

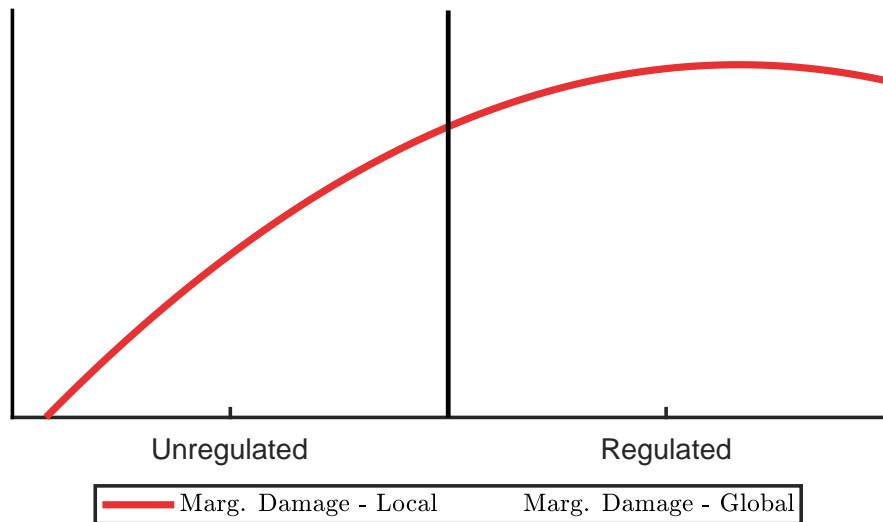
# Avoidance, Local Environmental Policy and Correlated Pollutants: Analyzing California's Ocean-going Vessel Fuel Rule

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## Motivation - Local Environmental Policy



## Motivation - Pollution from Ships

- Ocean-going vessels (OGVs) are major, historically unregulated, and growing source of particulate pollution
  - second largest source of PM in LA County (CARB)
  - 2.5% of global GHGs (IMO 2012)
  - move 90% of global trade by weight
- Particulate matter from ships related to sulfur content of fuel
  - residual fuel (around 2.7% sulfur)
  - distillate fuel (around 0.1%-0.5% sulfur)
  - price premium for distillate is  $\sim 50\%$
- Emissions Control Areas (ECAs) target particulate pollution from OGVs by requiring low-sulfur fuels in coastal waters

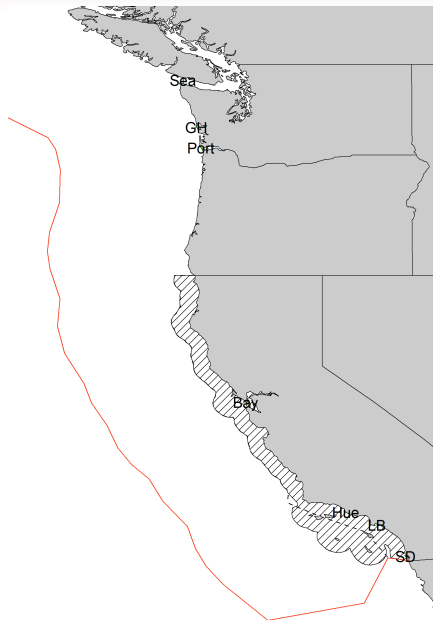
## Research Questions

- How do vessels respond to ECAs?
  - Avoid ECA (distance and location)
  - Reduce speed within ECA
  - Fuel consumption inside ECA falls by 60%, total fuel consumption rises, but shifts away from the coastline
- Does the policy pass a cost-benefit test?
  - Yes. Net benefits of \$5 million per year
- What is cost of changes in vessel behavior?
  - \$18 million in net benefits
  - \$5 million in fuel cost savings
  - \$22 million in local pollution damages
  - \$0.5 million in CO<sub>2</sub>

# Contributions

1. Show importance of avoidance as a leakage mechanism
  - Fowlie (2009), Goulder et al. (2012), Wolff (2014)
2. First empirical evaluation of ECA
  - Previous literature based on
    - inventories – e.g. Liu et al. (2016), Sofiev et al. (2018)
    - simulation methods – Wang and Corbett (2007)
    - visualizations – Moore et al. (2018)
    - observations – Lack et al. (2011)
  - Growing economics literature on vessel behavior
    - Brancaccio et al. (2018); Molina and McDonald (2019)
3. Studying GHG impacts of local pollution policy
  - Previous work on stationary sources
    - Burtraw et al. (2003); Holland (2010); Groosman et al. (2011), Fullerton and Karney (2018)

