyage terminated prior to a port or the study area boundary), while the "NoAIS" column reports the number of voyages for which there was an EC entrance but no corresponding entrance in the AIS data.

There are three major takeaways of the validation exercise. First, most activity in the Entrance/Clearance data set is also observable in the AIS data. Only a small fraction of entrances in the E/C dataset are not observed in the AIS data (NoAIS row). Second, our classification to routes works well for port-to-port and entrance/exit voyages. Across both LA/LB and San Francisco, the AIS voyages correctly classify a large fraction of vessel movements between west coast ports. We are also able to correctly classify the majority of vessel movements from foreign or East Coast ports as coming from the study area boundary. Third, there is a large number of voyages in the AIS data that are not captured by the EC data (AISonly row), which would be made up of vessels serving Alaska and Hawaii (e.g., tankers moving from Alaska to other west coast ports).

B.3 Validation of Fuel Consumption Measures

Our pre ECA estimates of fuel consumption within the ECA, reported in Table 2, 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).

B.4 Recovering Vessel IDs

For 2010 to 2014, the vessel identifiers (IMO and MMSI numbers) 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 numbers 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 (the Maritime Identification Digits, 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 data set of vessels with unique combinations of MMSI numbers, country code, length, width, and vessel type. This data set 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.

B.5 Filling Missing Characteristics

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`.

B.6 Fuel Consumption and Emissions 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.

In our main results, we assume the sulfur content of residual and distillate fuel are 2.7% and 0.1%, respectively. The residual emission factors are reported in IMO (2015). An emission factor for distillate fuel with 0.1% sulfur is not reported so we scale the residual emission factor down by 0.133, which is based on a linear interpolation of the reported emission scaling factors. The SO_2 emission factors are 0.0527 (residual) and 0.00195 (distillate) tons SO_2 per ton fuel (sulfur content of the fuel times $2 * 0.9754$). These apply to both main and auxilliary engines. PM emission factors for main engines are 0.00728 (residual) and 0.00097 (distillate) tons PM per ton fuel. For auxiliary engines the PM emission factors are 0.00634 and 0.000843 tons PM per ton fuel.

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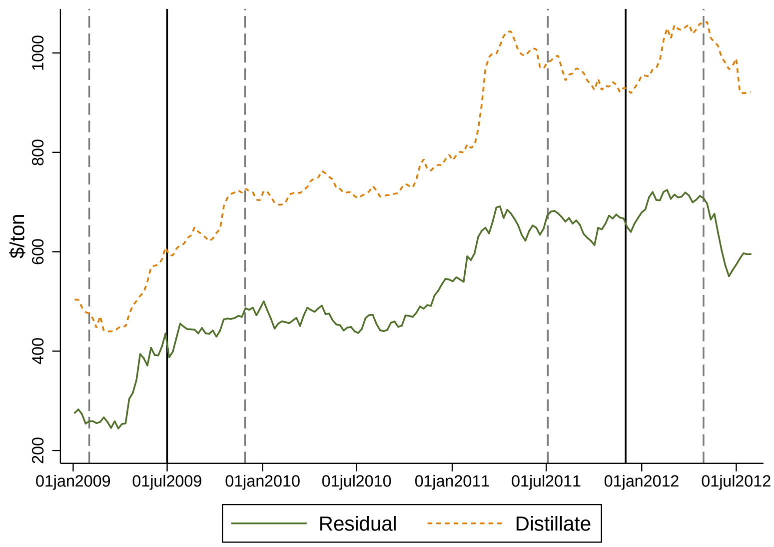
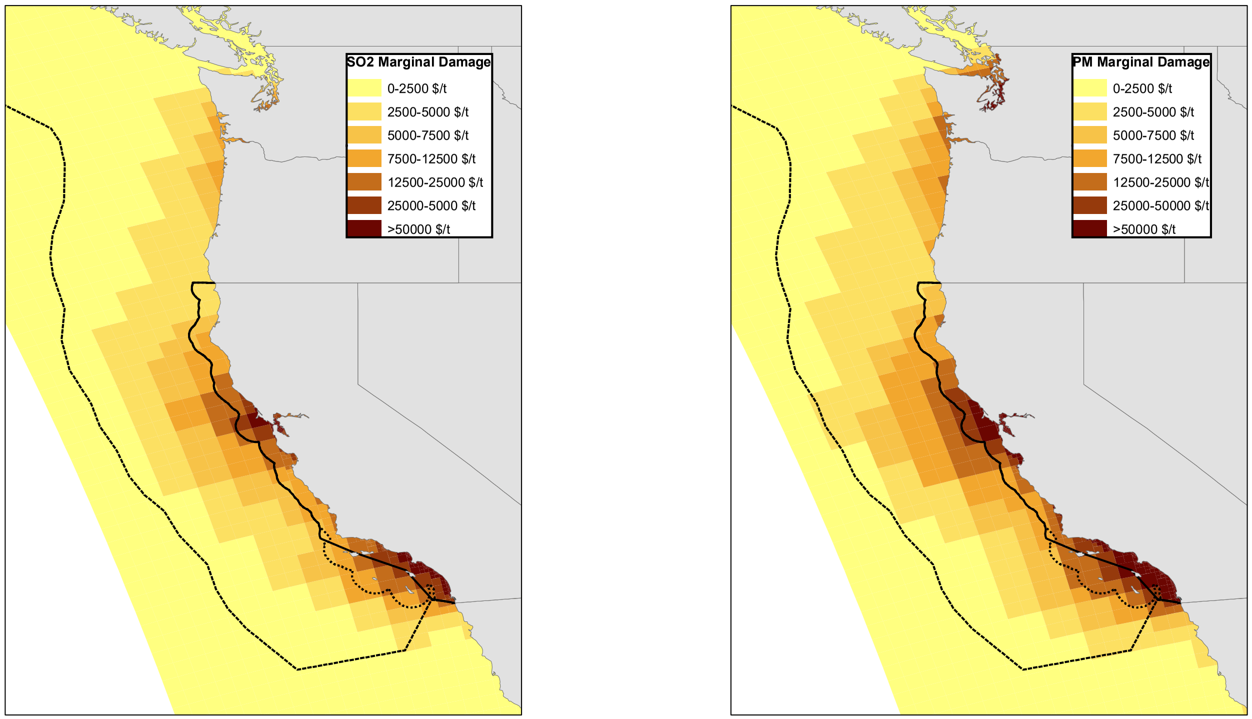


Notes: Residual and distillate fuel prices in Los Angeles from S&P Global. Prices exclude taxes, duties, and wharfage fees. Solid lines represent California ECA implementation and 2011 boundary change. Dashed gray lines depict 150 day window on either side of policy date.

