Uncharted Waters: Effects of Maritime Emission Regulation

Research Question

Historical international standards for ship exhaust are strikingly weak in comparison to standards for other forms of transport that occur close to populated areas. For example, in 2008 the maximum allowable sulfur content of marine fuel along US coastlines was 3,500 times higher than allowed in vehicles. Given that increasing ship traffic already accounts accounts for roughly 90 percent of global trade, pollution from ship exhaust is a main component of poor air quality both on shore as well as inland, and represents a significant threat to human and ecosystem health (U.S. EPA, 2009b,a, 2016).

To address this mounting concern, in 2012 the US government, in coordination with the International Maritime Organization (IMO), introduced its seminal regulation of maritime pollution, called emission control areas (ECAs). ECA regulation required all commercial ships to operate with low-sulfur fuel within 200 nautical miles of the coast, install abatement equipment, or face penalties. In 2020, following this initial ECA regulation, the IMO extended similar standards globally.

Despite the consequential scale and cost of these regulations for the maritime shipping and oil refining industries, the existing evidence informing them is incomplete in two substantial respects. First, it does not quantify the environmental and human health benefits of these standards. Without comprehensive evidence accounting for spatial heterogeneity in the effect of maritime emission regulations on coastal population health, uniform regulation of maritime fuel risks both abating too little for emissions near coastal populations and too much for emissions far from coastal populations. Moreover, efficient regulation of maritime emissions must balance competing environmental objectives. Namely, requirements to remove the sulfur content in traditional ship exhaust may exacerbate climate change because these aerosols provide radiative cooling that counteracts the consequences of climate change in the short term (Sofiev et al., 2018; Liu et al., 2016).

To circumvent these challenges, policy makers have relied on ex-ante predictions of the ECA's impact on air pollution and health to determine regulations. However, ex-ante predictions may not be realized due to imperfect enforcement of the regulation, behavioral changes by shipping firms that affect the degree to which they are bound by the regulation, and even behavioral changes by individuals that alter their exposure to pollutants. Understanding these behavioral responses is necessary to accurately quantify the benefits of a policy.

Second, existing evidence does not delineate the incidence of these presumed benefits across communities. While the environmental justice literature has documented higher exposure to pollution among disadvantaged populations for many land-based pollution sources (Currie, 2011; Gamper-Rabindran and Timmins, 2011; Banzhaf et al., 2019), the distributional effects of maritime emissions are unique because the sources are mobile and emissions occur off-shore. Therefore, the distributional equity of health benefits from maritime emission regulation is likely to be distinct relative to other reductions in air pollution.

The aim of this proposal is to evaluate the benefits of North America's historic ECA regulation, to characterize the demographic incidence of the benefits, and to compare the ex-post and ex-ante estimated benefits. **Specific objectives**:

1. Provide the first ex-post evaluation of maritime emissions standards in the US:
    - Determine what portion of the intended improvements in fine particulate matter from the EPA's ex-ante analysis were realized under the policy
    - Quantify the policy's impact on human health: infant health and mortality
2. Document the distributional equity of the policy and the heterogeneous effects on air quality and health for different demographic groups
3. Evaluate the ex-ante model approach:

- Explore whether policy-induced behavioral changes among ships and/or individuals, which are not incorporated into ex-ante models, can explain deviations of realized policy effects from anticipated effects
- Compare methods of measuring exposure to the policy: Does use of an atmospheric aerosol transport model yield improved estimates and precision over a standard applied microeconomics approach of distance to a pollution source?

Data & Methods

Defining where and to what extent the ECA policy affected air pollution for the on-land population is a first order challenge to estimating the benefits of the regulation. The typical approach of applying a binary proxy for exposure to the population immediately adjacent to the source is not ideal since this source is mobile and at-sea. In lieu of using a crude metric like distance to a port, we will compare the observed changes in air quality to the forecasted changes from the Community Multiscale Air Quality Modeling System (CMAQ) obtained from U.S. EPA (2009b). We will leverage variation in (i) the timing of the regulation and (ii) the intensity of the regulation across locations using a differences-in-differences design to measure the effects of the ECA. The CMAQ predictions of the difference in the air quality with and without the policy provide a scientific prior of the policy's intended intensity at each location, provided ships comply, that accounts for the universe of ship traffic and the atmospheric dispersion, disposition, and chemical interactions of pollution once emitted. Using these predictions, we will test whether the changes in air quality after the policy match the intended improvements from the EPA's pre-policy analysis.

To perform this estimation, we combine comprehensive geospatial data on air quality and weather with detailed data of infant health and mortality outcomes. Our main outcomes of interest are fine particulate matter (PM2.5), mortality, and infant health outcomes, such as the incidence of low birth weight and death within one year. We obtain records of births and deaths from the NCHS Vital Statistics Birth and Mortality Records which contain county of residence. We combine the data with information on air quality from ground monitors and the CMAQ predictions obtained from U.S. EPA (2009b). We also collate data on time spent outdoors and outdoor recreation as a way to measure individual behavioral response to changing air quality. These data come from the American Time Use Survey and campsite reservations from Recreation.gov.