# CA ECA and NA ECA



## CA ECA (hashed)

- Enforced 7/2009
- Updated 12/2011

## NA ECA (red line)

- Enforced 8/2012
- Same stringency as CA ECA 1/2015

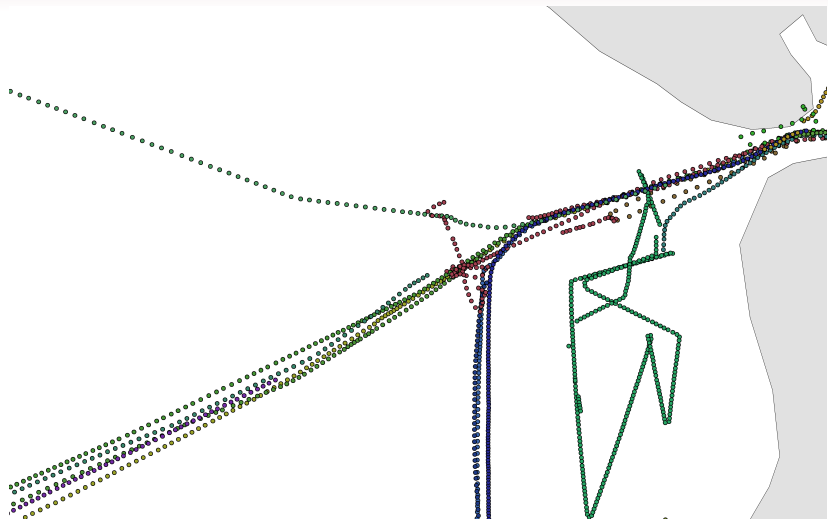
## Exemptions:

- Steam-turbines

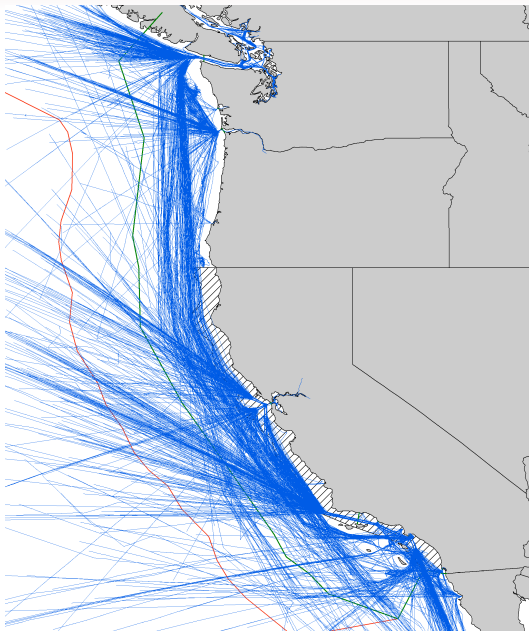
# Enforcement

- CA ECA enforced by CARB
  - ship inspections
  - testing fuel at supplier
  - bunker delivery notes
  - fuel records
- Civil penalties up to: \$45,000 per port visit
- Annual enforcement statistics between 2009 and 2016:
  - 300 to 1000 inspections
  - 94% to 99% compliance
  - \$100,000 to \$1 million in fines collected

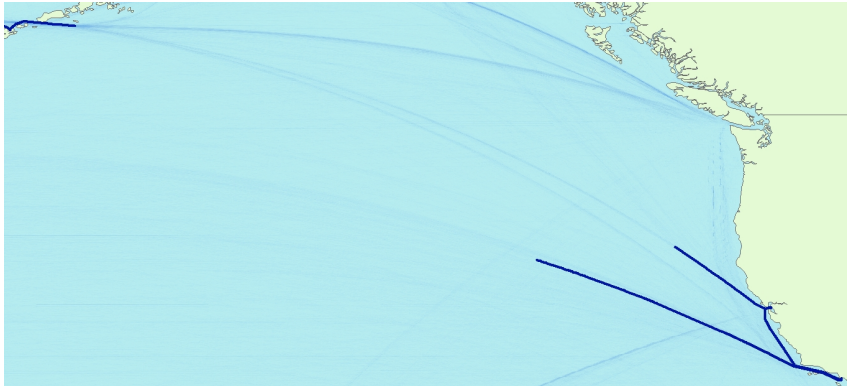
# AIS Data for San Francisco Bay, 8/1/2009 8am-4pm



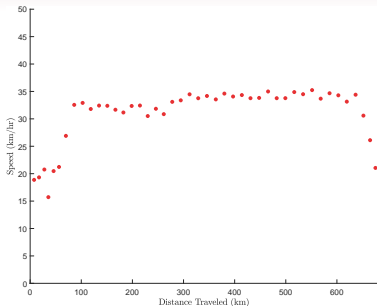
# Vessel Tracks, Cargo Ships May 2009



# Interpolating Longer Tracks



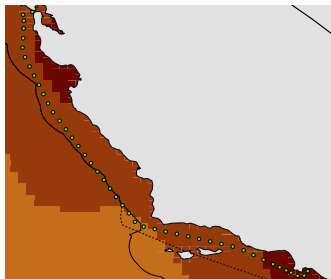
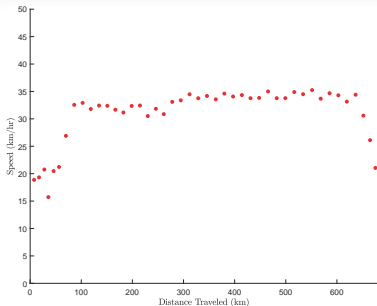
# Estimating Fuel Consumption and Damages