Figure A.1: Marine Fuel Prices over Time

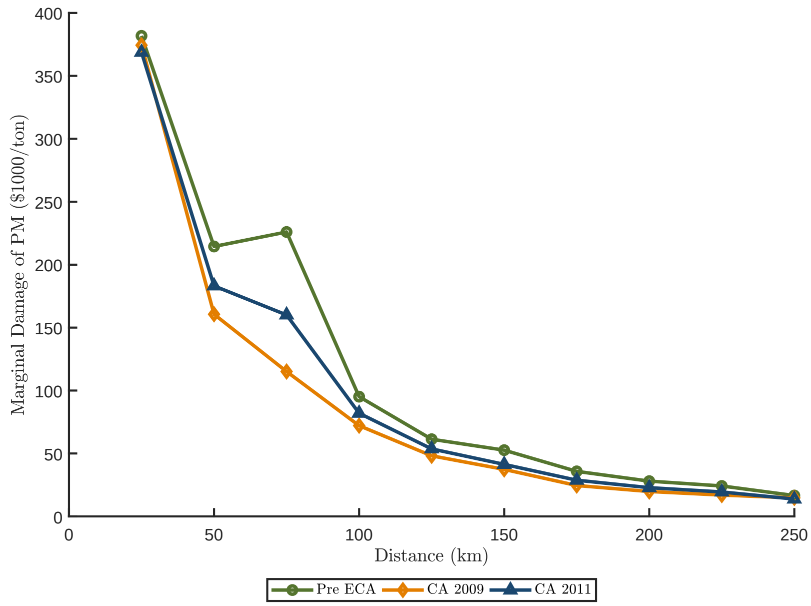


(a) SO_2

(b) PM 2.5

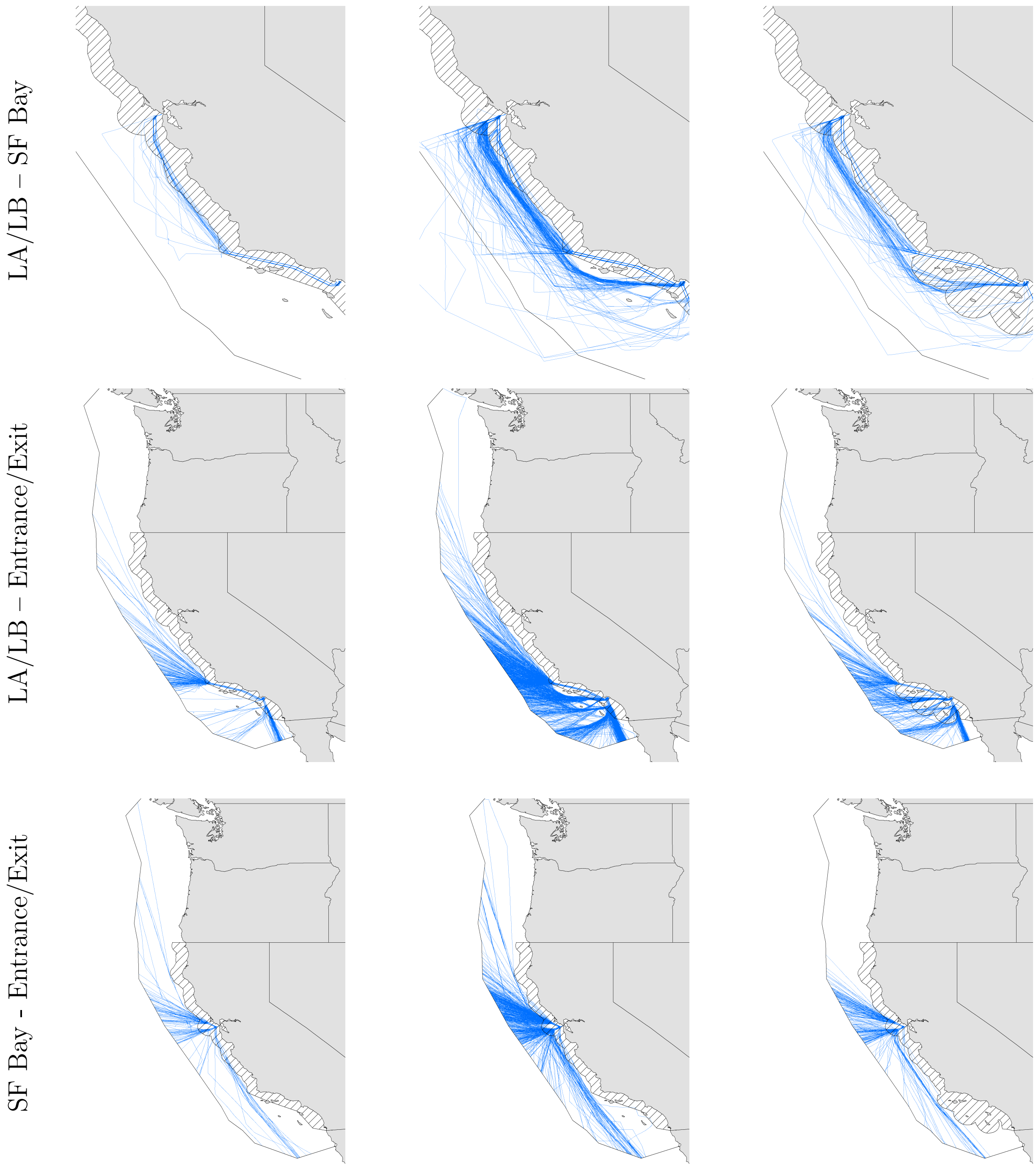
Notes: Marginal damage estimates for ground-level releases generated using the InMAP Source-Receptor Matrix (ISRM) (Goodkind et al. 2019). Grid size varies with finer spatial resolution in populated areas.

Figure A.2: Spatial Heterogeneity in Marginal Damages



Notes: Lines represent average marginal damages for $PM_{2.5}$ in distance bins for first 250km along route under different policy treatments. All vessels moving from LA/LB to SF Bay. Steam-turbine-powered vessels are excluded.

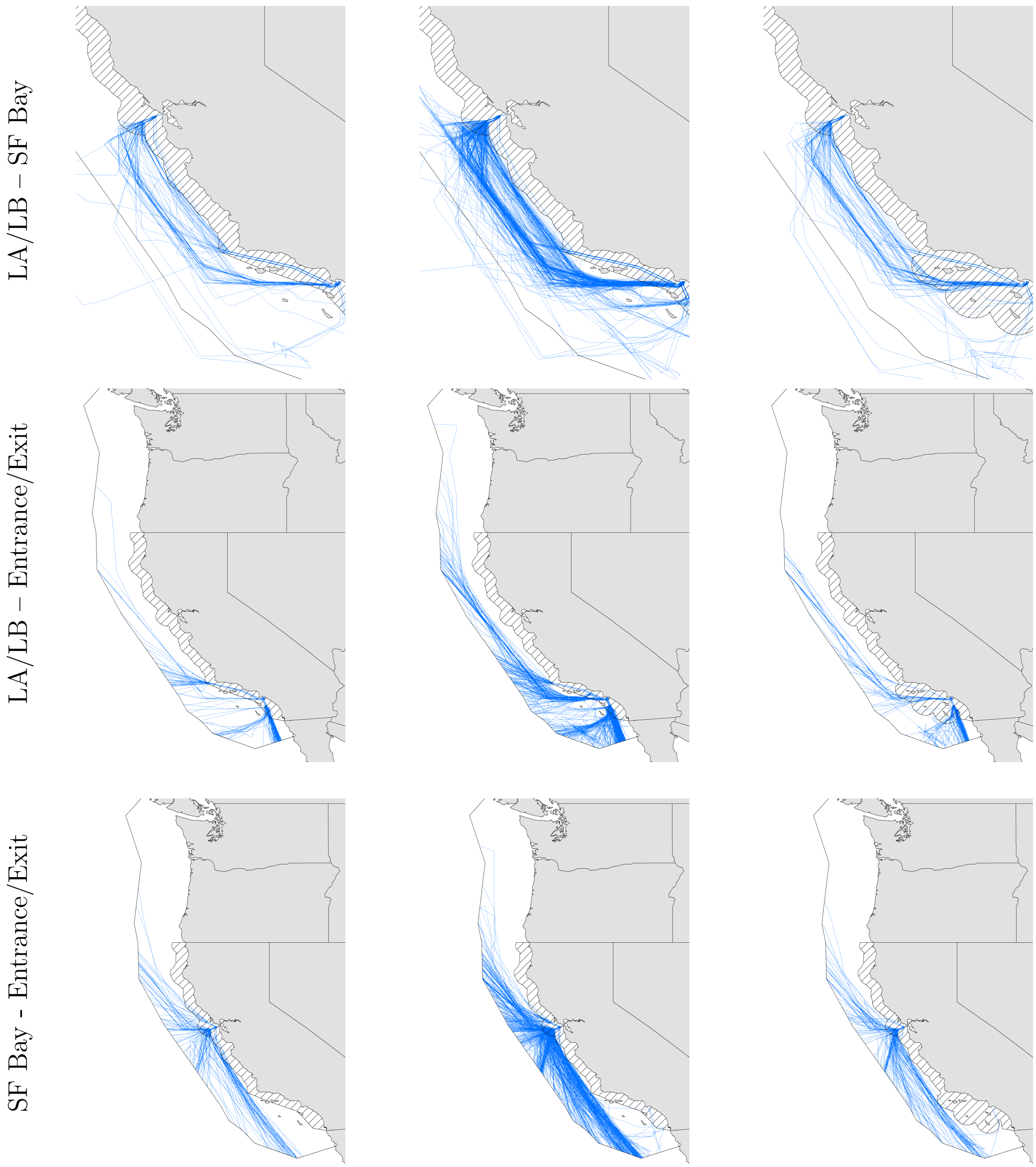
Figure A.3: Marginal Damages Profile for Container Ships From LA/LB to SF Bay



(a) Pre ECA (b) 2009 ECA (c) 2011 ECA

Solid black line represents the study area boundary. Hashed area depicts the relevant California ECA. For reference, the 2009 California ECA boundary is displayed in the Pre ECA maps. Pre ECA column includes voyages from January 2009 to June 2009; 2009 ECA column includes voyages from July 2009 to December 2011; 2011 ECA column includes voyages from January 2011 to July 2012.

