Essays on the Health, Environmental and Social Impacts of Fuel Regulations

by

Matthew J. McDonald

M.Sc., Dalhousie University, 2013
B.Sc., Memorial University, 2011

Thesis Submitted in Partial Fulfillment of the
Requirements for the Degree of
Doctor of Philosophy

in the
Department of Economics
Faculty of Arts and Social Sciences

SIMON FRASER UNIVERSITY
Summer 2023

Declaration of Committee

Name:	**Matthew J. McDonald**
Degree:	**Doctor of Philosophy**
Title:	**Essays on the Health, Environmental and Social Impacts of Fuel Regulations**
Committee:	**Chair:** **Bertille Antoine** Professor, Economics
	Kevin Schnepel Supervisor Associate Professor, Economics
	Hendrik Wolff Committee Member Professor, Economics
	Simon Woodcock Examiner Associate Professor, Economics
	Nicholas Sanders External Examiner Assistant Professor, Policy Analysis and Management Cornell University

Abstract

This thesis consists of three essays considering the health, environmental and social outcomes of two different types of regulations on fuels.

The first chapter examines a recent set of International Maritime Organization (IMO) policies regulating the sulfur content of fuels used in maritime transport, lowering sulfur levels to 0.1% from their initial average of a few percent. Using US county-level sulfur dioxide concentration measurements along with mortality rates, a difference-in-differences model comparing counties near ports and those further away is estimated. The results find that in counties within 50 km of major ports, the collective phases of the IMO sulfur regulations reduced SO_2 pollution by about 24% and total mortality rates of the 45+ population by 2.4%, with circulatory diseases driving most of the reduction. Taking into account higher fuel costs, the net benefit of the policy is estimated to approach $100 billion per year.

The second chapter studies the 2015 phase of the IMO shipping fuel policy capping sulfur at 0.1%, using the port city of Vancouver as a case study. A fuzzy regression discontinuity design is estimated using local SO_2 measurements and hospital admissions data to find a two thirds reduction in SO_2 and 12% reduction in circulatory-related admissions upon the enactment of the policy. Together, the results of the first two chapters results shed additional light on the set of benefits associated with maritime fuel sulfur limit policies, which have continued to expand.

The third chapter explores the impact of dramatic decreases in childhood lead exposure in Canada from the 1970s to the 1990s on rates of violent and property crime eighteen years later. Air lead and crime rate data from fourteen of Canada's largest cities are included in a difference-in-difference strategy that exploits city-level variation in the rate and timing of lead decline, with results showing that more than 10% of the observed 1992-2016 property crime decrease and 20% of the violent crime decrease can be attributed to the earlier declines in childhood lead exposure. This suggests a significant but unintended benefit to lead pollution control measures implemented in the latter half of the 20th century.

Keywords: air pollution; fuel sulfur; air lead; mortality rates; hospital admissions; crime rates

Acknowledgements

I would like to first acknowledge and thank my supervisory committee, Prof. Kevin Schnepel and Prof. Hendrik Wolff. My supervisor Kevin’s insights and ideas when I was on unsure footing have been invaluable in writing these essays, and with his guidance I have spent the last several years exploring some fascinating topics of academic inquiry. To Hendrik, I thank you for the feedback and suggestions, which greatly improved this thesis.

Next, the work of Graduate Chairs past and present in supporting all of us grad students must be acknowledged, but in particular Prof. Bertille Antoine and Prof. Alexander Karaivanov. Alex, I thank you for the patience and suggestions you had when I could not quite land on a topic of study, it is remembered. I have also appreciated the hard work and quick assistance of Graduate Assistant Lisa Agosti over the years.

I would also like to thank Pierre Cenerelli, Harjap Grewal and the rest of the Graduate Student Society team at SFU. As student jobs go, being a Director of the GSS must surely rank among the best, and I had plenty of engaging and important projects that kept me occupied between the research and regressions of this thesis.

Finally, my deepest gratitude to my wife, Monica. A Ph.D. is a long journey – economists don’t speak of forgone earnings from college for nothing! – and I might not have reached the end without her support.

Table of Contents

List of Tables

List of Figures

Chapter 1.

The Shipping Fuels: Sulfur Dioxide Regulation and Adult Mortality

1.1. Introduction

Over the last fifty years, the substantial costs of air pollution with respect to human health and well-being, the environment as well as the economy have become increasingly salient, leading to the enactment of a number of far-reaching regulations to curtail its production and impact. In particular, the gaseous pollutant sulfur dioxide (SO_2) and its atmospheric chemical reaction products, collectively labeled SO_x[1], have been named as a concern not only due to their role in producing the well-publicized acid rain phenomenon (Likens and Bormann, 1974; Schindler, 1988) but because the last few decades have seen a link established between exposure to SO_2 and the occurrence of various respiratory and cardiovascular ailments as well as higher adult and infant mortality rates (Rogers *et al.*, 2000; Pope *et al.*, 2002; Sunyer *et al.*, 2003; Lin *et al.*, 2004; Barnett *et al.*, 2005; Greenberg *et al.*, 2017; and Chen, Li, and Yao, 2018). While debate continues over the precise magnitude of long-term health risks of lower exposure levels (Chen *et al.*, 2007), confidence in the broad-reaching dangers of SO_2 has grown steadily. This has maintained public awareness of the issue and subsequent pressure on policymakers around the world to continue to reduce anthropogenic emissions of the pollutant gas.

The literature seeking to calculate the economic and environmental damages as well as abatement costs of air pollutants, prominently including SO_2, is enormous (e.g. Newbery, Sieber, and Vickers, 1990; Carson, Jeon, and McCubbin, 1997; Stavins, 1998; Joskow, Schmalensee, and Bailey, 1998; Becker, 2005; Chan *et al.*, 2018; and Mailloux *et al.*, 2022), and entire government agencies and offices have been created in the past half-century to regulate their emission. In addition to this, an economics literature using a

---

[1] SO_2 gas reacts in the atmosphere to form various sulfur-based solids and acids, with the reaction speed dependant on meteorological conditions. These can carry their own distinct environmental and health dangers: for example, small sulfate particles (which are solids) are included in measures of particulate pollution such as PM2.5.

variety of research methods has found a substantial negative impact of several types of air pollution on human health and economic activity (Ha *et al.*, 2003; Chay and Greenstone, 2003; Currie and Neidell, 2005; Currie, Neidell, and Schmieder, 2009; Moretti and Neidell, 2011; Currie, Heep Ray, and Neidell, 2011; Li *et al.*, 2016; Deschênes, Greenstone, and Shapiro, 2017; Halliday, Lynham, and de Paula, 2018; and Deryugina *et al.*, 2019). Fewer studies focus specifically on the impacts of SO_2 emissions. Shadbegian, Gray, and Morgan (2007) document significant savings in health care costs after the introduction of a US-based SO_2 cap and trade program; Luechinger (2014) uses the mandatory desulfurization of German power plants along with local wind pattern data to estimate the impact of sulfur pollution on infant mortality rates; Hanna and Oliva (2015) find large increases in weekly work hours following the closure of a large oil refinery in Mexico City which caused a 20% drop in SO_2 pollution; and Barreca, Neidell and Sanders (2021) show significant reductions in mortality due to sulfur controls imposed by the US Acid Rain Program. However, as policymakers continue to debate the rollout of restrictions on SO_2 emissions in many contexts, within national borders as well as in international waters, further evidence of the impact of past, present and proposed regulations remains in demand. This study looks at such a regulatory regime affecting maritime shipping.

Substantial quantities of SO_2 are emitted from natural phenomena such as volcanoes. However, the majority of the pollutant is produced by human activities such as metal smelting, paper production and in particular the burning or refining of fossil fuels such as coal and oil (Fioletov, V. E. *et al.*, 2011; McLinden *et al*., 2016). Models from the United States Environmental Protection Agency (EPA) suggest that SO_2 exposure and its concomitant health impact is generally a local dynamic, with danger primarily arising from nearby (i.e. distances on the order of tens of kilometers) industrial, utility or transportation activity (EPA, 2017)[2]. A longtime focus of environmental regulators around the world has thus been point source SO_2 emitters such as coal-fired electrical plants, and environmental policies have tended to focus on incentivizing the adoption of technologies like flue gas desulfurization for coal-fired electrical plants along

---

[2] There are several classes of atmospheric transport and dispersion (ATD) models that have been developed over the last few decades, including steady state, Gaussian, Lagrangian, Eulerian photochemical, and computational fluid mechanics. ATD models such as AERMOD are used for SO_2 regulatory purposes in the United States when physical monitoring is considered infeasible.

with mandating lower sulfur levels in fuels such as automobile diesel, to great success – in the continental United States, measured emissions of SO_2 have fallen by approximately 79% over the period from 1990 to 2014 (EPA, 2017). However, the shipping industry, which has traditionally relied on low-grade marine diesel[3] with a high sulfur content, has recently been estimated to produce 13% of global anthropogenic SO_2 emissions (Smith, T. W. P *et al.*, 2014). In addition, recent research has shown a variety of health impacts linked to these SO_2 emissions and other forms of shipping-linked air pollution (e.g. Corbett *et al.*, 2007; Liu *et al.*, 2016; Gillingham and Huang, 2021), and as such, regulators have more recently turned their focus toward maritime transport.

This paper is centered around the implementation of recent International Maritime Organization (IMO) regulation of the sulfur content of marine fuels used in waters in and around the continental United States, with the aim of estimating the causal impact of sulfur dioxide pollution on human health and gauging the costs and effectiveness of such policies. These new rules were introduced in phases, from the joining of a pre-existing global fuel sulfur content limit regime in 2009 to the 2012 creation and enforcement of a North American "Sulfur Emission Control Area" (SECA) and then to its further tightening in 2015. Moreover, a significant portion of transatlantic trade was also plausibly impacted by European fuel sulfur limits beginning in 2006. The difference-in-differences model used here exploits the timing of these policy phases and employs physical air monitor data spanning the years 2000 to 2019 in order to address three related questions. Did the capping of maximum allowable fuel sulfur content cause a significant reduction of SO_2 pollution in areas near shipping activity? If so, given the estimated impact on pollution levels, did the policy have long-term effects on mortality in affected communities? Finally, given estimates of their impact on air pollution and mortality rates, were these new fuel sulfur limit policies cost-effective?

The proliferation of terrestrial SO_2 regulations and variations in shipping volume alongside changing economic activity in the United States make it difficult to infer the specific contribution of shipping SO_2 regulations to the general long-run decline in this and other pollutants. However, this paper leverages heterogeneity in the air quality

---

[3] Marine diesel, also referred to as bunker fuel, has historically been of a lower quality and more viscous consistency than marine diesel. Bunker fuels are essentially the remnants of the oil refining process, and as a result they contain substantially higher amounts of impurities like sulfur.

impacts of the SO_2 shipping regulations across regions varying in their proximity to shipping activity. Specifically, the air quality within counties that are near major shipping ports are much more likely to benefit compared to counties that are far away from ports. These differences permit the creation of treatment and control counties as well as a continuous treatment measure based on the distance to a particular port and its volume of shipping activity.

Using a standard difference-in-differences (or two-way fixed effects) research design, this study first finds a strong connection between IMO regulation of marine fuel sulfur content and reductions in observed ground-level SO_2 concentrations. Specifically, estimates indicate that, collectively, the phases of IMO sulfur regulations reduced sulfur pollution by about 24% in counties within 50 km of major US ports. The North American SECA policy, which immediately reduced allowable sulfur concentrations in fuel by 70% upon its enactment, is responsible for the majority of this drop in measured SO_2.

Taking this evidence of substantial reductions in SO_2 pollution in areas near ports stemming from the implementation of the IMO regulation, this study then examines whether the declines in exposure to SO_2 and its chemical reaction products affected county-level mortality rates. Overall, the IMO fuel sulfur limit policies are found to reduce the total mortality of those aged 45 and older in affected counties by 2.4%, with diseases of the circulatory system driving most of the change.