$$Fuel_{ir} = \sum_b km_{irb} t km_{irb} = \alpha_i \sum_b km_{irb} s_{irb}^2$$

- $\alpha_i$  - vessel specific factor (design speed, power)
- $km_{irb}$  - distance of segment  $b$
- $s_{irb}$  - speed of vessel on segment  $b$

# Estimating Fuel Consumption and Damages



$$Fuel_{ir} = \sum_b km_{irb} t km_{irb} = \alpha_i \sum_b km_{irb} s_{irb}^2$$

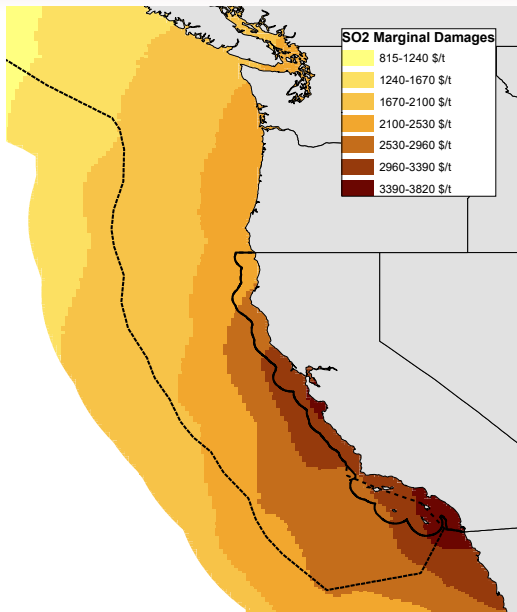
- $\alpha_i$  - vessel specific factor (design speed, power)
- $km_{irb}$  - distance of segment  $b$
- $s_{irb}$  - speed of vessel on segment  $b$

$$Cost_{ir} = \sum_b P_b km_{irb} t km_{irb}$$

$$Damage_{ir} = \sum_e \sum_b md_{eb} \phi_{eb} km_{irb} t km_{irb}$$

- $P_b$  - fuel price
- $\phi_{eb}$  - emissions factor for pollutant  $e$
- $md_{eb}$  - location varying marginal damages

# Marginal Damages from SO<sub>2</sub> (AP2)



## Final Dataset Exposed Routes, 2009-2012

|              | Tracks | Vessels | Distance<br>(km) | Fuel<br>(t) | Cost<br>(\$) | Damage<br>(\$) |
|--------------|--------|---------|------------------|-------------|--------------|----------------|
| Hono_LALB    | 304    | 16      | 4,165            | 362         | 146,444      | 24,103         |
| Hono_SFBay   | 296    | 25      | 3,876            | 301         | 115,539      | 18,805         |
| LALB_SFBay   | 4,586  | 600     | 749              | 65          | 25,674       | 12,556         |
| LALB_Sea     | 253    | 104     | 2,029            | 186         | 64,364       | 29,351         |
| LALB_Unimak  | 388    | 178     | 4,377            | 414         | 166,846      | 35,733         |
| SFBay_Port   | 81     | 16      | 1,101            | 57          | 23,323       | 8,696          |
| SFBay_Sea    | 803    | 153     | 1,344            | 118         | 48,956       | 17,034         |
| SFBay_Unimak | 1,342  | 395     | 3,715            | 335         | 129,053      | 24,136         |

# Empirical Strategy

$$\ln(y_{irt}) = \beta * ECA_t + f(t) + \mu_{ir} + \epsilon_{itd}$$

where:

- $ECA$  - 1) 2009 ECA implementation; 2) 2011 boundary change
- $\mu_{ir}$  - vessel by route fixed effect
- Control for marine fuel prices, unemployment rate
- Standard errors clustered by vessel

Local linear approach

- 180 days either side of policy date; slope changes at policy date
- Unexposed routes as placebo