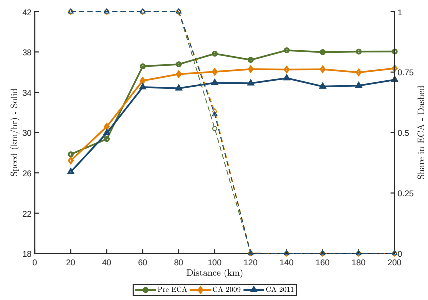
Figure A.4: Other Cargo Ship Voyages on Major Routes



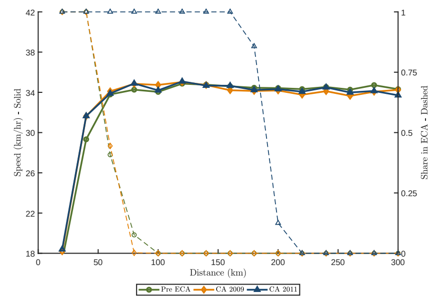
(a) Pre ECA (b) 2009 ECA (c) 2011 ECA

Solid black line represents the study area boundary. Hashed area depicts the relevant California ECA. For reference, the 2009 California ECA boundary is displayed in the Pre ECA maps. Pre ECA column includes voyages from January 2009 to June 2009; 2009 ECA column includes voyages from July 2009 to December 2011; 2011 ECA column includes voyages from January 2011 to July 2012.

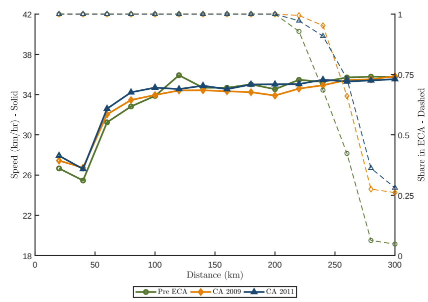
Figure A.5: Tanker Voyages on Major Routes



(a) San Francisco Bay – West



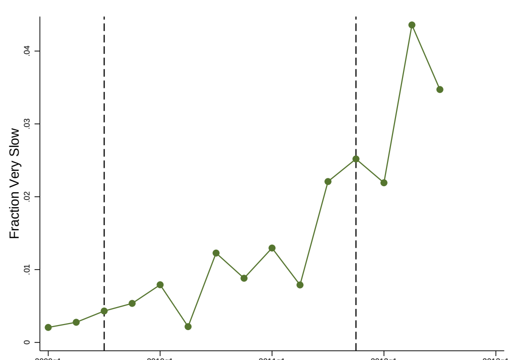
(b) LA/LB – West



(c) Seattle – San Francisco Bay

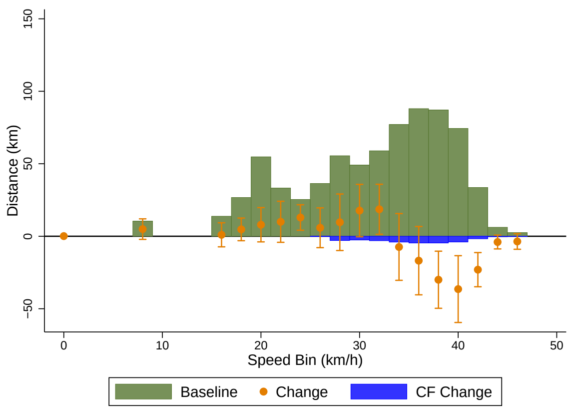
Notes: Solid lines represent average speed in distance bins under different policy treatments. Horizontal axis reports distance along route from the California port. Dashed lines represent average share of distance traveled within the ECA boundaries. All vessels moving from the first listed port to the second listed port. Panels (a) and (b) includes only vessels exiting California ports. Seattle–San Francisco Bay panel includes only vessels entering San Francisco. Pre ECA share within the ECA boundaries is based on the 2009 boundaries.

Figure A.6: Exempt Container Ship Speed Profiles on Major Routes

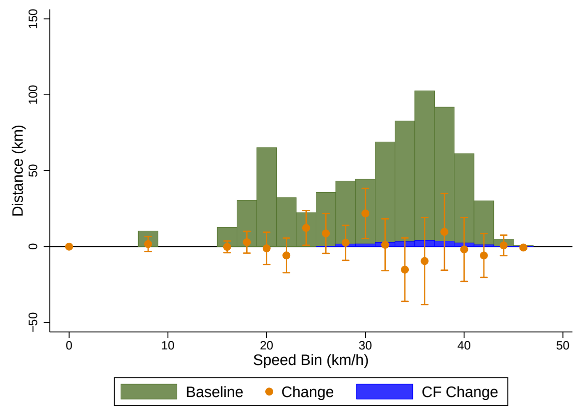


Notes: Plot denotes fraction of container ship voyages between California and other west coast ports that spend more than 75% of total distance traveling below 24 km/h. Dashed horizontal lines denote the establishment of the ECA in 2009 and the ECA boundary change in 2011.

Figure A.7: Adoption of Very Slow Steaming by Container Ships



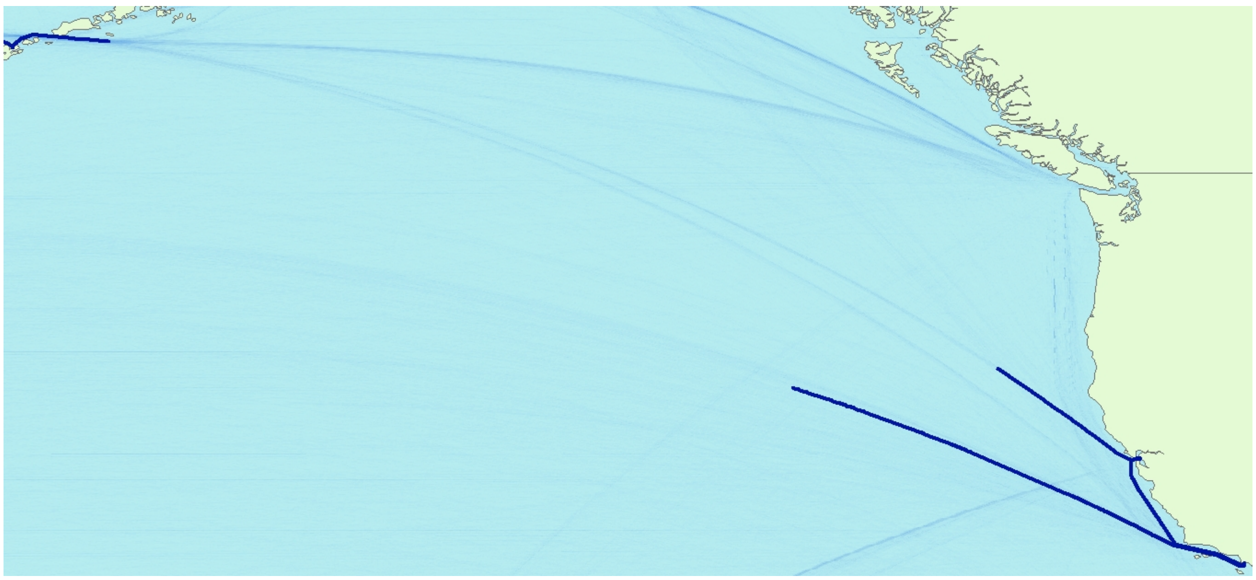
(a) Returners



(b) Avoiders

Notes: Speed bins are between 0-8 km/h, 8-16 km/h, and then in 2 km/h increments between 18 and 48 km/h. Orange points are changes in average distance traveled in each speed bin after policy change. These points are estimated in a regression that includes vessel-by-speed-bin fixed effects. Error bars represent 95% confidence intervals, clustered by vessel. The sample includes observations within 150 days of the policy change. Green bars are average distance traveled in each speed bin in the pre policy period. Blue bars are counterfactual changes in distance assuming that any additional distance been added proportionally to pre policy speed bins after removing the slowest 200 km.