Denote county i in year-month ym where m indicates the calendar month (January-December) and y indicates the year (2008-2016). The outcomes of interest y_{iym} are the mean air pollution or mean health measures. The following difference-in-difference specification estimates the overall effect of the policy:

$$y_{imy} = \beta postECA_y \times CMAQ_i + \delta X_{imy} + \tau_{ry} + \alpha_{is} + \epsilon_{imy} \tag{1}$$

where τ_{ry} are region-by-year fixed effects, α_{is} are county-by-season fixed effects, and X_{imy} are additional controls for county-month-year weather and employment. The exposure variable is $CMAQ_i$, the CMAQ forecast of the reduction in PM2.5 from the ECA, and $postECA_y$ is an indicator equal to one in years after the ECA policy comes into effect in 2012.

Preliminary Results

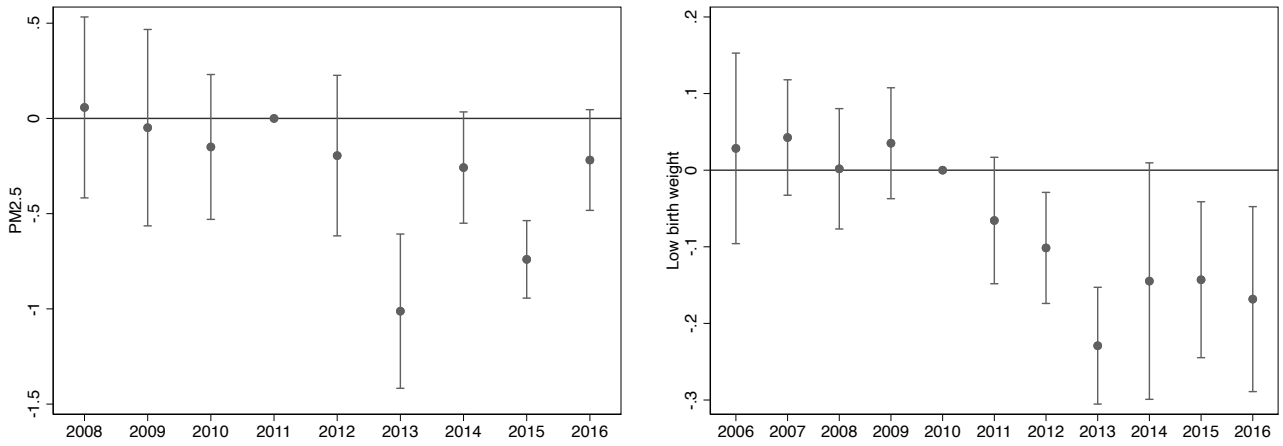
Preliminary results show strong evidence of air quality improvements for counties that were exposed to more intense forecasted changes in air pollution from the regulation. Table 1 shows estimates of equation 1. The introduction of maritime emissions control areas around the US coastline led to a substantial 5.5% fall in PM2.5. While this result is statistically significant and economically meaningful, we can reject the hypothesis that the decline in fine particulate matter forecasted by the CMAQ model

was realized ($p < 0.001$). The results suggest that only 0.51 units of fine particulate matter were abated for every 1 unit forecasted to be abated from the ECA policy. Nevertheless, this lead to a significant impact on health, resulting in a 2.6% reduction in the incidence of low birth weight and a 6.8% decline in infant mortality due to the policy. Preliminary results in Figure 1 show event-study style plots documenting an improvement in air quality and infant health after the policy. Reassuringly, there is no evidence of pre-trends for either outcome. In addition, we show evidence that predicted health based on maternal demographic characteristics are not changing simultaneously with the policy exposure in column 4. This coefficient is statistically insignificant, as expected.

Table 1: **Effects of ECA on Air Quality and Health at Birth**

	PM2.5	Low Birth Weight	Infant Mortality	Predicted Health Index
	(1)	(2)	(3)	(4)
post-ECA × CMAQ	-0.511***	-0.002***	-0.036***	1.142
	(0.102)	(0.000)	(0.008)	(0.791)
R^2	0.41	0.57	0.64	0.95
N	106,909	30,580	30,323	30,580
Mean	9.23	0.06	0.53	
%Change Post-ECA	-5.54	-2.55	-6.76	

Figure 1: **Effects of ECA on Air Quality and Health**



(a) PM 2.5

(b) Low Birth Weight

Note: The unit of observation is a county-year-month and the sample includes counties with centroids within 200km of heavy ship traffic. The depicted coefficients are the estimated effect of a one unit (μgm^{-3}) increase in a county's CMAQ predicted reduction from the ECA in each year relative to the year before the ECA came into effect in 2012. For infant health, year is measured as the conception year so we omit 2010. Conceptions in 2011 and 2012 may be partially treated, while conceptions in 2013 and after are fully treated during gestation. Robust standard errors are clustered at the county level and we report 95% confidence intervals. The results are weighted by the number of births conceived in county i in year-month ym.