# Empirical Strategy

$$\ln(y_{irt}) = \beta * ECA_t + f(t) + \mu_{ir} + \epsilon_{itd}$$

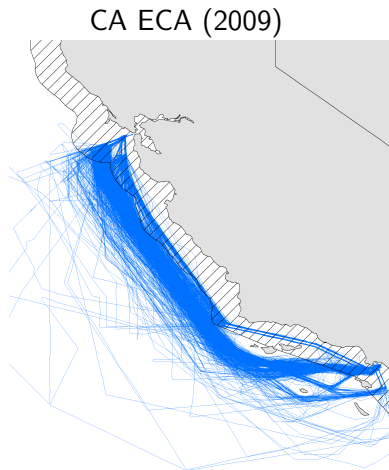
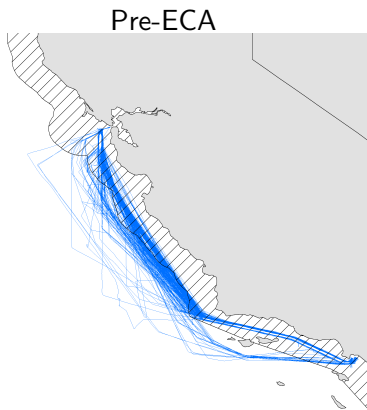
Primary concerns:

- Time-varying treatment effect (e.g. learning)
- ~~Anticipation~~

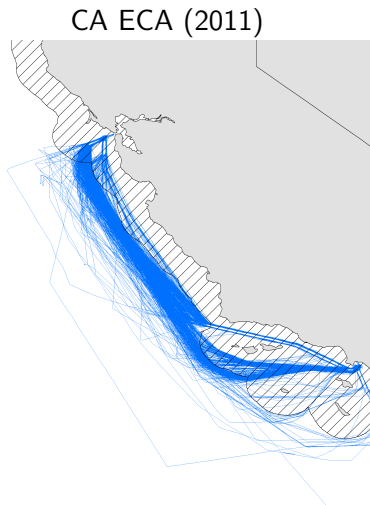
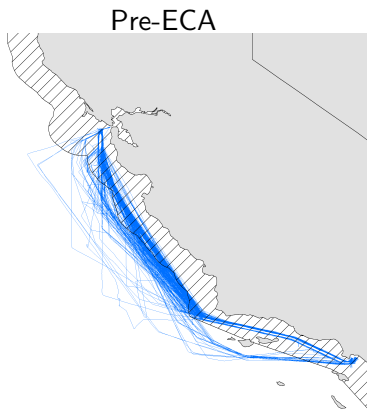
To do:

- heterogeneous time trends
- global polynomial
- revisit DiD

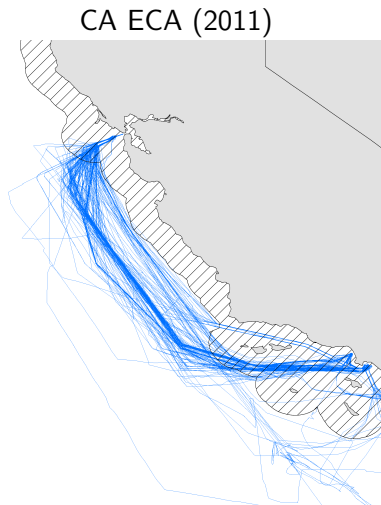
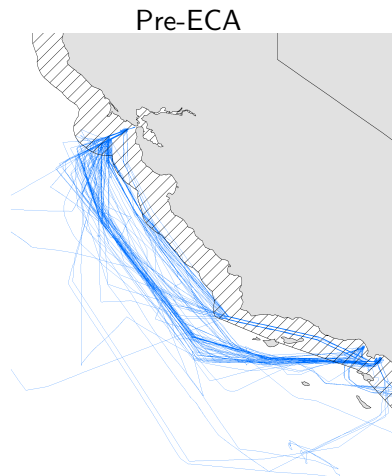
## Avoidance: LA/LB – SF Bay, Cargo Vessels



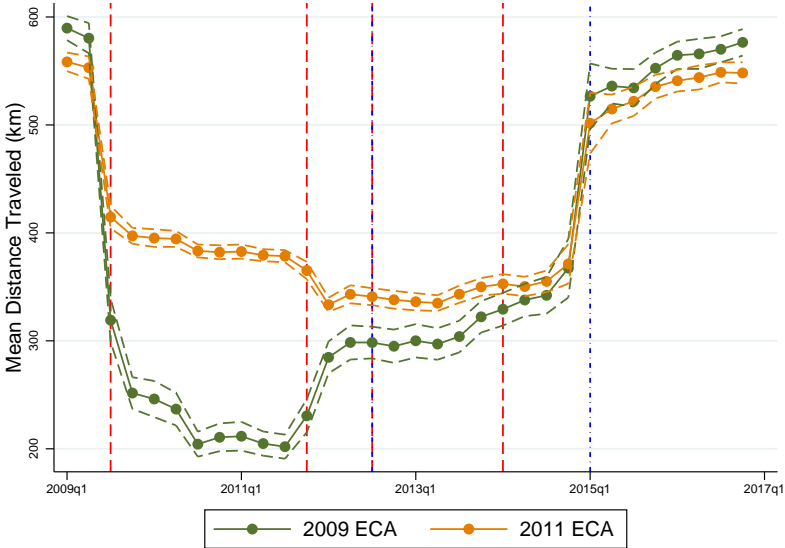
## Avoidance: LA/LB – SF Bay, Cargo Vessels