Figure A.8: Effect of the ECA Boundary Change on Container Ship Speed Profiles on LA/LB–San Francisco Bay Route



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 data set 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.9: Example of Interpolated Voyage

Table A.1: Voyage Counts by Route and Vessel Type

	Total	Container	Other Cargo	Tanker
(i) All West Coast Ports				
Total Voyages	48,640	22,435	19,350	6,855
Port-to-Port	14,240	7,328	4,608	2,304
Entrance/Exit	34,400	15,107	14,742	4,551
(ii) Southern California Ports				
Total Voyages	24,781	13,753	7,504	3,524
LA/LB	22,242	13,517	5,263	3,462
San Diego	1,546	222	1,305	19
Hueneme	1,613	21	1,543	49
Port-to-Port	9,526	5,612	2,422	1,492
to/from San Francisco Bay	7,167	5,321	839	1,007
to/from Seattle	1,342	275	618	449
to/from Portland	366	8	329	29
Entrance/Exit	15,255	8,141	5,082	2,032
South	6,889	2,506	2,862	1,521
West	8,217	5,526	2,198	493
North	149	109	22	18
(iii) Northern California Ports				
Total Voyages	9,094	5,065	1,890	2,139
San Francisco Bay	9,074	5,064	1,871	2,139
Port-to-Port	2,443	1,252	507	684
to/from Seattle	1,976	1,168	332	476
to/from Portland	460	83	173	204
Entrance/Exit	6,651	3,813	1,383	1,455
South	880	173	172	535
West	5,631	3,592	1,142	897
North	140	48	69	23
(iv) Other West Coast Ports				
Total Voyages	14,765	3,617	9,956	1,192
Seattle	11,998	3,602	7,310	1,086
Portland	4,289	477	3,594	218
Port-to-Port	2,271	464	1,679	128
Entrance/Exit	12,494	3,153	8,277	1,064
South	645	16	542	87
West	809	19	641	149
North	11,040	3,118	7,094	828

Notes: Sample includes all voyages that connected to west coast ports between January 2009 and the implementation of the North American ECA in August of 2012. Port breakdowns do not sum to totals because some minor ports are excluded from the table and because there are port-to-port routes within the aggregate port groupings (e.g., Hueneme to San Diego in southern California). Entrance/Exit classifications are based on where the voyages cross the study area boundary (Figure 1). South is the boundary south of San Diego. West is the boundary between San Diego and the California/Oregon border. North is the boundary north of the California/Oregon border. Starting in 2010, we classify cargo vessels with missing vessel characteristics to container or other cargo types based on length and ports visited (because container ships are unlikely to stop at smaller ports).

Table A.2: Mean Vessel Characteristics by Vessel Type

	Container	Other Cargo	Tanker
Length (m)	268	185	211
	(46.1)	(30.5)	(43.8)
Main Engine Power (kW)	41,828	9,889	11,597
	(18,985)	(3,798)	(5,022)
Speed (km/h)	32.4	24.7	21.3
	(5.3)	(5.96)	(6.83)
Fuel Consumption (t/km)	.0956	.0398	.0624
	(.0345)	(.0128)	(.0307)
N	2122	799	583

Notes: Standard deviations in parentheses. Sample includes all voyages connecting to California ports prior to the establishment of the ECA for which we are able to merge vessel characteristics.

Table A.3: Estimated Effects of the Establishment of the ECA, Supplemental Outcomes

	(1)	(2)	(3)	(4)	(5)
	Dist (km)	Fuel (t)	SB Channel	Travel Time (h)	ECA PM Comply Pre (t)
(i) Container – Port-to-Port (n=1,259, vessels=270)					
CA ECA (2009)	38.97***	2.977*	-0.366***	0.993*	-0.0274***
	(4.584)	(1.667)	(0.0546)	(0.553)	(0.00247)
R-squared	0.996	0.957	0.784	0.933	0.839
Mean (t=0)	849.9	79.39	0.847	26.71	0.0545
Mean (t=-30)	850.2	80.82	0.845	26.52	0.0549
% change	4.585	3.750	-43.18	3.720	-50.21
Spillover ratio					
(ii) Container – Ent/Exit (n=1,896, vessels=320)					
CA ECA (2009)	0.961	-0.877	-0.170***	-0.181	-0.00568***
	(4.986)	(1.028)	(0.0275)	(0.498)	(0.000852)
R-squared	0.972	0.953	0.885	0.801	0.843
Mean (t=0)	433.9	43.25	0.364	14.36	0.0166
Mean (t=-30)	432.6	43.50	0.362	14.08	0.0171
% change	0.222	-2.027	-46.77	-1.262	-34.15
Spillover ratio					
(iii) Other Cargo – Port-to-Port (n=317, vessels=189)					
CA ECA (2009)	-14.25	-2.278	-0.0635	3.268	-0.00336*
	(20.21)	(4.252)	(0.0634)	(4.931)	(0.00196)
R-squared	0.993	0.868	0.726	0.745	0.421
Mean (t=0)	1228	54.61	0.572	50.93	0.0128
Mean (t=-30)	1206	51.99	0.584	49.63	0.0130
% change	-1.160	-4.171	-11.10	6.416	-26.26
Spillover ratio					
(iv) Other Cargo – Ent/Exit (n=1,014, vessels=478)					
CA ECA (2009)	9.088*	1.421*	-0.0833***	3.977**	-0.000525
	(5.227)	(0.792)	(0.0270)	(1.900)	(0.000467)
R-squared	0.952	0.724	0.894	0.321	0.586
Mean (t=0)	388.9	14.20	0.321	15.46	0.00591
Mean (t=-30)	387.4	14.69	0.318	16.28	0.00607
% change	2.337	10.01	-25.93	25.72	-8.890
Spillover ratio					
(v) Tanker – Port-to-Port (n=336, vessels=119)					
CA ECA (2009)	-5.986	-3.287	-0.121	-7.700*	-0.00292
	(35.46)	(4.956)	(0.0955)	(4.409)	(0.00220)
R-squared	0.951	0.845	0.447	0.611	0.389
Mean (t=0)	1313	74.83	0.377	60.76	0.0126
Mean (t=-30)	1299	74.74	0.351	56.38	0.0122
% change	-0.456	-4.392	-31.96	-12.67	-23.11
Spillover ratio					
(vi) Tanker – Ent/Exit (n=658, vessels=286)					
CA ECA (2009)	1.850	-2.319	0.0211	-2.839	-0.00413
	(12.11)	(2.017)	(0.0177)	(5.998)	(0.00300)
R-squared	0.941	0.758	0.897	0.109	0.207
Mean (t=0)	417.7	29.46	0.0574	26.48	0.0130
Mean (t=-30)	419.5	28.37	0.0587	26.45	0.0120
% change	0.443	-7.872	36.81	-10.72	-31.68
Spillover ratio					

Notes: Standard errors in parentheses are clustered by vessel. All regressions include fuel prices, and route-specific linear time trends with different slopes on either side of the cutoff. Bandwidth is 150 days. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Container specifications include vessel-by-route fixed effects. Other cargo and tanker specifications include route fixed effects and vessel characteristic controls.

Table A.4: Estimated Effects of the Establishment of the ECA on Unexposed Routes

VARIABLES	(1) Dist (km)	(2) Speed (km/h)	(3) Fuel (t)	(4) Fuel Cost Comply Pre (USD)	(5) PM Comply Pre (t)	(6) Damage Comply Pre (USD)
CA (1.5%), 2009	1.013	1.398*	1.149**	578.3**	0.00842**	55.09**
	(1.137)	(0.718)	(0.529)	(266.2)	(0.00388)	(27.77)
Observations	572	572	572	572	572	572
R-squared	0.741	0.599	0.884	0.884	0.882	0.892
Vessels	123	123	123	123	123	123
Mean (t=0)	170.8	36.22	16.03	8067	0.115	834
% change	0.593	3.859	7.169	7.169	7.302	6.605

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample includes entrance/exit voyages to Seattle and Portland, but excludes routes with fewer than 5 observations on either side of the cutoff. We do not report estimates for unexposed port-to-port routes because there is only a small number of container ship voyages between Portland and Seattle.

Table A.5: Estimated Effects of the Establishment of the ECA on Container Ships Using Various Bandwidths

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ECA Distance (km)	-229.6***	-230.3***	-245.3***	-244.8***	-243.9***	-0.560	-9.041	-5.718	-9.190	-8.217
	(33.32)	(21.88)	(18.68)	(18.64)	(18.81)	(13.81)	(10.96)	(9.979)	(8.989)	(7.302)
ECA Speed (km/hr)	-5.135***	-3.656***	-4.125***	-4.101***	-3.925***	-0.227	-0.174	-0.0857	-0.199	0.148
	(1.109)	(0.734)	(0.626)	(0.614)	(0.611)	(0.389)	(0.363)	(0.341)	(0.309)	(0.282)
ECA Fuel (t)	-24.93***	-23.96***	-26.49***	-26.90***	-26.55***	-0.231	-0.763	-0.416	-0.809	-0.414
	(4.781)	(2.923)	(2.472)	(2.502)	(2.475)	(1.039)	(1.025)	(0.963)	(0.913)	(0.868)
Fuel Costs, Compy Pre ($)	-5,056**	-5,321***	-5,323***	-5,428***	-4,709***	-244.6	133.3	544.0	89.43	168.0
	(2,206)	(1,310)	(1,052)	(1,027)	(988.6)	(1,014)	(781.7)	(715.7)	(698.0)	(562.8)
PM, Comply Pre (t)	0.175***	0.162***	0.187***	0.190***	0.196***	-0.00145	0.00938	0.0119	0.00920	0.00652
	(0.0381)	(0.0230)	(0.0197)	(0.0201)	(0.0207)	(0.0156)	(0.0130)	(0.0123)	(0.0115)	(0.00943)
Damages, Comply Pre ($)	15,929***	14,993***	17,385***	17,641***	17,950***	-77.26	646.5	725.3	841.5	601.2
	(3,752)	(2,176)	(1,877)	(1,904)	(1,966)	(1,403)	(1,157)	(1,119)	(1,021)	(845.1)
Observations	622	949	1,259	1,578	2,320	760	1,046	1,273	1,513	3,319
Bandwidth - days	90	120	150	180	365	90	120	150	180	365
Vessels	178	228	270	299	347	185	218	236	256	352
Cut Shift - days						365	365	365	365	365