To conclude its analysis of the IMO fuel sulfur regulation, this study attempts to estimate the total economic costs and mortality benefit values of the policy. Removing sulfur from fuel is not costless, but over time economies of scale as well as technological innovation from the demand created by the IMO policies narrowed the fuel price premium over high-sulfur fuels. While exact numbers are difficult to calculate, this paper takes US Energy Information Administration data on fuel consumption along with annual average price premiums for low-sulfur fuels to calculate an estimated annual compliance cost of about 600 million in 2014 US$ over the period 2013-2019, rising to 1.1 billion by 2019, the last year examined. By contrast, a standard implementation of the Value of a Statistical Life (VSL) framework using the avoided mortality results in the 45+ age group suggests benefits of just under 100 billion a year after implementation of the US SECA, resulting in a very high benefit-cost ratio by the end of the study period.

This paper contributes to the literature in two principal ways. First, it advances our understanding of the health, environmental and economic impacts of shipping by examining, in a quasi-experimental setting, the outcome of a specific, strictly enforced marine fuel sulfur limit regime in the United States: the North American SECA and associated IMO policies. One other contemporaneous working paper, Hansen-Lewis and Marcus (2023), evaluates the contribution of the North American SECA maritime regulations to reductions in infant health and is discussed in detail below. Other research examining marine fuel sulfur regulations are either predictive studies, focus on specific ports or regions outside of the US or do not examine health outcomes.

Predictive studies in the literature typically utilize some combination of ATD modeling (see footnote 2) and shipping vessel information to forecast future SO_2 or PM2.5 emissions in a particular region. Among these is Johansson *et al.* (2013), which uses ship-board automatic identification system (AIS) data and a fuel sulfur model in order to inventory marine emissions in the North and Baltic Sea SECAs before and after a 2010 fuel sulfur limit decrease, predicting a 29% decrease in ship-based SO_x emissions. Another such study is Jonson *et al.* (2019), which model the concentrations of air pollutants and deposition of sulfur and nitrogen from the Baltic Sea SECA and predict decreases of 5-10% in PM2.5 concentrations near coastal areas. A subset of these predictive works examines possible changes in health outcomes, for example Geels *et al.* (2021), which models the potential impact of future expansions in Nordic SECA areas as well as additional fuel regulations in terms of regional air pollution and health outcomes, with stricter regulation simulations yielding significant drops in air pollution and associated premature mortality rates. In addition, Barregard *et al.* (2019) uses a pair of computational models along with 2014 and 2016 shipping and meteorological data in order to examine the effect of a 2015 Baltic Sea SECA fuel sulfur limit decrease on population exposure to air pollution as well as mortality rates, finding a 35% drop in premature mortality as well as non-fatal heart disease and stroke.

A second group of studies having partial overlap with the first group examines the impact of IMO fuel sulfur limit regimes in non-US regions such as the North and Baltic Sea SECAs or non-SECA territorial waters in countries such as China. This group includes simulations and forecasts such as Johansson *et al.* (2013) and Geels *et al.* (2021), but also includes quasi-experimental research designs. Studying the Canadian part of the North American SECA, Anastasopolos *et al.* (2021) use meteorological and physical air monitor data from 2010 to 2016 to examine the impact of the creation of the SECA and its fuel sulfur limit regimes on air pollution in five Canadian port cities, finding a 28% to 83% mean hourly drop in SO_2 concentrations after the regulation took effect. Zhang *et al.* (2019) find that a 0.5% sulfur control zone enacted in Shanghai in 2016, similar in design to a SECA, led to lowered SO_2 measurements in nearby port sites of 27 to 55%. In addition, a twelve-monitor study of 2009 California-specific sulfur regulations (separate from IMO policy) by Tao *et al.* (2013) found that the policy produced a 28 to 72% decrease in SO_2 concentrations, depending on distances between monitoring sites and shipping lanes.

However, while modeling and prediction are useful to policymakers gauging the impact of potential new regulatory regimes, the United States has now seen over a decade of implementation of the North American SECA and associated IMO fuel sulfur policies. Most papers from Europe or China study only a narrow window of time for their respective fuel sulfur policy frameworks, whereas this study uses 20 years of data, from well before the introduction of IMO policy to well after. By the same token, studies of similar regulation in other regions and countries provide a useful comparison point for the effectiveness of such policies, but differing economic, environmental, legal and social baselines in the United States suggest possible differences in environmental and health impacts that should be investigated directly.

The contemporaneous study closest to the work here is Hansen-Lewis and Marcus (2023), which uses PM2.5 air monitor data covering the coastal US from 2008 to 2016. To define treated areas, the authors use a EPA model predicting changes in PM2.5 concentrations produced by the implementation of the SECA. Hansen-Lewis and Marcus (2023) find significant decreases in PM2.5 that were less than predicted by the EPA model. This is linked to plausible behavioral changes among shippers, terrestrial polluters and individuals that countered some of the possible reductions in pollution. Despite the less-than-expected improvement in air quality, Hansen-Lewis and Marcus (2023) document significant declines in infant mortality as a result of the maritime regulations.

This study differs in two primary ways: first, by evaluating the direct impact of regulation on measures of SO_2 instead of PM2.5 and investigating policy changes before and after the 2012 implementation of the North American SECA; and second, by focusing on adult health outcomes instead of infant outcomes, providing estimates for a range of ages and mortality causes. While the PM2.5 measure attempts to capture overall air quality from many different pollutants, policymakers generally target reductions in its individual components separately, and the change in SO_2 levels estimated by this study provides a more direct measure of the fuel sulfur cap regulation's impact. In addition, while Hansen-Lewis and Marcus (2023) do provide an estimate for all-ages, all-cause mortality, this study more closely examines the strongly heterogeneous effect on various age groups and mortality causes. Overall, this study provides empirical evidence of the impact of maritime sulfur regulations that complement the analysis in Hansen-Lewis and Marcus (2023).

While this paper also joins a growing body of economics research empirically connecting air pollution with detrimental health and economic outcomes, as previously noted, existing studies with a primary focus on SO_2 allow for a far from comprehensive understanding of how the pollutant might best be managed in the public interest. By focusing specifically on a far-reaching sulfur regulation governing an industry of global concern, this work also extends the basis for the ongoing regulatory debate and gives additional clarity to questions surrounding the costs, benefits and most productive avenues of limiting sulfur emissions, especially in more developed countries. Estimates of the value of avoided mortality are paired with the trend in the price premium and total cost of switching to lower-sulfur bunker fuel as the IMO regulations were put into place, providing an analysis of how a large-scale policy aimed at combatting SO_2 pollution can spur the adoption of new technologies and fuels and provide large benefits to society.

1.2. Policy Background

1.2.1. Fuel sulfur regulatory eras

Large-scale US environmental regulation related to terrestrial emissions of SO_2 dates back to 1971 with the establishment of the first EPA National Ambient Air Quality Standard for SO_2 (EPA, 2017). However, as attention has more recently shifted to the role of shipping and other large-scale marine activity[4] in producing SO_2 emissions, a

---

[4] The cruise ship industry is also a notable contributor to marine sulfur emissions. While there are substantially fewer ships in operation compared to the cargo shipping industry, cruise ships burn similar grades of marine diesel in engines that are often substantially larger than those used in

greater understanding of its environmental and economic impact (e.g. Corbett *et al.*, 2007; Vutukuru and Dabdub, 2008; Eyring *et al.*, 2010) has developed in tandem with the introduction of strict international regulations on marine fuels. In 1997, coordinated action was proposed to control marine SO_2 emissions with the adoption of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL)[5]. Entering into force in May 2005 and quickly becoming the accepted global regulatory framework for fuel sulfur levels, signed today by 104 countries representing 97% of shipping activity[6], this component of MARPOL introduced a set of policies with staggered effect over time, aimed at reducing sulfur emissions with minimal disruption to the shipping industry. These changes are summarized in Figure 1.1, with United States participation in MARPOL Annex VI beginning in January 2009 and moving through four separate fuel sulfur limit eras as described below.

---

cargo ships due to higher onboard power needs. They are, however, subject to the same marine fuel sulfur content regulation discussed in this paper.

[5] MARPOL is the world's major marine pollution treaty, developed by the IMO, the United Nations agency for the regulation of shipping. Originally adopted in 1973 and modified in 1978, it first came into force as MARPOL 73/78 in 1983 and has since been amended multiple times, with 1997's Annex VI: Prevention of Air Pollution from Ships the first wholly new annex since the treaty's inception. The United States implemented Annexes I, II, III, V and VI of MARPOL through the Act to Prevent Pollution from Ships in 1980 and its later amendments, including the Maritime Pollution Prevention Act of 2008, as well as amendments to the Hazardous Materials Transportation Act in 1983.

[6] The International Maritime Organization maintains a Status of Treaties document which includes the number of signatory states to each treaty as well as the percentage of world shipping tonnage they represent, accessible at https://wwwcdn.imo.org/localresources/en/About/Conventions/StatusOfConventions/StatusOfTreaties.pdf.

Figure 1.1. The evolution of MARPOL Annex VI marine fuel sulfur content limits over time.

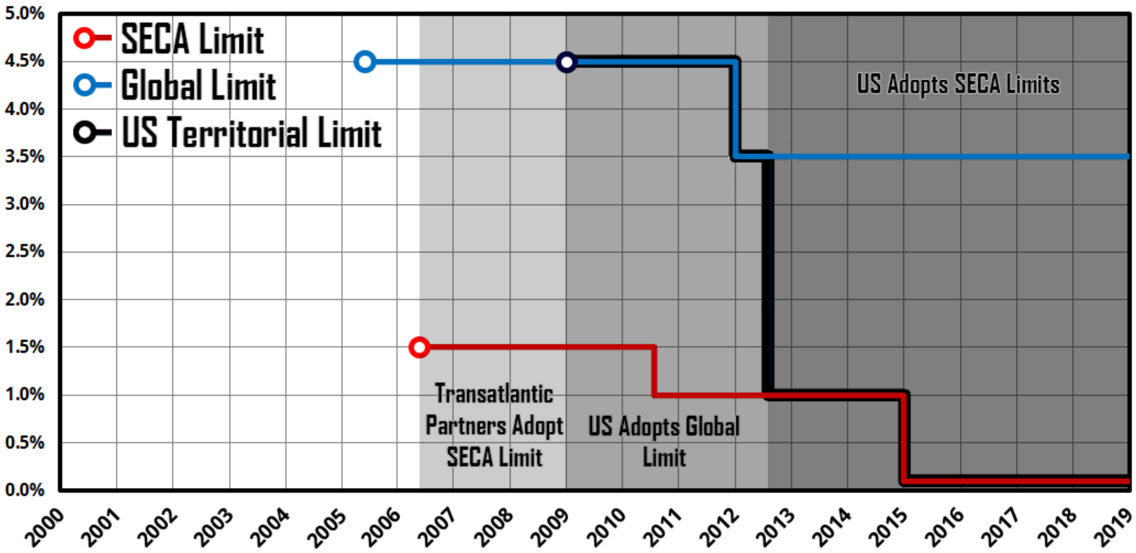

Figure 1.1 Notes: MARPOL Annex VI marine fuel sulfur content limits are given in percentages, with global limits shown in blue and SECA limits in red. Regulatory limits for the coastal territory of the United States (excluding California) are shown in black. The US first adopted the global limit in January 2009 and implemented the SECA limit in August 2012. While the US did not have a limit prior to 2009, a portion of transatlantic trade crossing the Baltic and then North Seas was influenced by those European SECA limits beginning in 2006.

"Transatlantic partner limit" era, from May 2006 to December 2008

The initial requirement of the MARPOL Annex VI regulation was for signatory nations to cap the sulfur content of marine fuels used by their ships anywhere in the world at 4.5% by mass, but the United States did not ratify and enforce the treaty until the beginning of 2009[7]. However, a second function of the treaty was to define the scope and conditions of new Sulfur Emission Control Areas (SECAs) where fuel sulfur content would be capped at a lower 1.5% by mass, while allowing the alternative of installing ship-based sulfur-cleaning emissions technology known as "sulfur scrubbers" as an equivalent requirement[8]. The Baltic Sea was the first such SECA, enacted in May 2006, followed by the North Sea in 2007 (Cullinane and Bergqvist, 2013).