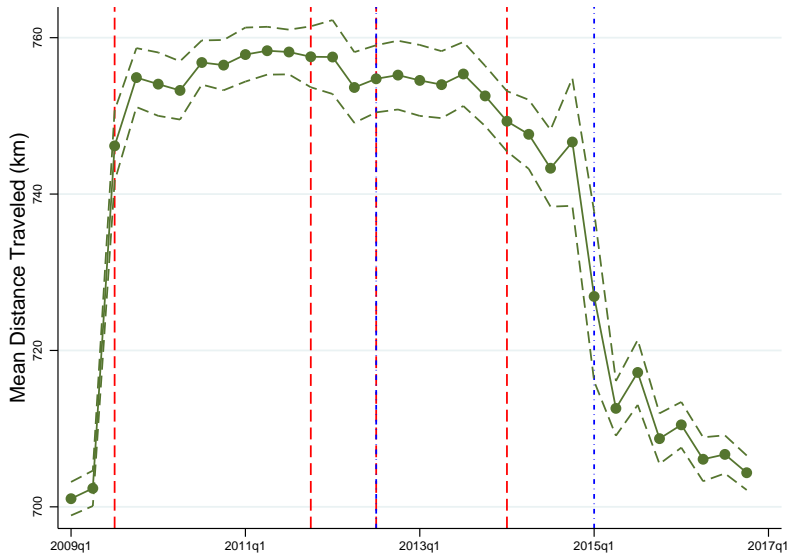
## Avoidance: LA/LB – SF Bay, Tankers



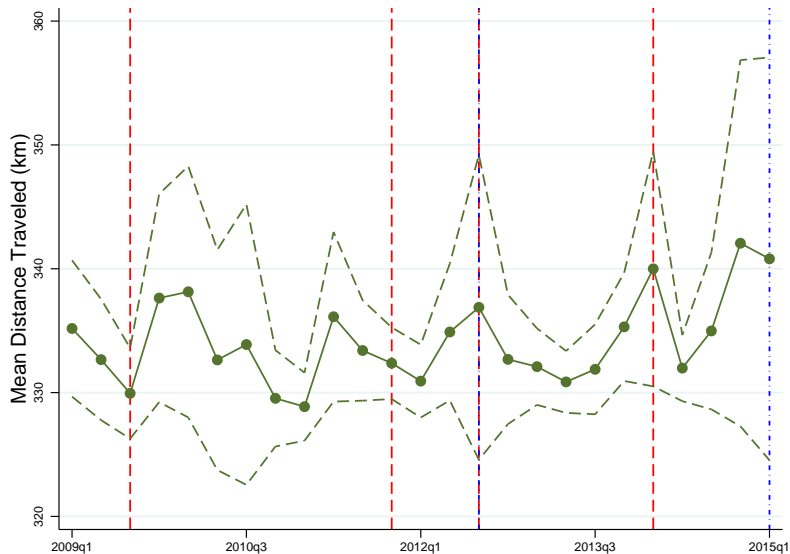
# Distance inside ECA, LA/LB – SF Bay, Containers



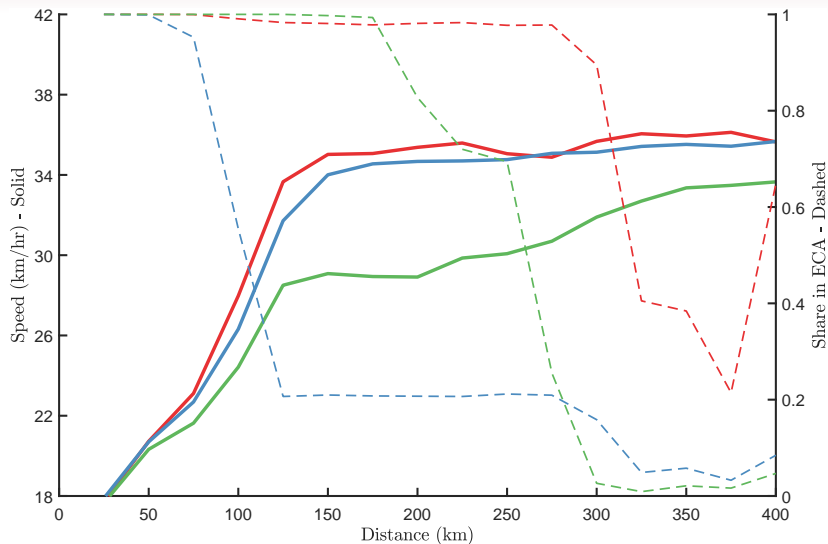
# Total Distance, LA/LB – SF Bay, Containers