(a) Port-to-Port

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
ECA Distance (km)	-13.88	-31.10***	-43.04***	-43.46***	-42.01***	3.281	3.543	3.009	2.380	3.236*
	(9.614)	(7.561)	(6.407)	(5.900)	(6.061)	(3.136)	(2.449)	(2.339)	(1.826)	(1.746)
ECA Speed (km/hr)	-1.295	-1.708**	-2.316***	-2.484***	-2.190***	0.609	0.450	0.494	0.173	0.369*
	(0.950)	(0.740)	(0.621)	(0.565)	(0.517)	(0.393)	(0.342)	(0.324)	(0.297)	(0.196)
ECA Fuel (t)	-2.332**	-3.759***	-5.439***	-5.330***	-5.342***	0.348	0.575**	0.528**	0.577***	0.596***
	(1.159)	(1.001)	(0.827)	(0.752)	(0.758)	(0.275)	(0.249)	(0.239)	(0.190)	(0.170)
Fuel Costs, Compy Pre ($)	-535.3	-1,981***	-1,842***	-1,567***	-1,669***	691.5	1,183**	1,137**	1,125**	50.25
	(967.5)	(758.5)	(607.3)	(586.5)	(571.8)	(503.1)	(480.3)	(475.8)	(452.5)	(322.9)
PM, Comply Pre (t)	0.0154	0.00879	0.0276***	0.0305***	0.0291***	0.00660	0.0114*	0.0112*	0.0106*	-0.00512
	(0.0135)	(0.0104)	(0.00792)	(0.00789)	(0.00814)	(0.00656)	(0.00631)	(0.00628)	(0.00613)	(0.00459)
Damages, Comply Pre ($)	1,323	1,771*	3,665***	4,022***	3,694***	578.9	983.7**	1,035**	1,074**	-156.1
	(1,221)	(947.4)	(778.8)	(757.7)	(767.9)	(522.3)	(489.4)	(472.2)	(442.8)	(352.6)
Observations	1,094	1,514	1,896	2,305	3,402	1,354	1,730	2,023	2,323	5,174
Bandwidth - days	90	120	150	180	365	90	120	150	180	365
Vessels	245	282	320	354	411	235	265	281	299	433
Cut Shift - days						365	365	365	365	365

(b) Entrance/Exit

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample excludes routes with fewer than 5 observations on either side of the cutoff. "Cut Shift" column reports the number of days the cutoff is shifted for placebo checks.

Table A.6: Estimated Effects of ECA on Container Ships Using Various Specifications, Port-to-Port

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ECA Distance (km)	-245.3***	-249.3***	-239.4***	-249.1***	-246.4***	-241.1***	-224.8***	-216.8***	-221.5***
	(18.68)	(18.03)	(18.19)	(18.75)	(20.84)	(22.99)	(22.05)	(19.57)	(19.09)
	0.852	0.852	0.852	0.845	0.808	0.852	0.661	0.586	0.614
ECA Speed (km/hr)	-4.125***	-4.419***	-3.865***	-4.195***	-4.257***	-4.576***	-4.115***	-3.466***	-3.586***
	(0.626)	(0.584)	(0.597)	(0.643)	(0.697)	(0.781)	(0.752)	(0.660)	(0.622)
	0.682	0.682	0.681	0.675	0.644	0.688	0.468	0.286	0.396
ECA Fuel (t)	-26.49***	-28.48***	-24.92***	-27.07***	-26.57***	-28.57***	-27.66***	-24.00***	-25.62***
	(2.472)	(2.471)	(2.309)	(2.585)	(2.800)	(3.274)	(3.198)	(2.710)	(2.373)
	0.834	0.834	0.834	0.824	0.798	0.837	0.603	0.461	0.627
Fuel Costs, Compy Pre ($)	-5,323***	-6,425***	-5,341***	-5,272***	-5,599***	-6,927***	-5,705***	-2,313	-4,016***
	(1,052)	(988.2)	(953.2)	(1,051)	(1,150)	(1,387)	(1,930)	(2,287)	(1,150)
	0.947	0.947	0.947	0.947	0.914	0.937	0.594	0.253	0.796
PM, Comply Pre (t)	0.187***	0.191***	0.171***	0.193***	0.184***	0.185***	0.193***	0.206***	0.197***
	(0.0197)	(0.0201)	(0.0186)	(0.0212)	(0.0220)	(0.0256)	(0.0278)	(0.0282)	(0.0229)
	0.928	0.928	0.928	0.924	0.852	0.923	0.736	0.553	0.718
Damages, Comply Pre ($)	17,385***	17,833***	15,912***	17,917***	17,515***	17,344***	17,175***	17,448***	16,921***
	(1,877)	(1,895)	(1,783)	(1,980)	(2,110)	(2,479)	(2,332)	(2,092)	(1,923)
	0.833	0.833	0.832	0.824	0.735	0.821	0.579	0.394	0.582
Observations	1,259	1,259	1,259	1,259	854	849	849	1,259	1,259
Bandwidth	150	150	150	150	150	150	150	150	150
Adj Time Index		Y							
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y			
Route-by-Operator FE							Y		
Route FE								Y	Y
Route Trends	Y	Y	Y	N	Y	Y	Y	Y	Y
Fuel Prices	Y	Y	N	Y	Y	Y	Y	Y	Y
Vessel Controls									Y
Sample	Main	Main	Main	Main	Pre+Post	Operator	Operator	Main	Main
Vessels	270	270	270	270	149	174	174	270	270

Notes: Standard errors in parentheses are clustered by vessel. R-squared is reported below the standard error. All specifications include linear trends with different slopes on either side of the cutoff (either by route or homogenous). Sample excludes routes with fewer than 5 observations on either side of the cutoff. The “Adj Time Index” row indicates when we shift the pre ECA time index forward by 30 days. Pre+Post sample includes only vessels that we observe before and after the policy change. Operator sample includes only vessels for which we have information on operators.

Table A.7: Estimated Effects of ECA on Container Ships Using Various Specifications, Entrance/Exit

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
ECA Distance (km)	-43.04***	-44.58***	-38.42***	-32.75***	-39.82***	-41.88***	-41.11***	-43.95***	-46.31***
	(6.407)	(5.888)	(5.872)	(7.008)	(7.169)	(7.391)	(8.117)	(6.221)	(5.998)
	0.859	0.855	0.858	0.791	0.837	0.873	0.759	0.679	0.694
ECA Speed (km/hr)	-2.316***	-2.617***	-2.114***	-1.999***	-2.106***	-2.621***	-2.320***	-2.210***	-2.329***
	(0.621)	(0.520)	(0.534)	(0.598)	(0.733)	(0.694)	(0.721)	(0.601)	(0.611)
	0.744	0.744	0.744	0.731	0.710	0.734	0.583	0.506	0.517
ECA Fuel (t)	-5.439***	-5.634***	-5.015***	-4.471***	-5.228***	-5.242***	-5.121***	-5.242***	-5.618***
	(0.827)	(0.735)	(0.767)	(0.885)	(0.910)	(0.911)	(1.007)	(0.825)	(0.748)
	0.841	0.837	0.841	0.782	0.827	0.868	0.719	0.587	0.672
Fuel Costs, Compy Pre ($)	-1,842***	-1,795***	-2,045***	-1,485**	-1,985***	-759.4	-419.4	-815.7	-1,087*
	(607.3)	(546.4)	(585.3)	(593.1)	(628.4)	(658.8)	(821.2)	(831.4)	(644.7)
	0.951	0.951	0.951	0.948	0.944	0.956	0.885	0.771	0.884
PM, Comply Pre (t)	0.0276***	0.0302***	0.0204***	0.0231***	0.0234***	0.0413***	0.0450***	0.0405***	0.0403***
	(0.00792)	(0.00729)	(0.00690)	(0.00850)	(0.00826)	(0.00971)	(0.0100)	(0.00889)	(0.00761)
	0.933	0.933	0.933	0.921	0.920	0.922	0.845	0.772	0.851
Damages, Comply Pre ($)	3,665***	4,000***	2,749***	3,204***	3,203***	4,720***	4,843***	4,427***	4,514***
	(778.8)	(705.0)	(667.5)	(842.8)	(843.3)	(970.4)	(941.5)	(736.2)	(683.7)
	0.895	0.893	0.894	0.865	0.863	0.877	0.767	0.687	0.764
Observations	1,896	1,896	1,896	1,896	1,261	1,376	1,376	1,896	1,896
Bandwidth	150	150	150	150	150	150	150	150	150
Adj Time Index		Y							
Route-by-Vessel FE	Y	Y	Y	Y	Y	Y			
Route-by-Operator FE							Y		
Route FE								Y	Y
Route Trends	Y	Y	Y	N	Y	Y	Y	Y	Y
Fuel Prices	Y	Y	N	Y	Y	Y	Y	Y	Y
Vessel Controls									Y
Sample	Main	Main	Main	Main	Pre+Post	Operator	Operator	Main	Main
Vessels	320	320	320	320	197	216	216	320	320

Notes: Standard errors in parentheses are clustered by vessel. R-squared is reported below the standard error. All specifications include linear trends with different slopes on either side of the cutoff (either by route or homogenous). Sample excludes routes with fewer than 5 observations on either side of the cutoff. The "Adj Time Index" row indicates when we shift the pre ECA time index forward by 30 days. Pre+Post sample includes only vessels that we observe before and after the policy change. Operator sample includes only vessels for which we have information on operators.