---

[7] MARPOL Annex VI was officially ratified by the United States on October 9, 2008, and enforcement of the 4.5% fuel sulfur content limit did not begin until January 8, 2009.

[8] Until the lead-up to an additional global fuel sulfur limit change in 2020, sulfur scrubbers were considered prohibitively expensive and were rarely installed. Data collected from DNV's Alternative Fuels Insights platform shows that only 19 ships worldwide had scrubbers installed in 2012, compared with 106 in 2014, 312 in 2016, 740 in 2018 and 4334 in 2020. For comparison, according to Statista, there were about 58,000 ships in the world merchant fleet in January 2022.

According to the U.S. Army Corps of Engineers Waterborne Commerce Statistics Center[9], in 2012 13% of US imports and exports had as source or destination Northern or Western European countries impacted by the Baltic and North Sea SECAs, a figure that rose to 21% for ports in the United States Census Bureau's Northeast region. All but the smallest commercial vessels have multiple fuel tanks capable of storing different grades of fuel and can switch between them during voyages[10]. However, from May 2006 until the January 2009 formal introduction of IMO policy in the US, it is possible there was some impact on US sulfur emissions stemming from shipping traffic transiting through the two SECAs in Europe and purchasing or storing low-sulfur fuels, or from the modernization of transatlantic fleets to more cost-effectively meet SECA rules in Europe.

"Global limit" era, from January 2009 to July 2012

At the beginning of 2009, the United States began enforcing MARPOL Annex VI and its associated global fuel sulfur limit of 4.5%. This treaty limit was later reduced to 3.5% in January 2012, which held until August of that year, when the North American SECA was created.

"US SECA" era, from August 2012 onward

After the North Sea, the next SECA to be created was in North America, with enforcement beginning in August 2012 (the most recent SECA is the U.S. Caribbean in 2014)[11]. The North American SECA, the focus of this work, extends up to 200 nautical

---

The danger of assigning a fall in SO_2 emissions to the implementation of the North American SECA that in reality was the result of an unrelated increase in scrubber installations is thus remote, as the pre-2012 baseline was negligible. In addition, given the low percentage of ships with installed scrubbers during the time period studied, the focus here remains with changes in fuel sulfur content.

[9] Author's calculations from the USACE's measures of annual import and export volumes, accessible at the WCSC website: https://publibrary.planusace.us/#/series/Waterborne%20Foreign%20Cargo.

[10] This was later addressed in March 2020, when a "carriage ban" of non-compliant marine fuels came into effect under MARPOL Annex VI. Under this new rule, the non-cargo transport of such fuel, that is, with intent to use it onboard the ship for propulsion or operation purposes, was prohibited without an installed sulfur scrubber. Inspection of fuel tanks for the presence of non-compliant fuel is sufficient to find a violation, and proof of consumption is unnecessary.

[11] MARPOL regulation allows for a twelve-month period between the entry into force of a SECA and enforcement of the SECA's fuel sulfur content limits by regional authorities, which can create some confusion when examining timelines. Dates given here represent the start of enforcement.

miles from most of Canada, the continental United States, Alaska and Hawaii[12], as shown in Figure 1.2. Under MARPOL Annex VI regulation, the fuel sulfur limit in all SECAs had been reduced from 1.5% to 1.0% in July 2010, so from August 2012 to December 2014, the limit near US coastline was 1.0%. In January 2015, the SECA fuel sulfur limit under Annex VI was further reduced to 0.1%, which held until the end of 2019, the last year considered in this study.

The major exception to this country-wide regulatory regime is for large ships travelling in the waters around California, extending 24 nautical miles out from the coast, where state-level regulatory action by the California Air Resources Board implemented roughly SECA-level fuel sulfur standards somewhat earlier than the rest of the United States and prohibited the use of sulfur scrubbers as an alternative mode of compliance[13]. However, Klotz and Berazneva (2022) found that in response, shippers both altered their routes and slowed their speeds (and fuel consumption) within the comparatively narrow California ECA, greatly dampening the effect of the policy.

---

[12] The North America SECA is formally defined as the sea waters enclosed by a set of geodesic lines connecting a list of given coordinates. These coordinates can be found in the International Maritime Organization reference file Ref. T5/1.01. MEPC.1/Circ.723, titled “Information on North American Emission Control Area (ECA) Under MARPOL Annex VI”, accessible at https://www.epa.gov/sites/default/files/2016-09/documents/mepc1-circ-re-na-eca.pdf.

[13] Specifically, the “Fuel Sulfur and Other Operational Requirements for Ocean-Going Vessels within California Waters and 24 Nautical Miles of the California Baseline” regulation became effective in July 2009, and required a diesel fuel sulfur limit of 0.5%, followed by a decrease to 0.1% in January 2014, a year ahead of SECAs. In addition to disallowing the use of scrubbers, California’s regulations have prohibited residual fuels and required distillate fuels of the necessary sulfur level, which make it a more restrictive policy regime compared to MARPOL Annex VI.

Figure 1.2. The geographic extent of the North American Sulfur Emission Control Area.

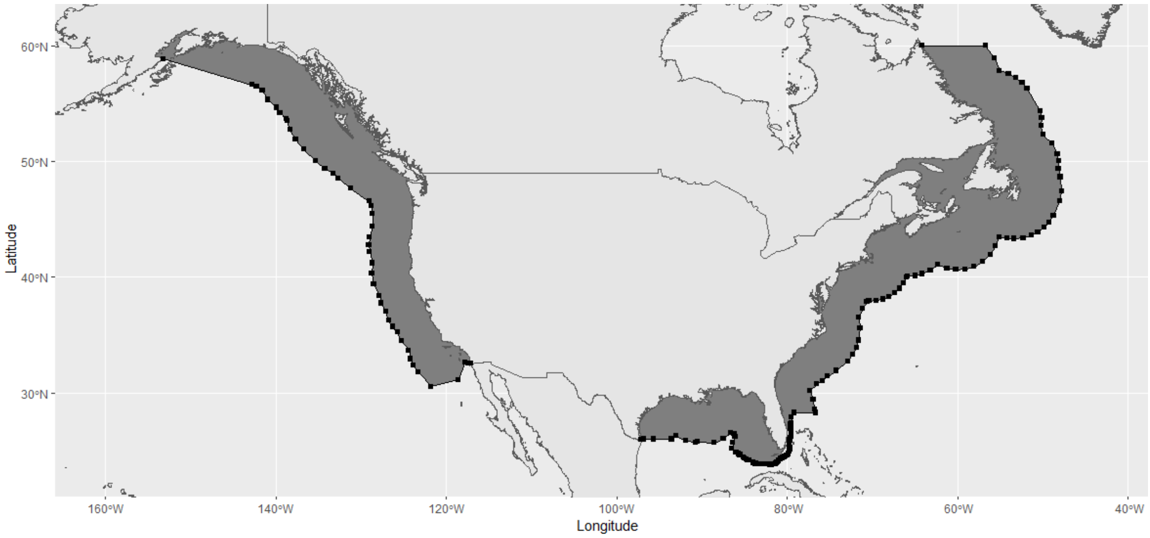

Figure 1.2 Notes: Continental (excluding Hawaii) boundary coordinates of the North American Sulfur Emission Control Area are presented as points and territory is shaded in grey.

How strongly each individual marine fuel policy was binding on vessel operators is a matter of some complexity. Endresen *et al.* (2005) report a slightly decreasing trend in global average residual fuel sulfur content from 2.95% in 1993 to 2.56% in 2002, which implies that the global limit era maxima of 4.5% and 3.5% were only partially binding, while the North American SECA limit era maxima of 1.0% and 0.1% were much more likely to uniformly affect shipping operators. Indeed, the years since the beginning of enforcement of the North American SECA have featured much industry discussion and debate about feasibility, and highly visible changes in fuel markets have taken place as the much tighter standards under the SECA necessitated a widespread move to new blends and types of fuel oils that contained far less sulfur than were broadly available beforehand.

1.2.2. Nitrogen oxide emission regulations under MARPOL Annex VI

While the focus of this study is the impact of changing SO_2 concentrations on mortality rates, MARPOL Annex VI also contains a set of regulations aimed controlling the emissions of nitric oxide (NO) and nitrogen dioxide (NO_2), together labeled NO_x. These compounds represent similar threats to human health and the environment, both directly as gases and indirectly as chemical precursors to particles[14], and have also been become the targeted pollutants of many new policies (Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society, 1996; Curtis *et al.*, 2006; and Jonson *et al.*, 2017).

However, as NO_x gases are produced through the combustion of fuels in air, which always has an ambient level of nitrogen gas, they cannot be reduced by mandating changes in shipping fuels, the primary method relied on for controlling SO_2 emissions. Annex VI instead attempts to reduce NO_x emissions by requiring all new ships built on or after certain dates to have engines that output fixed maximums of NO_x per unit of power generated, depending on the engine's size[15]. As shipping fleets can have a useful lifetime measured in decades[16], this results in much more gradual phase-ins of regulation compared to the fuel sulfur caps discussed in this study.

There are three tiers of regulation: Tier I, implemented in all US-controlled waterways in January 2004; Tier II, with emission standards 15-22% stricter than Tier I, implemented in all US-controlled waterways in January 2011; and finally Tier III, implemented only in the territory of the North American SECA in January 2016, with emissions standards 80% more strict than Tier I. Changes to the NO_x emission control framework thus tended to occur in the middle of the sulfur regulatory eras defined earlier, and due to the long and variable timeline of fleet turnover these changes are difficult to examine as discrete events. While these regulations cannot easily be used as a driver of changes in NO_x concentrations and mortality rates themselves, they raise a well-known concern: where the concentrations of multiple kinds of pollutants are correlated, it is difficult to properly infer the health impact of one chemical and separate it from another (e.g. Le Tertre *et al.*, 2002). Therefore, to avoid problems with identifying the impact of changes of the fuel sulfur policies on mortality rates, NO_2 concentrations

---

[14] Like sulfates, nitrate (NO_3) particles are included in measures of particulate pollution, most prominently PM2.5.

[15] Specific limitations in terms of grams of NO_x per kWh of power can be found on the Electronic Code of Federal Regulations website, accessible at https://www.ecfr.gov/current/title-40/chapter-I/subchapter-U/part-1043#p-1043.60(a). These are made possible by advancements in engine technology, including components that chemically or physically remove NO_x.

[16] According to Statista, in 2022 67% of container ships were at least 10 years old, and 19% were at least 20 years old.

are used as a control variable[17]. NO_2 also serves a second purpose as a control, as it is highly correlated with SO_2 and other pollutants from non-shipping emission sources that may otherwise introduce error into the analysis. It should be noted that NO_2 levels from shipping or even non-shipping industries may potentially be affected by economic feedback from the implementation of the fuel sulfur policies. However, omitting it is likely to create much more severe issues with identification, and so it is essential for isolating the impact of the fuel sulfur caps on SO_2 concentrations and health outcomes.

1.2.3. Regulation enforcement

In the United States, enforcement of MARPOL Annex VI and the North American SECA has been handled jointly by the EPA and United States Coast Guard (USCG) since 2011[18]. Ocean-going vessels operating under any state can, while traveling in the North American SECA, be fined or prosecuted by US authorities for violations of Annex VI occurring in SECA waters *as well as* for keeping falsified Annex VI records related to voyages occurring in non-SECA waters[19]. Past penalties issued by the United States for MARPOL violations, including those of Annex VI, have ranged from monetary fines to the impounding or permanent seizure of vessels to, in exceptional cases, the arrest and imprisonment of individual crew members[20].

---

[17] Results are also presented without each of the NO_2 and terrestrial-sourced SO_2 controls in order to evaluate their impact.

[18] The EPA maintains the joint EPA-USCG protocol document on its website, which can be accessed at https://www.epa.gov/sites/default/files/2019-07/documents/annexvifonarrevreferralprotocolfinaljointexecuted.pdf.