We will also explore whether the policy lead to behavioral changes that were not incorporated into ex-ante predictions. In preliminary results, we find that air quality improvements were significantly more

muted in areas with a narrower ECA boundary. This evidence is consistent with a behavioral change where ships re-route to avoid regulation. If funded, we plan to explore this further and make use of direct measures of shipping routes and traffic. Preliminary results also show that individuals increased time spent outdoors by 9.6% and visits to national park sites by 16%, altering their exposure to air pollution. In addition, we will consider the benefits of using an atmospheric aerosol transport model relative to using distance as a proxy for pollution exposure. Using distance in lieu of the CMAQ output may have reduced precision and understated the effects of the the ECA policy.

Contributions

First, this project will contribute to existing policy evaluations of maritime emissions regulation which have relied on ex-ante prediction approaches (Corbett et al., 2007; Winebrake et al., 2009; U.S. EPA, 2009b; Sofiev et al., 2018; Liu et al., 2016). Predictive models do not take into account compliance or the potential behavioral responses of ships or individuals. Ships may change shipping routes, speed, and frequency of trips in response to regulation requiring higher cost fuel in regulated areas. Similarly, if individuals take precautions to avoid pollution, then the realized health improvements will not reflect the predictions from a dose-response function. In contrast to existing ex-ante studies, our ex-post study explicitly compares observed air quality and health to the predictions of these prior studies to estimate the success of the policy implementation.

Second, the environmental justice literature has documented higher exposure to pollution among disadvantaged populations for many land-based pollution sources, such as Superfund sites, hazardous waste sites, landfills, and large polluters from the Toxic Release Inventory (TRI) (Currie, 2011; Gamper-Rabindran and Timmins, 2011; Banzhaf et al., 2019). We will document how the demographic composition of coastal populations exposed to maritime emissions is distinct from the typical exposed population in other pollution contexts and whether this impacts the benefits to health. Pollution may have a heterogeneous health impact across demographic groups, potentially due to differences in underlying health conditions or access to care. In addition, the dose of exposure to maritime pollution may differ across demographic groups due to differences in time spent outdoors or differential avoidance behaviors. The combination of a demographically distinct exposed population and the unique mixture of pollutants released from ships make this an unexamined context in which to explore not only the impact of maritime fuel regulation on pollution, but also on health.

Third, this project will also contributes to a growing body of literature in economics on the infant health effects of air pollution (Currie and Neidell, 2005; Arceo et al., 2016) and transportation emissions (Currie and Walker, 2011; Schlenker and Walker, 2015; Knittel et al., 2016; Marcus, 2017; Alexander and Schwandt, 2021). Within this literature, no paper examines a link between maritime fuel content regulation and infant health, even though emissions from shipping fuel have a high concentration of toxic sulfides and comprise a large portion of coastal air pollution. Infant health has been shown to be sensitive to air pollution and has implications for many later life outcomes, including earnings, cognitive development, education, and welfare take-up (Black et al., 2007; Oreopoulos et al., 2008).

Finally, this project connects methods across disciplines. Typically, the counterfactual health improvements from pollution regulation are measured with either the methods of applied microeconomics, reviewed in Graff Zivin and Neidell (2013), or a combination of atmospheric science and epidemiological results (Sofiev et al., 2018; Barrett et al., 2012; Qin et al., 2017). We employ advances in atmospheric aerosol transportation from the atmospheric sciences to improve on the econometric methods and allow for a direct comparison of various approaches. We hypothesize a failure to account for the complexity of atmospheric interactions can understate ex-post policy effects.

Research Team

Michelle Marcus (PhD) is an Assistant Professor of Economics at Vanderbilt University and a Faculty Research Fellow at NBER. Professor Marcus is well-equipped to conduct this study as her research focuses on quantifying the human health benefits of improvements in environmental quality from policy and regulation. In related work, she shows the effect of cleaner-burning gasoline content regulation on child asthma. She has published in the *American Economic Journal: Applied Economics*, *The Review of Economics and Statistics*, *Journal of Health Economics*, and the *Journal of the Association of Environmental and Resource Economists*, among others.

Jamie Hansen-Lewis (PhD) is an Assistant Professor of Agricultural and Resource Economics at University of California, Davis. Professor Hansen-Lewis uses tools from the natural sciences to improve measurement of the economic consequences of air pollution. She employs geospatial data from satellites and climate data sets along with administrative data sources in empirical analysis. In related work, she uses the meteorological dispersion of particulates to examine how air pollution affects manufacturing productivity in India. Previous funding sources for her research include the Giannini Foundation of Agricultural Economics, National Institute for Child Health and Human Development, and the United States Department of Agriculture.

We have no conflicts of interest to disclose.

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