Table A.8: Estimated Effects of the Establishment of the ECA on Container Ships by Route

	(1) ECA Dist (km)	(2) ECA Speed (km/h)	(3) ECA Fuel (t)	(4) Fuel Cost Comply Pre ($)	(5) PM Comply Pre (t)	(6) Damage Comply Pre ($)
(i) So. Cal – Port-to-Port (n=1,071, vessels=264)						
CA ECA (2009)	-259.3***	-4.021***	-28.39***	-5,249***	0.207***	18,998***
	(20.50)	(0.664)	(2.593)	(1,139)	(0.0210)	(2,058)
R-squared	0.832	0.674	0.821	0.937	0.900	0.821
Mean (t=0)	594.8	31.26	56.49	50943	0.168	11255
% change	-43.59	-12.86	-50.26	-10.30	123.3	168.8
Spillover ratio	1.161		1.144			
Δ no behave				13914	-0.336	-77273
% of no behave				-37.72	-61.54	-24.59
(ii) No. Cal – Port-to-Port (n=188, vessels=50)						
CA ECA (2009)	-155.2***	-4.734***	-14.24**	-5,787**	0.0578	6,968**
	(46.18)	(1.573)	(5.644)	(2,662)	(0.0496)	(3,181)
R-squared	0.798	0.710	0.698	0.967	0.959	0.931
Mean (t=0)	265.8	33.60	20.84	66620	0.747	29780
% change	-58.40	-14.09	-68.35	-8.687	7.738	23.40
Spillover ratio	1.139		0.704			
Δ no behave				5289	-0.128	-29843
% of no behave				-109.4	-45.30	-23.35
(iii) So. Cal – Ent/Exit West (n=870, vessels=208)						
CA ECA (2009)	-85.18***	-4.042***	-9.758***	-2,258*	0.0645***	7,363***
	(12.70)	(0.840)	(1.645)	(1,196)	(0.0155)	(1,500)
R-squared	0.837	0.702	0.821	0.938	0.918	0.872
Mean (t=0)	254	27.35	22.44	35594	0.287	16129
% change	-33.54	-14.78	-43.49	-6.343	22.49	45.65
Spillover ratio	1.082		1.052			
Δ no behave				6329	-0.153	-44216
% of no behave				-35.67	-42.25	-16.65
(iv) So. Cal – Ent/Exit South (n=477, vessels=108)						
CA ECA (2009)	-9.029**	0.470	-1.774***	-1,387***	-0.00236	600.1
	(3.806)	(1.414)	(0.660)	(506.5)	(0.00492)	(688.6)
R-squared	0.895	0.417	0.802	0.899	0.864	0.705
Mean (t=0)	111.3	21.44	7.437	11338	0.0882	5803
% change	-8.116	2.194	-23.86	-12.23	-2.675	10.34
Spillover ratio	1.414		-0.0412			
Δ no behave				1957	-0.0466	-21664
% of no behave				-70.84	5.058	-2.770
(v) No. Cal – Ent/Exit (n=549, vessels=163)						
CA ECA (2009)	-13.30*	-2.837***	-2.492***	-1,561	0.00247	1,086
	(7.644)	(0.688)	(0.897)	(1,138)	(0.0124)	(963.5)
R-squared	0.672	0.721	0.768	0.872	0.861	0.867
Mean (t=0)	120.1	34.43	10.98	22465	0.213	18284
% change	-11.07	-8.241	-22.69	-6.948	1.163	5.940
Spillover ratio	0.275		0.267			
Δ no behave				2972	-0.0719	-29544
% of no behave				-52.52	-3.440	-3.676

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Spillover ratio is change in outcome outside the ECA divided by reduction in outcome within the ECA and only reported if the within-ECA change is statistically significant with $p<0.1$. "Δ no behave" row is change in outcome had vessels only adopted lower sulfur fuels and not adjusted on other margins, which is calculated using pre policy observations. "% of no behave" is change in outcome due to behavioral adjustments relative to the no behavior change counterfactual.

Table A.9: Estimated Effect of the ECA Boundary Change on Container Ships by Route

	(1)	(2)	(3)	(4)	(5)	(6)
	ECA Dist (km)	ECA Speed (km/h)	ECA Fuel (t)	Fuel Cost Comply Pre ($)	PM Comply Pre (t)	Damage Comply Pre ($)
(i) So. Cal – Port-to-Port (n=914, vessels=197)						
CA ECA (2011)	-29.46***	-0.887**	-3.957***	-897.5	0.0265**	2,196**
	(6.234)	(0.423)	(0.865)	(1,157)	(0.0133)	(860.4)
R-squared	0.726	0.502	0.733	0.789	0.750	0.764
Mean (t=0)	371.2	27.88	28.32	41868	0.318	23216
% change	-7.936	-3.182	-13.97	-2.144	8.353	9.460
Spillover ratio	0.863		1.061			
Δ no behave				4349	-0.105	-15108
% of no behave				-20.63	-25.19	-14.54
(ii) No. Cal – Port-to-Port (n=203, vessels=52)						
CA ECA (2011)	-2.013	-0.176	0.0332	-2,110	-0.0315	-2,266
	(5.426)	(1.051)	(0.821)	(3,335)	(0.0455)	(2,188)
R-squared	0.811	0.662	0.804	0.926	0.922	0.912
Mean (t=0)	115.2	28.35	7.418	65673	0.866	41163
% change	-1.747	-0.619	0.447	-3.213	-3.640	-5.506
Spillover ratio						
(iii) So. Cal – Ent/Exit West (n=921, vessels=185)						
CA ECA (2011)	-20.25***	-2.287***	-4.425***	-2,539***	0.00745	1,219**
	(4.248)	(0.474)	(0.750)	(880.3)	(0.00951)	(498.2)
R-squared	0.839	0.618	0.816	0.871	0.852	0.862
Mean (t=0)	258.1	26.34	20.52	30306	0.230	11194
% change	-7.846	-8.684	-21.57	-8.377	3.246	10.89
Spillover ratio	0.780		0.372			
Δ no behave				4122	-0.0995	-14472
% of no behave				-61.59	-7.492	-8.423
(iv) So. Cal – Ent/Exit South (n=357, vessels=74)						
CA ECA (2011)	-21.18***	0.379	-1.775***	-900.3*	0.00463	1,171
	(5.939)	(0.903)	(0.600)	(470.9)	(0.00751)	(867.9)
R-squared	0.878	0.362	0.736	0.803	0.731	0.651
Mean (t=0)	111.4	20.39	6.425	10365	0.0841	6010
% change	-19.01	1.861	-27.63	-8.687	5.508	19.48
Spillover ratio	0.878		0.504			
Δ no behave					-0.00914	-1898
% of no behave					-50.66	-61.69
(v) No. Cal – Ent/Exit (n=507, vessels=144)						
CA ECA (2011)	-0.778	0.735	0.205	2,536***	0.0343***	2,451***
	(2.474)	(0.567)	(0.268)	(799.2)	(0.0108)	(756.3)
R-squared	0.586	0.690	0.784	0.789	0.744	0.807
Mean (t=0)	100.6	27.11	6.461	14069	0.136	13402
% change	-0.773	2.709	3.174	18.03	25.13	18.29
Spillover ratio						

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Spillover ratio is change in outcome outside the ECA divided by reduction in outcome within the ECA and only reported if the within-ECA change is statistically significant with p<0.1. "Δ no behave" row is change in outcome had vessels only adopted lower sulfur fuels and not adjusted on other margins, which is calculated using pre policy observations. "% of no behave" is change in outcome due to behavioral adjustments relative to the no behavior change counterfactual.