[19] The USCG maintains a list of statutes empowering it to take such enforcement actions on its website, as well as guidelines for marine operators. These documents can be accessed at https://www.dco.uscg.mil/Our-Organization/Assistant-Commandant-for-Prevention-Policy-CG-5P/Inspections-Compliance-CG-5PC-/Commercial-Vessel-Compliance/Domestic-Compliance-Division/MARPOL/.

[20] The United States Department of Justice describes a selection of prominent MARPOL-related legal cases on its website, accessible at https://www.justice.gov/enrd/vessel-pollution-enforcement. One standout case from 2006 is *United States of America v. Noel Abrogar*. Mr. Abrogar was a citizen of the Philippines serving aboard a Panama-flagged vessel, but was prosecuted and jailed in the United States for falsifying his ship’s logbook in order to conceal the illegal dumping of waste oil outside United States waters. While the appeals court clarified that the illegal dumping was not a crime punishable in the United States but rather a matter for Panama to respond to, travelling into US waters with falsified records was a criminal offense.

1.3. Data Description

1.3.1. Sulfur dioxide measurements

Daily SO_2 concentration data recorded by physical air monitors across the United States was collected from the EPA's Air Quality System (AQS) for the years 2000 to 2019. In total, 1047 monitors recorded at least some data tracking SO_2 in that period. The AQS provided mean daily SO_2 concentrations at each site, averaged using available readings in each 24-hour period. Daily site averages were aggregated to the monthly level and the fraction of missing hourly data was tracked as a separate variable to control for potential measurement issues. SO_2 was interpolated for a maximum of three months between readings[21] and the variability of site data availability was later used to explore the robustness of the results when limiting sites to those with good coverage over the entire analysis period. NO_2 concentration data was also available from the AQS for use as a control and was aggregated similarly[22].

As health outcomes are given at the level of the county and not the air monitor site, the analysis in this study required aggregation of SO_2 concentration to the county level. Following one standard practice in recent literature (e.g. Currie and Neidell, 2005; Borgschulte, Molitor, and Zou, 2022), monthly SO_2 concentrations were transformed into county data by calculating a weighted average of all sites within a fixed distance of a given county's centroid, here 50 km, with the normalized inverse of the distance between the county centroid and air monitor as the weight. The result numbered 503 counties with at least some SO_2 data coverage over the time period of the analysis.

There are a few limitations to the use of the data. First, it is important to note that SO_2 (or NO_2) concentration as relayed by a physical air monitor network may not overlap neatly onto population exposure patterns for multiple reasons well covered in the literature (e.g. Moretti and Neidell, 2011). Most importantly, monitors are located in a

---

[21] Interpolated data represented only a very small fraction of the total. Most sites with low coverage either began or ended their data collection partway through the 2000 to 2019 time period, and generally recorded long uninterrupted monthly series of data when active.

[22] 893 monitoring sites recorded at least some NO_2 data from the years 2000 to 2019, although many were not co-located with SO_2 sites or even located in the same county as an SO_2 site. Its use as a control substantially but unavoidably lowers the amount of available data, as seen in the observation counts of Table 1.2.

variety of locations and their placement in some cases may be independent of regional population densities. Second, this study does not directly measure the concentration of sulfate particles or SO_x as a whole, only SO_2 gas. While alternative measures of air pollution such as PM2.5 include sulfate particulates, they also include many other species of air pollutants unrelated to sulfur that are difficult to control for. Given the focus on regulation of SO_2 emissions from the shipping industry, analysis is done on the change in SO_2 concentrations and their resultant impact on health measures, but it is important to note that impacts on human health are a result of changes in SO_2 as well as its chemical reaction products.

To isolate the impact of the shipping regulations on SO_2, data on point source sulfur dioxide emissions from the coal, oil and gas industries (major facilities where these fuels are processed or burned for any purpose) were retrieved from the EPA's Air Markets Program Data service and used as a control[23]. This "terrestrial SO_2" data was aggregated to each physical air monitoring site and deflated with an inverse distance rule[24], then transformed into county-level data along with the air monitor data. One question that arises is whether MARPOL Annex VI policy potentially impacted terrestrial SO_2 through economic links between shipping and the coal, oil and gas industries. However, while Hansen-Lewis and Marcus (2023) conducted a placebo analysis on terrestrial PM2.5 data from the same EPA source and found no significant result, the inclusion here of terrestrial SO_2 assists in smoothing out pre- and post- policy differential trends in SO_2 and health outcomes between affected and non-affected counties.

1.3.2. Shipping volume

The intensity of the impact of the shipping regulations depends directly on the proximity of an area to shipping activity as well as the volume of shipping activity. Annual measures of shipping volume (by weight) from 2000 to 2019, including both intra- and international trade in goods and commodities, were retrieved from the U.S. Army Corps of Engineers Waterborne Commerce Statistics Center. These volume measures were

---

[23] Results are fairly sensitive to this control as shown in Table 1.3. The large drop in terrestrial US SO_2 emissions over the time period of the analysis is not uniform by region.

[24] Specifically, each monitoring site's monthly terrestrial SO_2 value was the sum of each point source emission in the EPA database divided by the distance between the source and monitor, up to a distance of 50 km.

used to construct a list of the top 126 ports in the United States with consistent data and to produce an additional synthetic variable for the purposes of testing the relationship between distance, shipping volume, and regulatory impact, described in the next section.

One natural question arising from the fuel sulfur caps is whether they impacted shipping volume by mandating the use (directly or through blending) of more expensive low-sulfur fuel like distillates, or if this effect was too small compared to broader economic changes to detect. Figure 1.3 plots the average shipping volume from the top 25 US ports[25] in millions of tons (left axis) and the price premium between high and low sulfur fuels (right-axis), discussed in more detail in Section 1.7. The correlation between these two series was -0.56, although with weak significance (p = 0.094). The most immediate feature of the plot is that 2008-2009, the time of the Global Financial Crisis, saw a sharper drop in shipping volume far more than any other period, while the introduction of the US SECA and its tightening in 2015 did not significantly or persistently reduce shipping volume even though the use of lower sulfur fuel carrying the premium was mandatory. Instead, 2015 marks a sharp and persistent drop in distillate premiums. While a true counterfactual trend in shipping activity is difficult to produce, overall shipping volumes show no obvious response to the changing financial impact of the MARPOL Annex VI regulations.

---

[25] The top 25 ports were chosen based on 2010 shipping volumes, although the plot and correlation results do not significantly change when using the top 126 or other years.

Figure 1.3. Changes in top 25 port average shipping volume (left axis) and low-sulfur fuel premiums (right axis) over time.

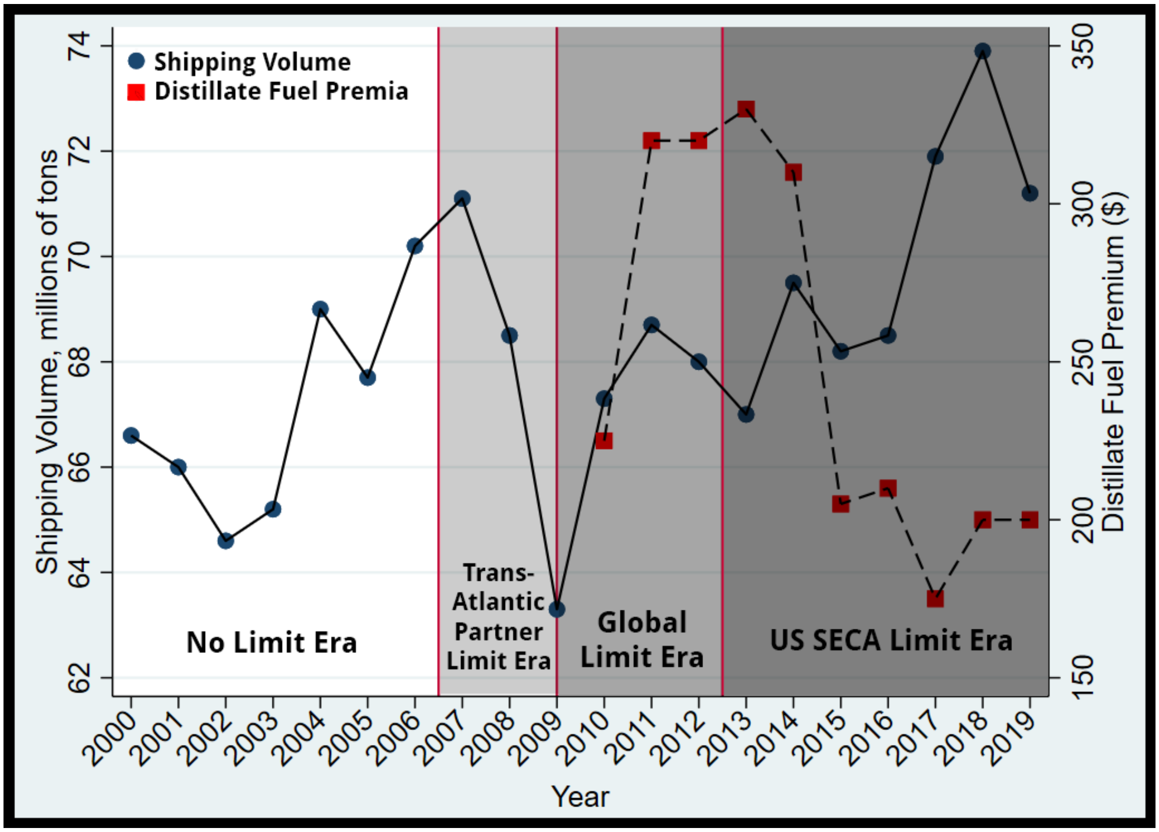

Figure 1.3 Notes: Shipping volume is given in millions of short tons. The top 25 ports were chosen based on 2010 volume data and distillate (marine gasoil) premiums over high-sulfur IFO380 grade bunker fuel from 2010 onward were calculated in 2013 dollars based on den Boer, Ahdour, and Meerwaldt, 2016; Notteboom, 2020; and Ship & Bunker data. Annual data on premiums was not available prior to 2010. Vertical red lines mark the chronological boundaries of the different regulatory eras, labeled near the plotted values.

1.3.3. Mortality rates

Annual county-level all-cause and specific-cause mortality rates per 100,000 people for the United States, based on death certificates for U.S. residents, were collected through the Centers for Disease Control and Prevention (CDC) Wide-ranging OnLine Data for Epidemiologic Research (WONDER) database for the years 2000 to 2019. County-level total mortality rates, specific cause mortality rates, and age-specific mortality rates were matched with SO_2 readings. Mortality data based on 0-9 annual deaths in a given category was suppressed by CDC and dropped in the analysis.[26]

As air pollution may impact mortality rates through a variety of disorders, mortality rate data subdivided by International Classification of Diseases, 10th revision (ICD-10) chapters II (neoplasms, broadly synonymous with cancers), IX (diseases of the circulatory system) and X (diseases of the respiratory system) was also collected, consisting of about 75% of total mortality rates. Unfortunately, county-level annual mortality rates for the remaining causes in the WONDER database were largely missing due to their small values and aggregated to an “other causes” category.

1.3.4. Other county-level controls

A variety of county-level controls capturing changes in local economic conditions were included, including per-capita income available from the US Bureau of Economic Analysis and unemployment rates available from the Integrated Public Use Microdata Series (IPUMS). Daily local temperature and wind speed, which affect the dispersion of SO_2 pollution, were collected from the National Aeronautics and Space Administration’s Prediction of Worldwide Energy Resources (POWER) Data Services, aggregated to the monthly site level, then transformed into county-level data along with site SO_2 readings. Annual smoking rates by county were retrieved from the Institute for Health Metrics and Evaluation as well as the University of Wisconsin Population Health Institute, with underlying data a product of the CDC Behavioral Risk Factor Surveillance System.