# Total Distance, Portland – Seattle, Containers



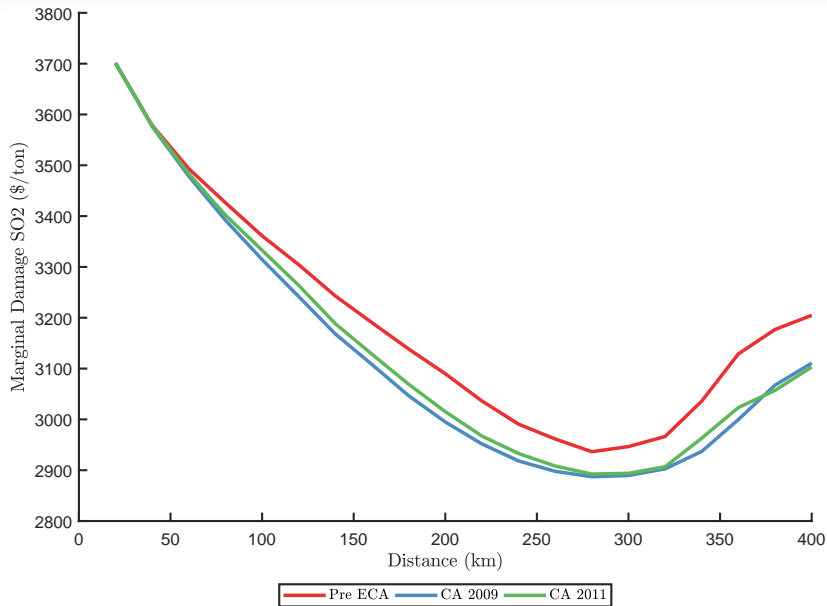
# Speed Profiles, LA/LB – SF Bay, Containers



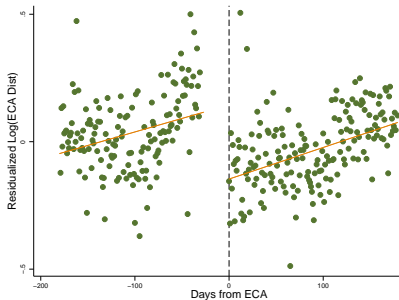
Vessels: 8316

Pre ECA CA 2009 CA 2011

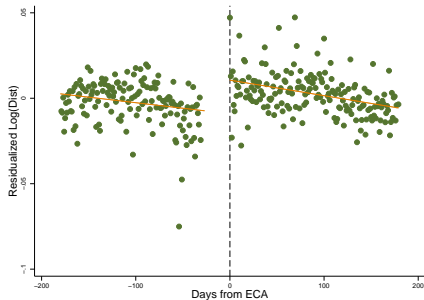
# SO<sub>2</sub> Marginal Damages, LA/LB – SF Bay, Containers



# Impact of 2009 ECA on Distance, Container

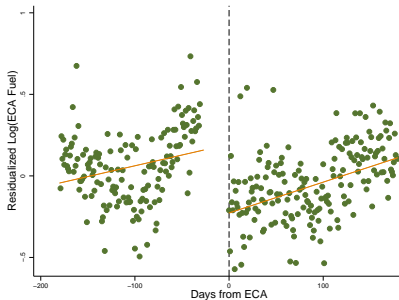


Distance in ECA

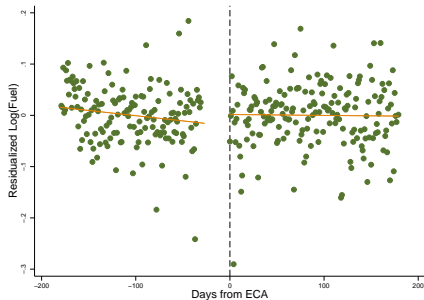


Total Distance

# Impact of 2009 ECA on Fuel Consumed, Container



Fuel in ECA



Total Fuel

## Impact on Distance and Fuel within ECA

| VARIABLES       | (1)<br>Log(ECA Dist)  | (2)<br>Log(ECA Fuel t/km) | (3)<br>Log(ECA Fuel)  |
|-----------------|-----------------------|---------------------------|-----------------------|
| CA (1.5%), 2009 | -0.574***<br>(0.0519) | -0.338***<br>(0.0323)     | -0.912***<br>(0.0735) |
| Observations    | 2,075                 | 2,075                     | 2,075                 |
| R-squared       | 0.872                 | 0.878                     | 0.875                 |
| Vessels         | 318                   | 318                       | 318                   |
| Pre ECA mean    | 424.9                 | 0.0791                    | 35.45                 |
| Level Change    | -185.6                | -0.0227                   | -21.21                |