Table A.10: Heterogeneity due to Avoidance in the Effects of the ECA Boundary Change for Container Ships

	(1)	(2)	(3)	(4)	(5)	(6)
				Fuel Cost	PM	Damage
	ECA Dist	ECA Speed	ECA Fuel	Comply Pre	Comply Pre	Comply Pre
	(km)	(km/h)	(t)	($)	(t)	($)
(i) Returners (n=379, vessels=69)						
CA ECA (2011)	3.115	-1.044*	-2.516**	-4,242***	-0.0360**	-957.1
	(8.197)	(0.556)	(1.155)	(1,586)	(0.0166)	(1,208)
R-squared	0.457	0.549	0.637	0.727	0.678	0.664
Mean (t=0)	359.7	28.23	29.46	44732	0.347	25490
% change	0.866	-3.699	-8.542	-9.483	-10.37	-3.755
Spillover ratio			-1.839			
Δ no behave				5199	-0.126	-17981
% of no behave				-81.59	28.60	5.323
(ii) Avoiders (n=386, vessels=81)						
CA ECA (2011)	-46.27***	-1.464**	-5.953***	-885.7	0.0464**	2,844**
	(7.643)	(0.607)	(1.278)	(1,823)	(0.0199)	(1,263)
R-squared	0.752	0.480	0.794	0.826	0.797	0.806
Mean (t=0)	359.4	27.87	27.94	42875	0.336	24128
% change	-12.87	-5.253	-21.30	-2.066	13.82	11.79
Spillover ratio	1.389		1.216			
Δ no behave				4842	-0.117	-16593
% of no behave				-18.29	-39.62	-17.14

Notes: Standard errors in parentheses are clustered by vessel. Bandwidth is 150 days. Sample includes container ships on the LA/LB–San Francisco Route. We restrict sample to vessels that did not use the Santa Barbara Channel prior to the boundary change, then classify vessels based on whether they use ("returners") or do not use ("avoiders") the channel post boundary change. We then restrict our sample further to include only vessels that were observed both pre and post policy. Spillover ratio is change in outcome outside the ECA divided by reduction in outcome within the ECA and only reported if the within-ECA change is statistically significant with $p<0.1$. "Δ no behave" row is change in outcome had vessels only adopted lower sulfur fuels and not adjusted on other margins, which is calculated using pre policy observations. "% of no behave" is change in outcome due to behavioral adjustments relative to the no behavior change counterfactual.

Table A.11: Balance of Vessel Characteristics by Use of the Santa Barbara Channel

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag	(7) Voyages
Avoider	-2.463***	-5,757***	-7.862***	-0.266***	-2,896**	0.0657***	0.758***
	(0.443)	(1,618)	(2.903)	(0.102)	(1,343)	(0.0237)	(0.189)
Constant	2,001***	65,142***	279.0***	13.17***	45,937***	0.0806***	5.478***
	(0.249)	(1,156)	(1.983)	(0.0719)	(1,001)	(0.0149)	(0.0951)
Observations	704	704	704	704	704	704	704
R-squared	0.041	0.018	0.010	0.009	0.007	0.011	0.021

(a) Establishment of the ECA

VARIABLES	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag	(7) Voyages
Returner	-2.520***	-123.3	2.370	-0.122	1,691	0.237***	1.074***
	(0.513)	(1,693)	(2.997)	(0.0947)	(1,248)	(0.0238)	(0.167)
Constant	2,003***	66,158***	280.1***	13.20***	46,207***	0	5.749***
	(0.225)	(1,163)	(2.299)	(0.0615)	(870.0)	(2.68e-10)	(0.0989)
Observations	707	707	707	707	707	707	707
R-squared	0.037	0.000	0.001	0.002	0.003	0.145	0.057

(b) ECA Boundary Change

Notes: Robust standard errors in parentheses. All columns show bi-variate regression of vessel characteristic on indicator for whether vessel "switched" behavior, that is avoided the Santa Barbara Channel after implementation of the ECA or returned to the Santa Barbara Channel

Table A.12: Effects of the Establishment of the ECA on Distance Traveled by Container Ships Outside the Study Area

	Hawaii		Unimak	
	Pre	Post	Pre	Post
(i) Southern California				
Distance in ECA	59.0	48.2	283.3	136.2
	(38.9)	(3.0)	(96.5)	(91.4)
Total Distance	4170.7	4153.5	4376.6	4409.9
	(42.5)	(7.3)	(94.1)	(115.8)
Distance Within Study Area	345.9	345.4	1002.9	974.5
	(23.1)	(11.7)	(248.3)	(303.7)
Distance Outside Study Area	3824.8	3808.1	3373.7	3435.4
	(42.1)	(15.2)	(172.3)	(243.1)
Fuel Cost within Study Area	13658.7	14836.9	57677.9	58133.1
	(3098.5)	(2303.9)	(28158.5)	(23901.8)
Damage within Study Area	35346.3	32895.3	92782.9	52249.7
	(9243.7)	(15958.4)	(36043.3)	(26477.6)
Observations	34	68	18	34
(ii) Northern California				
Distance in ECA	91.2	90.5	173.7	112.1
	(2.3)	(2.0)	(49.1)	(22.8)
Total Distance	3877.1	3878.9	3703.5	3715.5
	(26.5)	(34.7)	(25.8)	(24.5)
Distance Within Study Area	216.9	216.7	477.9	446.7
	(6.5)	(5.4)	(76.5)	(81.2)
Distance Outside Study Area	3660.2	3662.2	3225.6	3268.8
	(20.8)	(31.6)	(73.6)	(87.9)
Fuel Cost within Study Area	8001.7	8477.5	26163.0	25317.9
	(1398.7)	(1113.9)	(7980.6)	(8181.6)
Damage within Study Area	22803.9	13385.5	59599.3	23882.7
	(4360.0)	(10405.1)	(13822.8)	(7731.0)
Observations	30	61	88	97

Notes: Sample includes all interpolated voyages for container ships for which we observe AIS records crossing the study area boundary. Sample is limited to voyages within 150 days of the establishment of the ECA.

Table A.13: Effects of the Establishment of the ECA on Container Ships Under Alternative Fuel Modeling Assumptions

	(1)	(2)	(3)	(4)	(5)
ECA Fuel (t)	-26.49***	-33.40***	-24.46***	-26.85***	-21.21***
	(2.472)	(3.136)	(2.389)	(2.326)	(1.947)
Total Fuel (t)	2.977*	3.541*	2.660	3.005*	2.417*
	(1.667)	(2.121)	(1.746)	(1.534)	(1.277)
Fuel Costs, Compy Pre ($)	-5,323***	-6,818***	-4,960***	-5,402***	-4,247***
	(1,052)	(1,356)	(1,107)	(989.0)	(812.2)
Damages, Comply Pre ($)	17,385***	21,611***	15,994***	16,849***	13,136***
	(1,877)	(2,337)	(1,775)	(1,619)	(1,401)
Observations	1,259	1,259	1,259	1,259	1,259
α	Consump	Power	Consump	Mean	5th Perc
Main Only			X		
Vessels	270	270	270	270	270

(a) Port-to-Port

	(1)	(2)	(3)	(4)	(5)
ECA Fuel (t)	-5.439***	-6.574***	-4.942***	-5.078***	-4.310***
	(0.827)	(1.014)	(0.780)	(0.715)	(0.656)
Total Fuel (t)	-0.877	-1.072	-0.838	-1.048	-0.628
	(1.028)	(1.298)	(1.030)	(0.897)	(0.820)
Fuel Costs, Compy Pre ($)	-1,842***	-2,232***	-1,694***	-1,835***	-1,426***
	(607.3)	(765.7)	(609.1)	(540.0)	(484.7)
Damages, Comply Pre ($)	3,665***	4,395***	3,339***	3,053***	2,744***
	(778.8)	(948.7)	(729.9)	(608.6)	(577.8)
Observations	1,896	1,896	1,896	1,896	1,896
α	Consump	Power	Consump	Mean	5th Perc
Main Only			X		
Vessels	320	320	320	320	320

(b) Entrance/Exit

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Central results are reported in column (1). Results in column (2) replace α in Equation (1) with one derived using hourly fuel consumption based on reported vessel power and a uniform fuel oil consumption factor. Results in column (3) account for only main engine fuel consumption. Results in columns (4) and (5) replace each vessels' α with the mean and 5th percentile α by vessel type.