1.4. Shipping Intensity and Treatment

1.4.1. Shipping intensity definition

As the impact of the MARPOL Annex VI fuel sulfur limits is related both to the volume of shipping and how close this activity is to a given county, a “shipping intensity” variable for each air monitor *i* was constructed by taking all ports *j* within 50 km of the air

---

[26] Results are not changed when using an average 4.5 deaths in place of suppressed mortality data, as health outcome regressions are weighted by county population and counties with suppressed death counts tend to have very small populations.

monitor, dividing each port's shipping volume in millions of short tons by the monitor-port distance in km, and summing the results, as follows:

$$Intensity_{i,t} = \sum_j \frac{Volume_{j,t}}{Distance_{i,j}}, Distance_{i,j} \leq 50\ km. \tag{1.1}$$

Figure 1.4 gives a representative curve for shipping intensity as the distance between a site and a single fixed-volume port is increased. In general, shipping intensity drops off quickly according to its inverse-distance component(s), with the result that intensity values beyond the 50 km cut-off are negligible. Of all air monitoring sites with a port located within the 50 km cut-off, the typical range of distances between site and nearest port is shaded in the graph, corresponding to significantly larger shipping intensity values than those near the cut-off.

This variable was transformed into county-level data along with air monitor data, keeping the same weights for shipping intensity as individual monitors' SO_2 readings. For use in regressions, county-level shipping intensity was then Z-scored so that each unit refers to one standard deviation above or below the mean shipping intensity for a county within 50km of a major port.

Figure 1.4. Variation in shipping intensity as port-site distance increases to the 50 km cut-off.

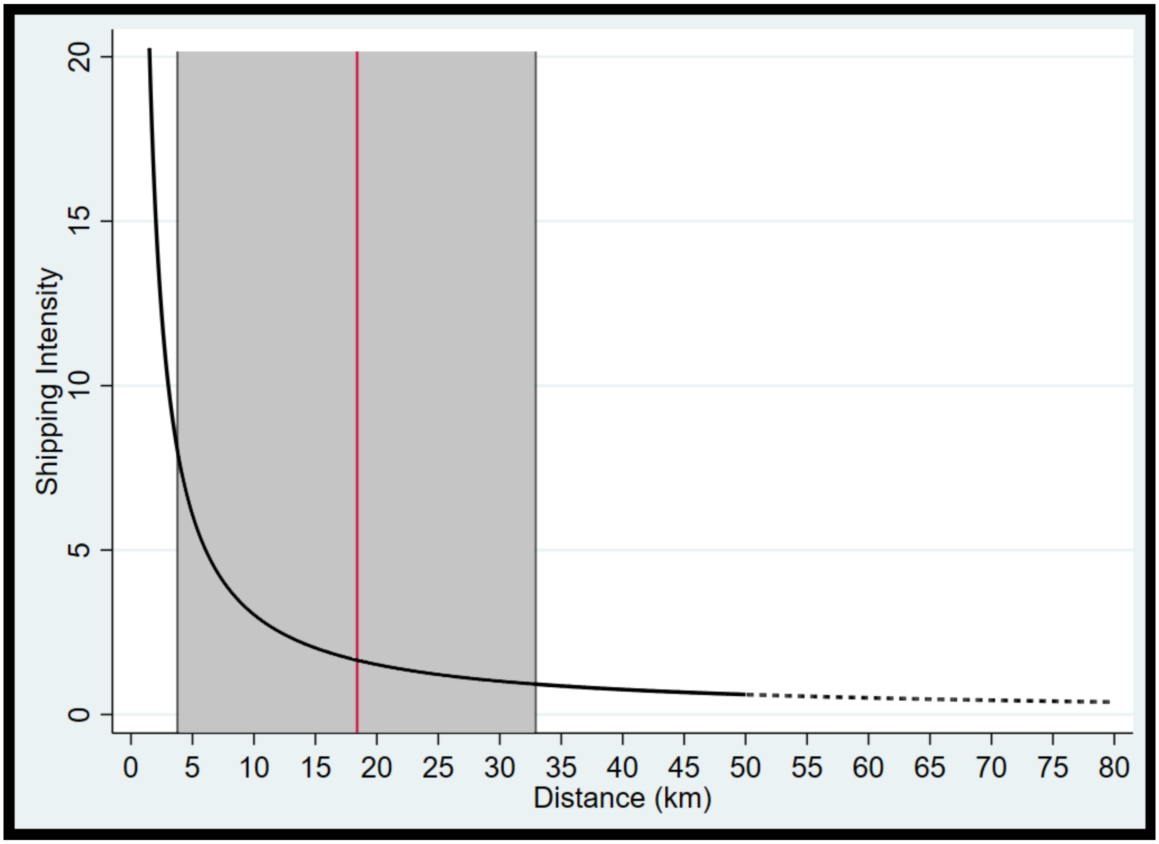

Figure 1.4 Notes: For calculating shipping intensity, the subset of air monitor sites having at least one port within 50 km was selected and the mean volume of their nearest ports was used as the numerator in Equation 1.1, varying the distance denominator on the x-axis. The vertical red line marks the mean distance between sites and their closest port in this chosen subset of sites, with the shaded area containing one standard deviation in distance from the mean. The dashed line from 50 km represents the cut-off point in the calculation.

1.4.2. Treatment group and continuous treatment measure

While the adoption of IMO fuel sulfur policies was simultaneous across the continental United States[27], this study is able to exploit variation in the impact on air quality that the reduction in sulfur emissions from the shipping industry produced after each regulatory change. This is primarily due to the fact that the concentration of SO_2

---

[27] Excluding California, whose policies were enacted earlier but whose monitoring sites were likely to be significantly impacted by non-California fuel sulfur limit regimes for geographical reasons. The exclusion of Californian monitoring data is therefore used as a robustness check, but it is included in the main results. It is also true that in the period before US regulation, any impact stemming from the European SECAs would unevenly affect regions near US ports due to their differing fractions of transatlantic shipping – much higher in New York state than Washington state, for example. Regional analyses are included in order to elaborate on this detail.

pollution declines as the distance to the source increases. While ultimately dependent on atmospheric conditions, the drop-off can be inversely proportional to distance or even sharper, a common feature of ATD models such as Gaussian plumes when distances to emission sources are on the order of kilometers, such as in Bourque and Arp (1996)[28].

This feature of SO_2 pollution suggests two approaches for a difference-in-differences framework[29]. First, a treatment group of 150 counties is selected based on a distance cut-off between country centroids and major US ports, here 50 km. This approach seeks to compare counties that are impacted by the changing fuel sulfur limits with those that are not, on the assumption that concentrations of SO_2 emissions resulting from ports located beyond the cut-off are negligible, along with their health impacts.

Next, the previous construction of shipping intensity in Equation 1.1 is used to check that the expected relationship between the volume and distance of shipping activity and the impact of the IMO regulations holds, whether on SO_2 concentrations or mortality rates. In this study, this modification involves adding interactions between the policy era indicator variables and the shipping intensity variable. This second approach is based on the theory that on average and conditional on other controls, counties closer to higher traffic ports will show both a higher baseline SO_2 concentration and larger decreases as fuel sulfur limits are implemented over time, compared to counties near the cut-off distance or those adjacent to lower traffic ports. Similarly, the fuel sulfur regulations should more strongly impact the mortality rates of counties near busier ports relative to those influenced by more distant ports with less activity. This represents an additional source of variation that allows for a confirmation of the first approach.

Figure 1.5 provides a basis for some of these assumptions, presenting bin-scatter graphs and the correlation of SO_2 concentrations with county centroid-port distance (panel A) and shipping intensity (panel B), using data before the

---

[28] In Gaussian plume models, distance dependence enters the model through lateral and vertical dispersion coefficients, which additionally depend on atmospheric parameters. The more “unstable” the atmosphere (that is, toward conditions of bright sunlight and no wind), the faster the drop-off of SO_2 by distance. As a reasonable simplification of these dynamics, we can say that the concentrations of SO_2 produced by polluters the size of individual shipping vessels are greatest near the source and diminish to the point of being negligible above a few tens of kilometers away. However, the geography and local weather conditions of each port may create SO_2 plumes that vary somewhat from day to day in their reach over the continental US.

[29] This takes a similar approach to Equation 2 in Lindgren (2021), except that both distance and shipping volume are used.

implementation of MARPOL Annex VI policy. On average, increasing distance between a county and its nearest port is associated with lower measured SO_2 concentrations, with the rate of decline slowing according to a quadratic fit as distances get larger[30]. There is also a positive correlation of 0.156 between shipping intensity values and measured SO_2, suggesting that on average, closer or busier ports expose a given monitoring site to more pollution than those further away or with less activity.

---

[30] Counties with very large distances to ports are unlikely to see any impact from shipping, but the regression in Panel A of Figure 1.5 uses the entire sample and does not include controls.

Figure 1.5. Bin-scatter graphs of county SO_2 concentrations versus A) county centroid-port distance and B) shipping intensity.

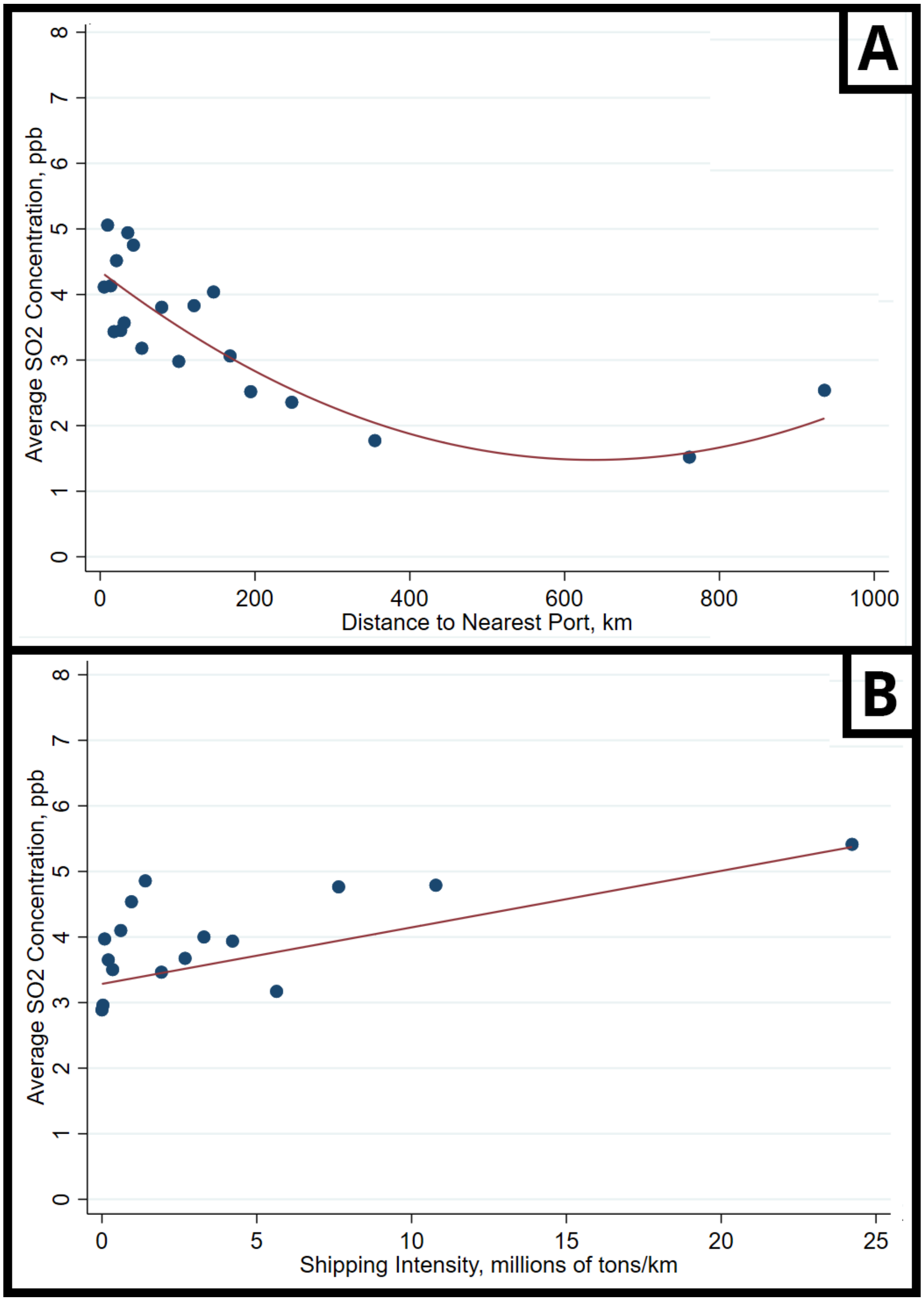

Figure 1.5 Notes: For ease of viewing, bin-scatter graphs divide the x-axis data (distance or shipping intensity) into a number of equal sized bins, create data points of the mean x- and y-axis (SO_2) data in each bin, then add a polynomial best-fit (quadratic in panel A, linear in panel B) for the overall dataset. Both panels use data from 2000 to 2008, before direct US participation in MARPOL Annex VI.