# Costs and Benefits of 2009 ECA, Containers

| VARIABLES       | (1)<br>Log(Dist)       | (2)<br>Log(Fuel)     | (3)<br>Log(Fuel Cost) | (4)<br>Log(Damage)    |
|-----------------|------------------------|----------------------|-----------------------|-----------------------|
| CA (1.5%), 2009 | 0.0373***<br>(0.00478) | 0.0263<br>(0.0220)   | 0.0784***<br>(0.0215) | -0.375***<br>(0.0606) |
| Observations    | 2,075                  | 2,075                | 2,075                 | 2,075                 |
| R-squared       | 0.999                  | 0.980                | 0.981                 | 0.871                 |
| Vessels         | 318                    | 318                  | 318                   | 318                   |
| Pre ECA mean    | 1718                   | 154.9                | 34631                 | 16945                 |
| Level Change    | 65.27                  | 4.127                | 2826                  | -5300                 |
| Exposed         |                        |                      |                       |                       |
| VARIABLES       | (1)<br>Log(Dist)       | (2)<br>Log(Fuel)     | (3)<br>Log(Fuel Cost) | (4)<br>Log(Damage)    |
| CA (1.5%), 2009 | -0.00556<br>(0.00372)  | -0.00323<br>(0.0333) | -0.0250<br>(0.0338)   | 0.00164<br>(0.0326)   |
| Observations    | 849                    | 849                  | 849                   | 849                   |
| R-squared       | 1.000                  | 0.980                | 0.981                 | 0.966                 |
| Vessels         | 182                    | 182                  | 182                   | 182                   |
| Pre ECA mean    | 2447                   | 213.8                | 47699                 | 12982                 |
| Level Change    | -13.56                 | -0.690               | -1180                 | 21.27                 |
| Unexposed       |                        |                      |                       |                       |

# Costs and Benefits of 2009 ECA, Containers by Port

| VARIABLES       | (1)<br>Log(Dist)       | (2)<br>Log(Fuel)   | (3)<br>Log(Fuel Cost) | (4)<br>Log(Damage)    |
|-----------------|------------------------|--------------------|-----------------------|-----------------------|
| CA (1.5%), 2009 | 0.0517***<br>(0.00635) | 0.0405<br>(0.0299) | 0.120***<br>(0.0293)  | -0.515***<br>(0.0829) |
| Observations    | 1,416                  | 1,416              | 1,416                 | 1,416                 |
| R-squared       | 0.997                  | 0.962              | 0.969                 | 0.839                 |
| Sample          | LA/LB                  | LA/LB              | LA/LB                 | LA/LB                 |
| Vessels         | 313                    | 313                | 313                   | 313                   |
| Pre ECA mean    | 1085                   | 94.55              | 20896                 | 14551                 |
| Level Change    | 57.63                  | 3.904              | 2676                  | -5859                 |

LA/LB Routes

| VARIABLES       | (1)<br>Log(Dist)        | (2)<br>Log(Fuel)    | (3)<br>Log(Fuel Cost) | (4)<br>Log(Damage)    |
|-----------------|-------------------------|---------------------|-----------------------|-----------------------|
| CA (1.5%), 2009 | 0.00776***<br>(0.00225) | 0.00531<br>(0.0256) | -0.000386<br>(0.0257) | -0.0590**<br>(0.0267) |
| Observations    | 659                     | 659                 | 659                   | 659                   |
| R-squared       | 1.000                   | 0.984               | 0.985                 | 0.961                 |
| Sample          | Other                   | Other               | Other                 | Other                 |
| Vessels         | 160                     | 160                 | 160                   | 160                   |
| Pre ECA mean    | 3019                    | 278.9               | 62865                 | 21866                 |
| Level Change    | 23.51                   | 1.486               | -24.28                | -1252                 |

Other Routes

## Costs and Benefits of Behavior Change?

Impacts of policy are:

$$D(KM_1, S_1, EF_1) - D(KM_0, S_0, EF_0)$$

Impacts of behavior change:

$$D(KM_1, S_1, EF_1) - D(KM_0, S_0, EF_1)$$

# Cost and Benefits of Behavior Changes

| VARIABLES       | (1)<br>Log(Fuel Cost) | (2)<br>Log(Fuel Cost<br>Comply) | (3)<br>Log(Damage)    | (4)<br>Log(Damage<br>Comply) |
|-----------------|-----------------------|---------------------------------|-----------------------|------------------------------|
| CA (1.5%), 2009 | 0.120***<br>(0.0293)  | -0.0676**<br>(0.0284)           | -0.515***<br>(0.0829) | 0.973***<br>(0.101)          |
| Observations    | 1,416                 | 1,416                           | 1,416                 | 1,416                        |
| R-squared       | 0.969                 | 0.956                           | 0.839                 | 0.864                        |
| Sample          | LA/LB                 | LA/LB                           | LA/LB                 | LA/LB                        |
| Vessels         | 313                   | 313                             | 313                   | 313                          |
| Pre ECA mean    | 20896                 | 27449                           | 14551                 | 5978                         |
| Level Change    | 2676                  | -1795                           | -5859                 | 9843                         |