Table A.14: Effects of the Establishment of the ECA on Container Ships Under Alternative Modeling Assumptions

	(1) Fuel Cost Comply Pre ($)	(2) Fuel Cost (1%) Comply Pre ($)	(3) Damage Comply Pre ($)	(4) Damage (1%) Comply Pre ($)	(5) Damage AP2 Comply Pre ($)
(i) Port-to-Port (n=1,259, vessels=270)					
CA ECA (2009)	-5,323***	-2,936***	17,385***	9,725***	7,503***
	(1,052)	(934.7)	(1,877)	(1,597)	(762.1)
R-squared	0.947	0.953	0.833	0.856	0.891
Mean (t=0)	53224	48578	13675	45360	6799
% change	-10	-6.044	127.1	21.44	110.3
Δ no behave	12831	8340	-71315	-40180	-13171
% of no behave	-41.49	-35.20	-24.38	-24.20	-56.96
(ii) Ent/Exit (n=1,896, vessels=320)					
CA ECA (2009)	-1,842***	-1,351**	3,665***	18.59	1,128***
	(607.3)	(568.4)	(778.8)	(1,143)	(279.5)
R-squared	0.951	0.953	0.895	0.867	0.925
Mean (t=0)	25694	24318	14225	30718	7144
% change	-7.168	-5.557	25.77	0.0605	15.79
Δ no behave	4488	2917	-35386	-18611	-4601
% of no behave	-41.03	-46.32	-10.36	-0.0999	-24.51

Notes: Standard errors in parentheses are clustered by vessel. 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. Sample excludes routes with fewer than 5 observations on either side of the cutoff. Central results are reported in columns (1) and (3). Columns labeled "(1%)" report estimates assuming that vessels consume fuels with 1% sulfur content – the average of OGV Rule's MGO and MDO sulfur limits in 2009 – within the ECA. Estimates in column (5) report changes in damages using marginal damages from AP2.

Table A.15: Effects of the Establishment of the ECA on Container Ship Composition

	(1) Built (y)	(2) DWT (t)	(3) Length (m)	(4) Draft	(5) Power (kw)	(6) US Flag
(i) So. Cal – Port-to-Port (n=1,164, vessels=350)						
CA ECA (2009)	0.605	83.01	-0.929	-0.138	160.7	-0.0106
	(0.679)	(2,499)	(4.726)	(0.169)	(2,084)	(0.0300)
R-squared	0.018	0.014	0.032	0.011	0.007	0.015
Mean (t=0)	2000	61032	272	12.98	43402	0.121
% change	0.0303	0.136	-0.342	-1.060	0.370	-8.790
(ii) No. Cal – Port-to-Port (n=206, vessels=68)						
CA ECA (2009)	0.935	8,761	11.26	0.138	8,138*	-0.0948
	(1.918)	(5,534)	(11.38)	(0.420)	(4,769)	(0.0932)
R-squared	0.043	0.131	0.126	0.096	0.163	0.044
Mean (t=0)	1996	36281	228	11.46	20133	0.222
% change	0.0468	24.15	4.938	1.200	40.42	-42.74
(iii) So. Cal – Ent/Exit West (n=1,138, vessels=343)						
CA ECA (2009)	0.488	3,200	2.157	-0.0758	141.6	-0.0126
	(0.635)	(2,803)	(4.458)	(0.145)	(2,038)	(0.0332)
R-squared	0.093	0.212	0.250	0.249	0.191	0.205
Mean (t=0)	2001	62845	275	13.16	44966	0.224
% change	0.0244	5.092	0.784	-0.576	0.315	-5.621
(iv) So. Cal – Ent/Exit South (n=528, vessels=159)						
CA ECA (2009)	1.092	-1,609	-4.146	-0.290	-2,974	
	(0.965)	(3,490)	(9.332)	(0.314)	(2,860)	
R-squared	0.224	0.206	0.123	0.229	0.091	
Mean (t=0)	1998	42742	233.7	11.68	30337	0
% change	0.0546	-3.764	-1.774	-2.482	-9.802	0
(v) No. Cal – Ent/Exit (n=710, vessels=267)						
CA ECA (2009)	1.616	1,786	1.773	-0.0608	529.9	-0.0423
	(1.054)	(3,623)	(6.533)	(0.228)	(2,827)	(0.0402)
R-squared	0.072	0.170	0.194	0.206	0.155	0.193
Mean (t=0)	1998	57632	271	12.84	42040	0.276
% change	0.0809	3.099	0.654	-0.473	1.261	-15.30

Notes: Standard errors in parentheses are clustered by vessel. All regressions include route fixed effects, fuel prices, and linear route trends with different slopes on either side of the cutoff. Bandwidth is 150 days.

Table A.16: Estimated Effects of the Establishment of the ECA on Within-Port Outcomes

	(1) Dist (km)	(2) Fuel (t)	(3) Aux Fuel (t)	(4) Fuel Cost ($)	(5) Damage ($)	(6) Damage AP2 ($)
(i) Container – So. Cal (n=1,390, vessels=381)						
CA ECA (2009)	0.827*	3.814***	3.672***	5,391***	-106,146***	-2,921***
	(0.434)	(1.292)	(1.214)	(863.1)	(13,250)	(356.4)
R-squared	0.126	0.435	0.440	0.475	0.506	0.517
Mean (t=0)	7.343	9.434	8.829	4711	112763	3005
(ii) Container – No. Cal (n=934, vessels=304)						
CA ECA (2009)	-0.400	-0.775	-0.560	1,607***	-54,477***	-2,335***
	(0.605)	(0.478)	(0.418)	(318.8)	(2,744)	(122.3)
R-squared	0.080	0.190	0.157	0.321	0.791	0.782
Mean (t=0)	43.49	8.574	6.655	4255	59451	2470
(iii) Other Cargo –So. Cal (n=666, vessels=379)						
CA ECA (2009)	0.735	1.107	1.072	1,544**	-22,080***	-807.1***
	(0.614)	(1.185)	(1.072)	(732.9)	(8,092)	(251.3)
R-squared	0.870	0.212	0.268	0.243	0.310	0.355
Mean (t=0)	6.265	3.836	3.168	2214	25197	854
(iv) Other Cargo – No. Cal (n=120, vessels=76)						
CA ECA (2009)	-5.788	1.717	0.238	2,989	-37,708***	-1,775***
	(19.03)	(3.056)	(1.790)	(1,915)	(12,039)	(631.9)
R-squared	0.218	0.268	0.272	0.328	0.604	0.598
Mean (t=0)	90.51	5.813	4.099	2695	38701	1882
(v) Tanker – So. Cal (n=464, vessels=204)						
CA ECA (2009)	3.609***	9.887***	9.434***	9,031***	-61,616***	-1,717***
	(1.382)	(2.702)	(2.562)	(1,743)	(22,283)	(593.4)
R-squared	0.155	0.127	0.135	0.181	0.308	0.317
Mean (t=0)	7.359	4.689	4.417	2115	68154	1775
(vi) Tanker – No. Cal (n=454, vessels=170)						
CA ECA (2009)	-3.073	0.135	0.128	3,747**	-69,430***	-3,858***
	(8.909)	(2.408)	(1.813)	(1,508)	(12,548)	(589.0)
R-squared	0.296	0.141	0.140	0.190	0.514	0.585
Mean (t=0)	95.26	15.50	10.68	8344	69016	3764

Notes: Standard errors in parentheses are clustered by vessel. All regressions include port fixed effects, fuel prices, and linear port trends with different slopes on either side of the cutoff. Bandwidth is 150 days.

	Boundary	California	Other WC	Correct	N/A	NoAIS	Total
California	8	933	5	923	60	35	1041
Other WC	29	4	357	356	104	9	503
HI/AK	32				8	1	41
N. Am	1149	26	222		457	20	1874
Asia	3722	2	1		334	92	4151
ROW	899	13	2		318	182	1414
AISonly	1036	464	72		344		1916

(a) LA/LB

	Boundary	California	Other WC	Correct	N/A	NoAIS	Total
California	51	3724	7	3581	574	50	4406
Other WC	42	7	694	692	138	12	893
HI/AK	43	1			12	1	57
N. Am	299	23	46		104	8	480
Asia	562	7	1		121	32	723
ROW	445	32	1		225	17	720
AISonly	220	254	246		256		976

(b) San Francisco Bay

Notes: Rows represent entrances by origin in the Entrance/Clearance (EC) data, while columns represent the origin determined by the AIS data. We also report entrances that do not have classified origins in the EC data ("N/A" row) or are only in the AIS data ("AISonly" row). The "N/A" column tabulates voyages that we cannot classify to a route (e.g., a voyage ended prior to one of our ports), while the "NoAIS" column reports the number of voyages for which there was an EC entry but no corresponding entry in the AIS data. The number of voyages that are classified to the route implied by the EC are tabulated in the "Correct" column. Note that it is only possible for us to determine exact routes between west coast ports using the AIS data. "Other WC" – Other west coast ports; "HI/AK" – Hawaii or Alaska; "N. Am" – Other North American ports; "ROW" – Rest of the world.

Table A.17: Validating AIS Voyages