1.4.3. “Intermediate treatment” counties

One potential issue with both difference-in-differences approaches is the fact that shipping is carried out in routes that can involve close proximity to the US coastline or the traversal of major rivers. Figure 1.6 gives the location of US borders, coastline (including Great Lakes shoreline), the 126 major ports, and the portions of rivers potentially relevant to shipping traffic to those ports. However, unlike fixed port locations, the speed of passing ships and the exact distance between coast or waterways and shipping routes can have a large impact on the amount of SO_2 emitted in these areas, and the use of the shipping intensity variable calculated previously is not an appropriate proxy since ports are not matched one-to-one with shipping routes.

To examine this dynamic in more detail, a group of 102 “intermediate treatment” counties is selected with two criteria: first, having a distance of over 50 km between the county centroid and a major port, and second, there being less than 50 km between the county centroid and the nearest section of US coastline, Great Lakes shoreline, or river hosting a port as shown in Figure 1.6. As some of these intermediate treatment counties may be more “treatment-like” or more “control-like” in terms of their actual exposure to SO_2 emissions from shipping, this group is dropped from the analysis, but in checking the robustness of the main results it is added to the treatment, added to the control, and used as the sole treatment group.[31]

---

[31] Table 1.4 contains these results, which are largely unchanged in all combinations except for the introduction of large amounts of error, underlining the variable and ambiguous status of this group.

Figure 1.6. US borders, coastline, major ports, and the river portions potentially relevant to the ports.

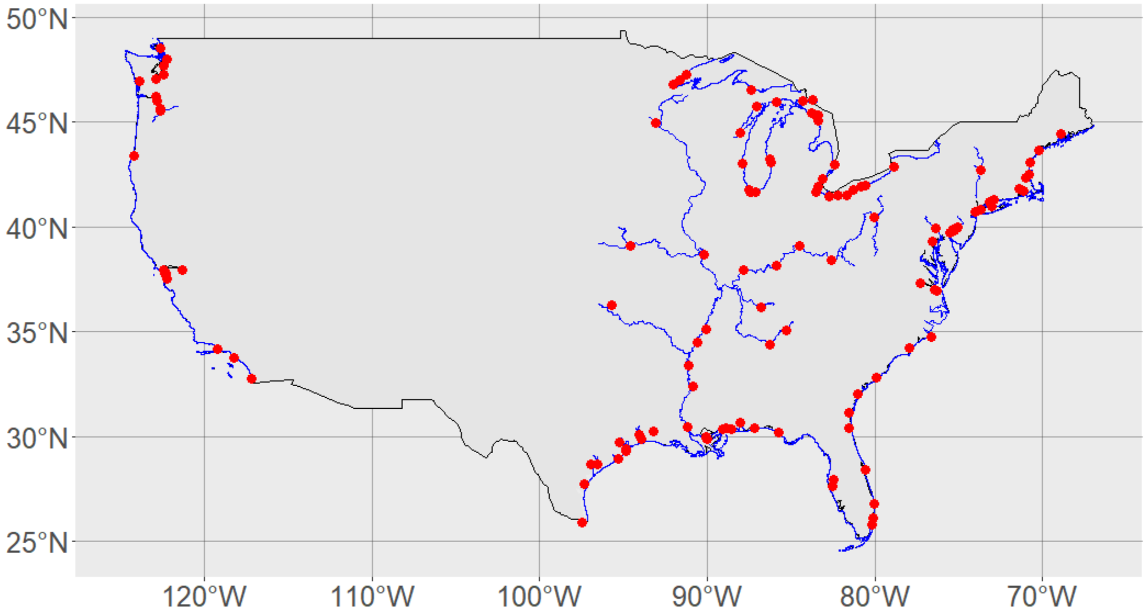

Figure 1.6 Notes: US borders are given in black; coastline, Great Lakes shoreline and river portions potentially relevant to shipping traffic in blue; and the locations of the 126 major ports in red.

1.5. Empirical Strategy

1.5.1. Summary statistics

Table 1.1 gives summary statistics of county SO_2 concentrations, all-ages mortality rates and controls for the continental United States, as a whole and separated by treatment status. Intermediate treatment counties are excluded, leaving 150 treated counties and 251 control counties. Means, standard deviations and percent decline from 2000 to 2019 averages were calculated, and only control data for county-date pairs which also included SO_2 monitoring data was considered. Statistics that were aggregated to the county from the air monitor site level are only reported at the county level. In addition, since shipping intensity is only non-zero for counties with centroids located within 50 km of a port by definition, summary statistics for this variable are only available in the control group. They are here summarized in absolute (not Z-scored) form.

Of particular interest is how steep the decline in sulfur pollution is across the country over the time period of the study, including from terrestrial sources which underlines its importance as a control. The large drop in measured SO_2 concentrations in both the treatment and control groups is further illustrated in Figure 1.7. This era included many changes in technology and policy intended to combat SO_2 pollution, on land as well as on sea, which makes quantifying any reduction in emissions from the IMO fuel sulfur regulation difficult without exploiting some heterogeneity in its impact.

Table 1.1. Summary statistics for county SO_2 concentrations, mortality rates and county-level controls.

	All Counties			Treatment Group			Control Group		
	Mean	Standard Deviation	Percent Decline	Mean	Standard Deviation	Percent Decline	Mean	Standard Deviation	Percent Decline
SO_2 Concentration	2.21	2.45	84.4	2.69	2.71	87.0	1.82	2.15	81.0
Mortality Rates (All Ages)	922	217	-3.9	898	184	-4.9	943	238	-2.4
Mortality Rates (45+)	2106	366	12.2	2080	342	13.3	2126	383	11.6
NO_2 Concentration	10.5	6.9	51.5	12.6	6.8	46.5	8.2	6.3	53.8
Data Availability	72.0	27.6	8.8	69.6	26.7	17.4	74.0	28.2	2.9
Terrestrial SO_2	192	536	90.0	229	521	92.1	162	536	87.3
Temperature	12.8	10.0	-3.1	13.6	9.7	-4.4	12.2	10.3	-3.5
Wind Speed	3.58	1.24	0.5	3.63	1.20	0.8	3.53	1.27	-0.7
Income	39.9	12.5	-80.6	42.2	13.0	-76.4	38.0	11.8	-89.7
Unemployment	5.7	2.4	5.9	5.8	2.1	2.7	5.6	2.6	8.5
County Population	495	913	-4.6	758	1199	-10.2	284	496	-21.9
Smoking Rates	23.2	4.5	28.8	23.1	4.7	30.1	23.3	4.3	28.0
Shipping Intensity	-	-	-	4.32	6.85	1.0	-	-	-

Table 1.1 Notes: County SO_2 and NO_2 concentrations are given in parts per billion, mortality rates in deaths per 100,000, data availability in percentages, terrestrial SO_2 in tons/km, temperature in degrees Celsius, wind speed in meters per second, income in thousands of US dollars, unemployment in percentages, county population in thousands, smoking rates in percentages, and shipping intensity in millions of tons/km. Percentage declines are from 2000 to 2019 and are calculated using annual averages over all sites with existing data in each year, with negative numbers corresponding to a percentage *increase* from the 2000 base.

Figure 1.7. Average concentration of SO_2 over time in counties in both the treatment and control groups.

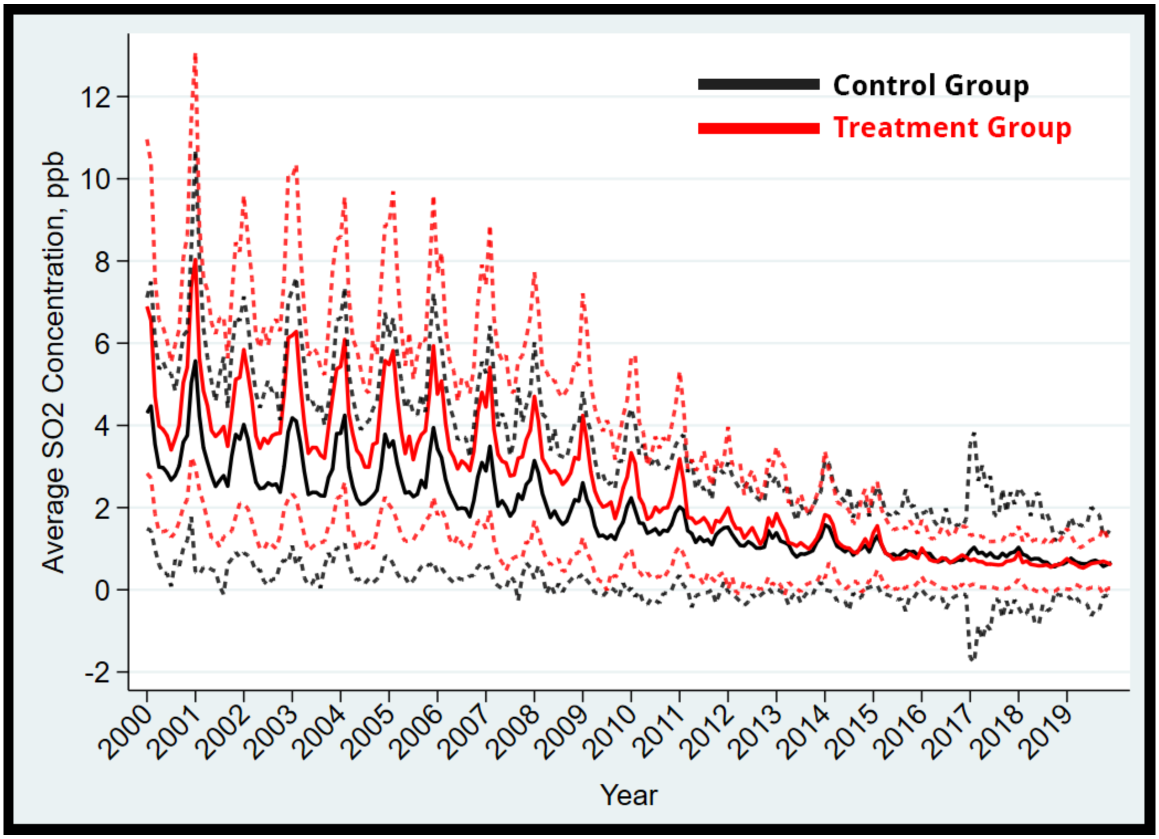

Figure 1.7 Notes: County SO_2 concentrations are given in parts per billion with solid lines representing monthly means of counties within each group and dashed lines representing one standard deviation away from the mean.