LA/LB Routes

| VARIABLES       | (1)<br>Log(Fuel Cost) | (2)<br>Log(Fuel Cost<br>Comply) | (3)<br>Log(Damage)    | (4)<br>Log(Damage<br>Comply) |
|-----------------|-----------------------|---------------------------------|-----------------------|------------------------------|
| CA (1.5%), 2009 | -0.000386<br>(0.0257) | -0.0188<br>(0.0264)             | -0.0590**<br>(0.0267) | 0.0671**<br>(0.0305)         |
| Observations    | 659                   | 659                             | 659                   | 659                          |
| R-squared       | 0.985                 | 0.984                           | 0.961                 | 0.948                        |
| Sample          | Other                 | Other                           | Other                 | Other                        |
| Vessels         | 160                   | 160                             | 160                   | 160                          |
| Pre ECA mean    | 62865                 | 64988                           | 21866                 | 19268                        |
| Level Change    | -24.28                | -1208                           | -1252                 | 1337                         |

Other Routes

## Other Results

- Other cargo ships and tankers
- Other bandwidths and specifications
- Vessel composition
- 2011 boundary change

## Cost-Benefit Summary, Container Ships

---

|                |       |
|----------------|-------|
| Trips per Year | 2,250 |
|----------------|-------|

### **Welfare**

|                          |               |
|--------------------------|---------------|
| Local Pollution Benefits | \$8.6 million |
| Fuel Costs               | \$3.2 million |
| CO <sub>2</sub> Costs    | \$0.5 million |
| Net Benefits             | \$4.9 million |

### **Welfare, no behavioral adjustments**

|                          |                |
|--------------------------|----------------|
| Local Pollution Benefits | \$30.9 million |
| Fuel Costs               | \$8.3 million  |
| Net Benefits             | \$22.7 million |

### **Welfare, implications of behavior**

|                          |                 |
|--------------------------|-----------------|
| Local Pollution Benefits | -\$22.3 million |
| Fuel Costs               | -\$5.0 million  |
| CO <sub>2</sub> Costs    | \$0.5 million   |
| Net Benefits             | -\$17.8 million |

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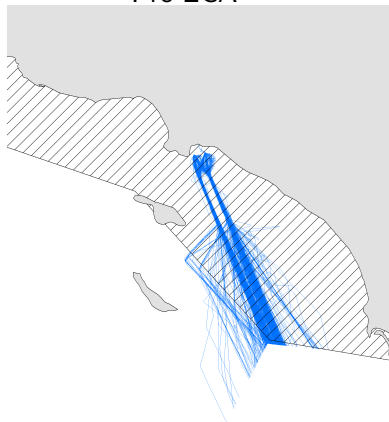
# Conclusions

- Vessels respond dramatically to ECA
  - Container ships avoid ECA and reduce speed inside ECA
  - Biggest response for LA/LB
  - Less evidence of adjustments for other vessel types
- California's ECA generates net benefits
- Changes in vessel behavior extremely costly
  - \$1 fuel cost saved → ↑ \$4 local pollution and ↑ \$0.1 CO<sub>2</sub>
- Suggests large efficiency gains from preventing avoidance
  - Expand zone - how big?
  - Rebating distillate costs? costs \$11.5 million for \$30 million in benefits

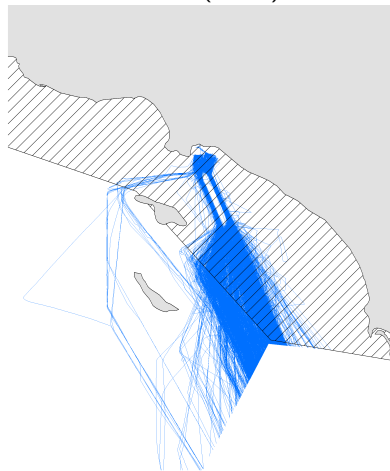
## Appendix Slides

## Avoidance: LA/LB – Exit, Cargo Vessels

Pre-ECA

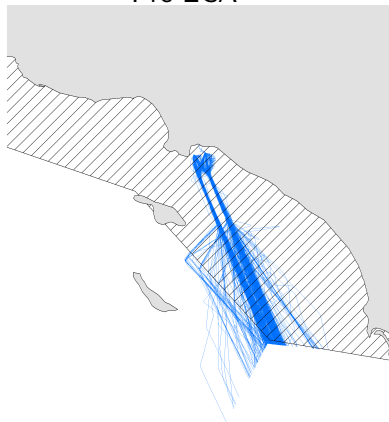


CA ECA (2009)



## Avoidance: LA/LB – Exit, Cargo Vessels

Pre-ECA



CA ECA (2011)