1.5.2. Model specification

This study estimates the impact of the different fuel sulfur limit policy eras in the continental United States on SO_2 as well as annual mortality rates from 2000 to 2019 using a standard difference-in-differences, or two-way fixed effects, panel data specification:

$$y_{i,t} = \alpha + \beta_1 Treatment_i * I_{1t} + \beta_2 Treatment_i * I_{2t} + \beta_3 Treatment_i * I_{3t} + \mu_i + \mu_t + \gamma X_{i,t} + \varepsilon_{i,t}, \tag{1.2}$$

where $y_{i,t}$ represents the dependent variable, either the concentration of SO_2 in parts per billion or the mortality rate in deaths per 100,000 measured by county *i* during month *t*, and $Treatment_i$ represents the treatment status of county *i*, which is equal to one if a county centroid is within the cut-off distance of 50 km from a major port and zero otherwise. Three policy indicators represent the three successive fuel sulfur limit policy eras after the baseline period without limits, all defined by the month of their enactment: the transatlantic partner limit era (I_1), the global limit era (I_2), and the US SECA limit era (I_3). County (μ_i) and year-by-month (μ_t) fixed effects are included, which control for location-specific time-invariant factors that might impact concentrations of SO_2 such as local population density or traffic, and those which might create different baseline levels of mortality rates like education or lifestyle habits, as well as common shocks to SO_2 concentrations and trends in mortality rates across the US. Finally, $X_{i,t}$ represents a vector of county-level environmental and demographic control variables[32]. Standard errors are clustered at the county level.

The impact of each era of IMO fuel sulfur limits is measured by the three β_i coefficients, which in this difference-in-differences setting represent the average reduction in the dependent variable (SO_2 concentrations or mortality rates) measured by counties in the treated group during each era, relative to counties in the control group. The focus of this study is on the reduced-form estimates, instead of using an instrumental variables approach, since SO_2 can impact health outcomes directly as well as through its atmospheric chemical products such as sulfate particles.

An alternative specification adds a set of interactions between shipping intensity and the policy timing variables to take into account the relative proximity of counties to major ports as well as their level of activity:

$$y_{i,t} = \alpha + \beta_1 Treatment_i * I_{1t} + \beta_2 Treatment_i * I_{2t} + \beta_3 Treatment_i * I_{3t} +$$

$$\beta_4 Intensity_{i,t} * I_{1t} + \beta_5 Intensity_{i,t} * I_{2t} + \beta_6 Intensity_{i,t} * I_{3t} + \beta_7 Intensity_{i,t} +$$

$$\mu_i + \mu_t + \gamma X_{i,t} + \varepsilon_{i,t}, \qquad (1.3)$$

where $Intensity_{i,t}$ is defined in Equation 1.1 for each county i (and is zero for non-treated counties) and other variables are as described in Equation 1.2. To be consistent with the results of the primary specifications, the coefficient on $Intensity_{i,t}$ should be positive in analysis of both dependent variables, showing that either more shipping activity or a closer county-port distance is related to both higher SO_2 concentrations and

---

[32] These include data availability, NO_2, terrestrial SO_2, temperature, wind speed, income, unemployment and county population. For mortality regressions, smoking rates and the fraction of the county population in the age group of interest are added.

higher mortality rates, and the coefficients β_4-β_6 should be negative and increasing in magnitude, suggesting that the successive fuel sulfur limits had the most impact on sulfur measured in counties with the highest shipping intensity scores.

1.5.3. Identification strategy

In general, difference-in-difference models such as the one used here rely on the premise that the observed trends in the response variable (e.g. SO_2 or mortality rates) between treated and untreated units move in parallel before and after the treatment, and that the treatment is the only cause of a departure from these parallel trends. There are a few key threats to this identification assumption in this setting.

First, due to EPA regulations and various technological changes, SO_2 levels have been decreasing nearly everywhere in the US, primarily from coal-fired electrical generation and other heavy industry which has historically made up a large percentage of total US sulfur emissions. Fortunately, EPA data on emissions from these sources is high-quality and spatially precise, which allows for its use as a control along with other standard measures of (pollution-generating) economic activity, namely income, unemployment and total population. However, there is some potential for the fuel sulfur policy changes to affect the emissions of non-shipping polluters. As a mechanism, Hansen-Lewis and Marcus (2023) suggest that counties with air quality near the National Ambient Air Quality Standards may undertake less costly terrestrial abatement measures in light of the additional “room” provided by the lower shipping emissions, but the evidence is not conclusive. To the extent that land-based polluters emit more SO_2 than they would in the absence of the MARPOL Annex VI policies, the overall changes in SO_2 due to the fuel sulfur caps will be mitigated.

Second, the IMO fuel sulfur policies could lead to differentials in measured mortality rates through possible effects on economic activity, if they significantly impacted shipping volumes and by doing so the economies of port regions. It is well known that shocks to the level of unemployment and income can impact mortality rates (e.g. Strumpf et al., 2017). However, as shown in Figure 1.3, the introduction of the US SECA and the mandatory use of low sulfur fuels pushed down price premiums while shipping followed an upward trend. While this is only suggestive, not dispositive evidence, shipping volume is included as a control (through the shipping intensity variable) only in the second setting as a check of the primary results[33].

In addition, a perennial concern with attempts to link a specific air pollutant with health impacts is the fact that the levels of most common pollutants tend to be correlated. Since the MARPOL Annex VI policies impact both SO_2 and NO_2, albeit with different timing and speed due to the nature of the respective regulations, the inclusion of the latter as a control is essential. However, other major pollutants such as ozone or carbon monoxide should be unaffected by the fuel sulfur cap and engine NO_2 emissions controls.

1.6. Results

1.6.1. Regression analysis: SO_2 concentrations

Analysis of the impact of the fuel sulfur policies starts by estimating a model where, instead of policy era indicators, year indicators are interacted with the indicator of whether a county is within 50 km of a major port. Figure 1.8 plots the difference in county SO_2 concentrations between treatment and control counties relative to the first year of the analysis, 2000, with the three key policy eras shaded and labeled. Supporting the identification assumption, trends in SO_2 between treated and untreated counties are similar both before and after the policy shocks.

The introduction of the different policies creates large and persistent differentials between the groups, with counties near ports experiencing much larger declines in measured SO_2 relative to counties not near a port. As expected, given the limited impact of European regulations starting in 2006 on fuel used by ships traveling to and from North America, the transatlantic partner limit era does not cause a significant departure from pre-2006 differentials. Sulfur pollution in port counties starts to decline rapidly during the global limit era (2009-2012) and by 2013, the first full year of the SECA implementation, the SO_2 differential is large, sustained, and fully statistically distinguishable from that of the initial year of the study.

---

[33] The addition of the shipping intensity variable by itself (i.e., without interactions) does not change the primary results.

Figure 1.8. Event study coefficients corresponding to the implementation of MARPOL Annex VI fuel sulfur limit eras.

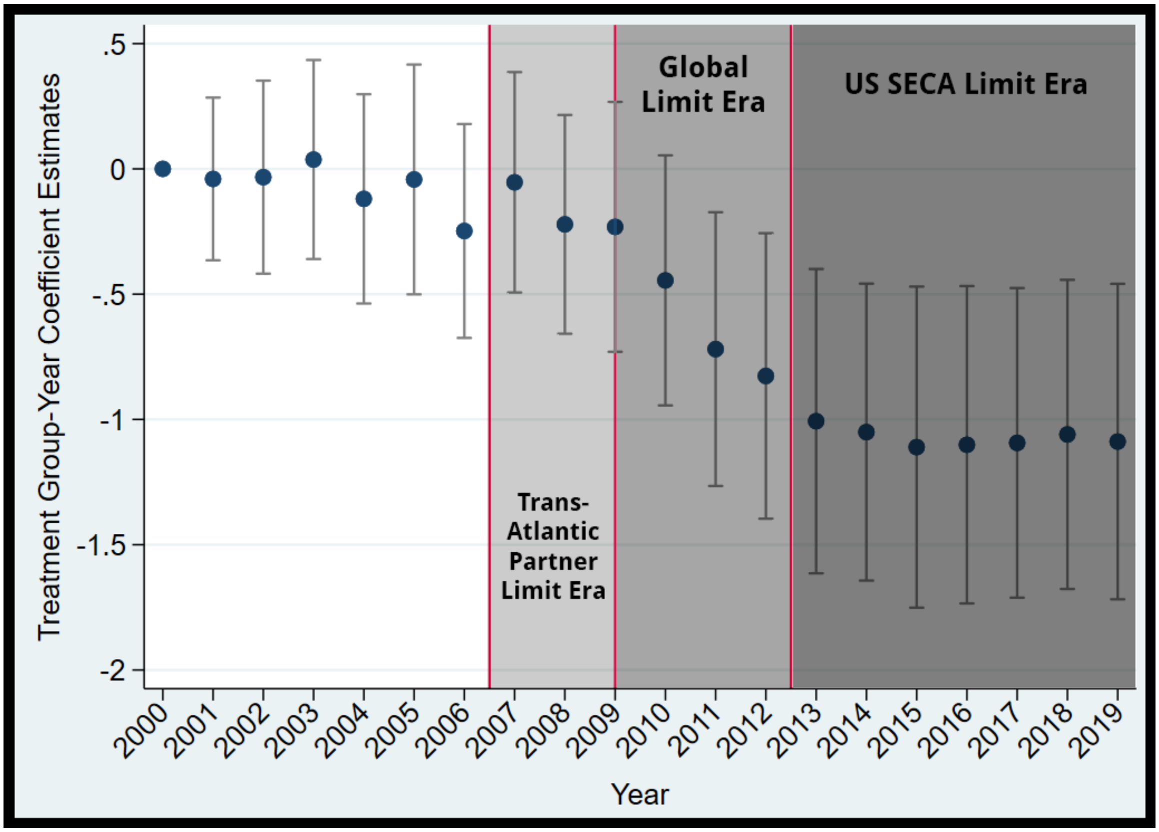

Figure 1.8 Notes: This event study presents the coefficients of a regression of county SO_2 concentrations on the interaction of the 50 km cut-off treatment indicator with yearly indicators as well as the full set of county fixed effects, economic and environmental controls given in the preferred specification in Table 1.2. Errors were clustered at the county level and the difference estimate for the initial year is set to 0. Error bars represent 95% confidence intervals, and vertical red lines mark the chronological boundaries of the different regulatory eras, labeled near the plotted coefficients.

Interestingly, while the US SECA era's treatment-control SO_2 difference stays constant from 2013 on, the global limit regime appears to take some time to phase in. This could be due to US regulation and enforcement capacity of the new law taking time to build, or that the new economic burden on the worst-polluting vessels pushed them out of service over the period of the global limit era. It is also notable that the 2015 tightening of the North American SECA does not seem to meaningfully or at least persistently reduce SO_2 concentrations in the treatment group relative to the control group, a result consistent with the findings of Hansen-Lewis and Marcus (2023) with regard to PM2.5 concentrations.

Following Equation 1.2, Table 1.2 gives the primary results from regressing SO_2 concentrations measured in counties on the interaction of the treatment indicator defined by the 50 km cut-off distance with the fuel sulfur limit era indicator variables. This treatment group consists of 150 counties or 37% of the total set. County fixed effects along with the data availability control are included in all specifications and year-by-month fixed effects are in specifications **(2)** and **(3)**. County-level controls, specifically NO_2 concentrations, temperature and wind speed averages, unemployment rates, per-capita income and population, as well as SO_2 emitted from nearby terrestrial fossil fuel sources are included in **(3)**, the preferred specification.

Table 1.2. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration.

Specification	**(1)**	**(2)**	**(3)**
Transatlantic Partner Limit (β_1)	-0.443 (0.142) ***	-0.438 (0.142) ***	-0.159 (0.149)
Global Limit (β_2)	-0.861 (0.195) ***	-0.859 (0.195) ***	-0.496 (0.221) **
US SECA Limit (β_3)	-1.449 (0.255) ***	-1.424 (0.255) ***	-1.064 (0.284) ***
Observations	57789	57789	32320
Data Availability	Y	Y	Y
County Fixed Effects	Y	Y	Y
Time Fixed Effects	N	Y	Y
Economic & Environmental Controls	N	N	Y

Table 1.2 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level.

Considering the regression results for the preferred specification in Table 1.2, both the global limit and US SECA limit eras are associated with large and highly significant declines in SO_2 exposure near major ports. Consistent with the event study plot in Figure 1.8, no significant decline can be linked to the IMO regulations affecting the Baltic and North Seas.

The average 1.064 ppb decrease in SO_2 concentrations measured in treatment group counties relative to control group counties that can be attributed to the total series of fuel sulfur limit regulations corresponds to a 23.8% decrease from the pre-policy era average among treated counties. Based on these summary coefficients in Table 1.2, the implementation of the North American SECA is responsible for a 12.7% decrease, over half of the total decline relative to the baseline period. A comparative analysis can be found in Table A.1, including the preferred specification **(3)** from Table 1.2 along with the same regression carried out using SO_2, fixed effects and controls at the site level. Unsurprisingly, aggregation to the county level attenuates point estimates, both absolutely and as a fraction of the mean SO_2 of each treated group. The total estimated impact of the MARPOL Annex VI policy is reduced by 25%, suggesting that the estimates in Table 1.2 represent a reasonable lower bound on the reduction of SO_2 induced by the fuel sulfur caps.

The estimated total impact agrees reasonably well with the literature on similar policies: Johansson *et al.* (2013) predict a 29% decrease in ship-based sulfur emissions as a result of the establishment of the European SECAs, while Zhang *et al.* (2019) find that the Shanghai 0.5% sulfur control zone led to decreases in SO_2 concentrations of 27-55%. Tao *et al.* (2013) found that a 28-72% decrease in SO_2 concentrations could be ascribed to California fuel sulfur limits.

While Hansen-Lewis and Marcus (2023) focused on PM2.5 measures, they also applied the same EPA forecast of the changes on PM2.5 from the fuel sulfur cap to SO_2 concentrations. As they explain, differences in atmospheric dynamics mean that a forecast of one is likely to have very high error in predicting the other, and indeed no significant impact was found. However, they also applied a model including an interaction between the policy indicator and the linear distance between counties and ports, finding just a 0.4% decline in SO_2 – although, for comparison, the estimated decline in PM2.5 in their primary specification was 4%. However, their sample was substantially different than that of this study, using only 68 counties within 200 km of the coastline, and their intensity of treatment did not include shipping volume.

Much has been made of the possible error resulting from distance-based treatment effect models in studies of air pollution, as exact distance dependencies vary with atmospheric conditions. However, it is also true that even complicated atmospheric model forecasts cannot take into account future micro- and macro-economic, social, technological or weather and climate changes that potentially impact estimated pollution effects from a policy such as the SECA before its implementation, with the added problem of the number of competing and variable pollution sources contributing to noise in the overall pollution measurements. It follows that measured post-policy departure from the forecast may not be fully due to behavioral changes but also original or accumulated pre-policy error in the original forecasting. For this reason, well-calibrated distance-based treatment methods may be better seen as complementary to atmospheric modeling approaches rather than as superseded by them.

To check the robustness of these results, Tables 1.3 and 1.4 tests a variety of specifications that help assess the sensitivity of the results to various factors. The first, Table 1.3, focuses on modifications of Equation 1.2, while the second, Table 1.4, examines modifications to the control group, treatment group, or entire county sample. Results from the preferred specification, column **(3)** of Table 1.2, are reproduced in the first column of both Table 1.3 and Table 1.4 to help ease comparison of the main results to these alternative specifications.

First, in Table 1.3, as there may be county-specific, time-varying unobserved factors that are correlated with changes in measured SO_2, specification **(2)** includes county-specific linear trends. Specification **(3)** adds Census region-by-time fixed effects to account for region-specific shocks. Finally, specifications **(4)** and **(5)** remove the NO_2 and terrestrial SO_2 controls respectively to examine how these competing pollution sources contribute to the main results.

Table 1.3. Checking the robustness of the measured impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration: modifications of Equation 1.2.

Specification	(1)	(2)	(3)	(4)	(5)
Transatlantic Partner Limit (β_1)	-0.159 (0.149)	-0.121 (0.145)	-0.115 (0.148)	-0.408 (0.139) ***	-0.320 (0.155) **
Global Limit (β_2)	-0.496 (0.221) **	-0.330 (0.204)	-0.362 (0.184) *	-0.794 (0.191) ***	-0.761 (0.231) ***
US SECA Limit (β_3)	-1.064 (0.284) ***	-0.640 (0.269) ***	-0.852 (0.228) ***	-1.367 (0.242) ***	-1.461 (0.297) ***
Observations	32320	32320	32320	57789	32320
Data Availability	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y
County Linear Trends	N	Y	N	N	N
Time Fixed Effects	Y	Y	Y	Y	Y
Region-by-Time Fixed Effects	N	N	Y	N	N
Economic & Environmental Controls	Y	Y	Y	All but NO_2	All but terrestrial SO_2

Table 1.3 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level.

Table 1.4 first considers the "intermediate treatment" group of 102 counties: counties within 50 km of the US coastline or within 50 km of shipping-relevant rivers for the major ports, but not located within 50 km of a port itself. Specification **(2)** adds these counties as part of the treatment group, while specification **(3)** adds them to the control, reflecting their ambiguous status. Specification **(4)** drops the primary treatment group from the sample, those counties within 50 km of a port, and gives the results of Equation 1.2 using the intermediate treatment group instead. Next, while dropping the intermediate treatment group from the sample as in Table 1.2, results excluding counties within California and those that do not have SO_2 measures meeting the 40% average availability threshold are presented in columns **(5)** and **(6)**. All specifications in Table 1.4 include county and year-by-month fixed effects along with the full set of county-level controls.

Table 1.4. Checking the robustness of the measured impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration: modifications of the control group, treatment group, or entire sample.

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Transatlantic Partner Limit (β_1)	-0.159	-0.200	-0.089	-0.316	-0.153	-0.253
	(0.149)	(0.139)	(0.150)	(0.272)	(0.153)	(0.155)
Global Limit (β_2)	-0.496	-0.539	-0.344	-0.750	-0.471	-0.528
	(0.221)	(0.208)	(0.226)	(0.445)	(0.233)	(0.235)
	**	***		*	**	**
US SECA Limit (β_3)	-1.064	-1.077	-0.889	-1.075	-1.058	-1.149
	(0.284)	(0.272)	(0.286)	(0.598)	(0.295)	(0.312)
	***	***	***	*	***	***
Observations	32320	36556	36556	19588	30359	26126
Data Availability	Y	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y	Y
Economic & Environmental Controls	Y	Y	Y	Y	Y	Y
Intermediate Treatment Group Included	N	Added to treatment	Added to control	Used as treatment	N	N
California Excluded	N	N	N	N	Y	N
40% Availability Threshold	N	N	N	N	N	Y

Table 1.4 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level.

Overall, results are robust across all of these specifications in both Table 1.3 and Table 1.4. One exception is the removal of NO_2 and terrestrial SO_2 controls. Without either of these controls, there is the appearance of a regulatory effect in the transatlantic partner limit era which disappears in all other specifications, along with a strengthening of the size of the coefficient associated with the global limit and US SECA limit eras. The contribution of NO_2 is related here to its high correlation with SO_2 from non-shipping sources which have decreased over time, and similarly, regulations on industrial and other large point source emitters of SO_2 have succeeded in greatly reducing non-shipping sources of SO_2 across the US over the time period of analysis. Moreover, county-specific linear time trends and Census region-by-time fixed effects attenuate the impacts but still suggest a substantial decline in port counties following the series of IMO regulations.

The ambiguous status of the intermediate treatment group of counties is confirmed by Table 1.4. Added to the treatment group, it does not change the results of the primary specification. Added to the control group, it attenuates them. Used as the sole treatment group, estimates are reasonably similar but with less precision. As previously discussed, the implication is that there are a variety of “treatment-like” and “control-like” counties within this group, with treatment intensity varying over highly complicated parameters. While this suggests that counties not near major ports but near passing ships also benefit from IMO regulations to some extent, without the requisite precise geographic data on individual shipping routes over the time period of the study, the intermediate treatment group as a whole remains difficult to classify and so is excluded in the remainder of the analysis. However, the effects of the regulations on these counties close to waterways but not close to ports helps to mitigate concerns about economic impacts from changes to port activity influencing county-level health measures.

As the choice of cut-off distance may have an effect on the estimated impact of the fuel sulfur policies, coefficients from regressions using a variety of treatment group cut-offs 10 km apart are plotted in Figure 1.9 as a final robustness check. As expected, point estimates gradually increase in magnitude as distance decreases. The coefficients on the transatlantic partner limit era are always small and statistically insignificant, while those on the global limit era remain moderate in size and remain near the edge of significance. However, each era’s coefficients cannot be statistically distinguished from their companions regardless of distance. Error tends to increase as the cut-off shrinks, since lowering this distance quickly reduces the size of the treatment group: at 20 km the reduction is to 63 counties, just 42% of the size of the group at 50 km.

Figure 1.9. **Regression coefficients and confidence intervals corresponding to the three policy era indicator variables as treatment group cut-off distance is varied.**

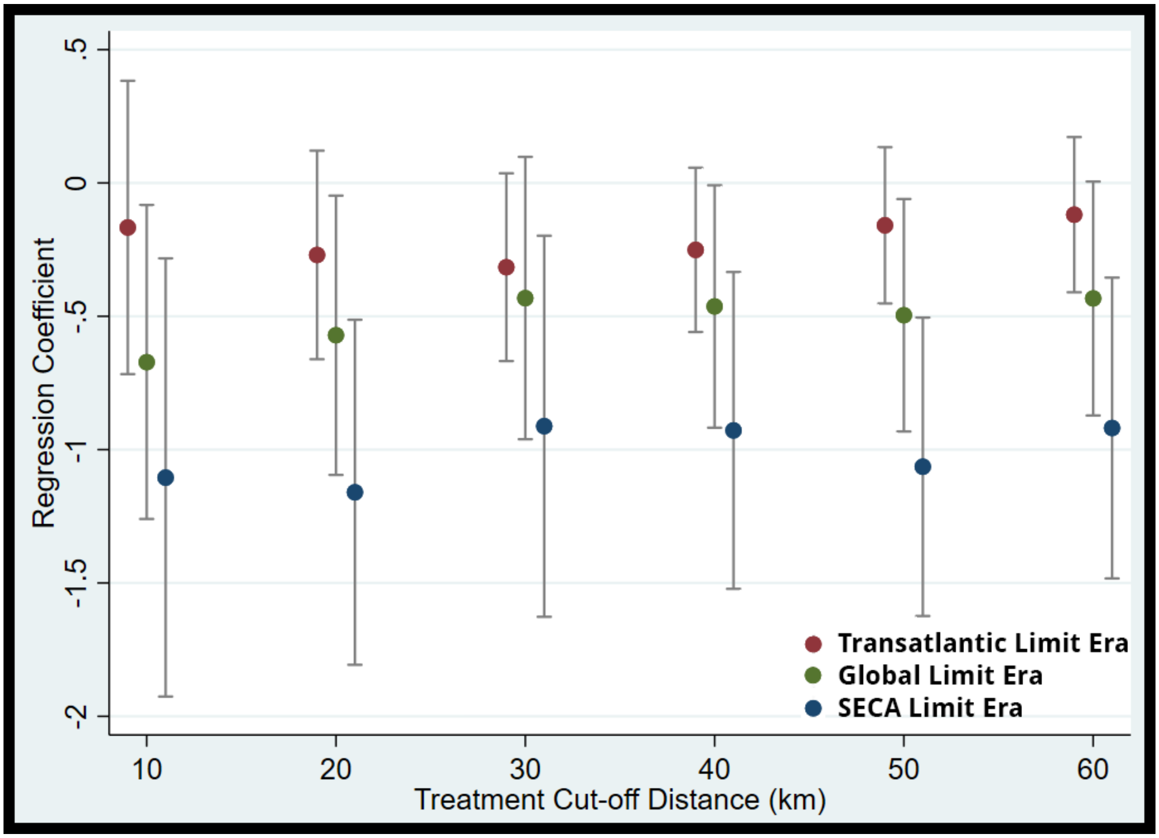

Figure 1.9 Notes: Estimates result from regressions of county SO_2 concentrations on the interaction of the 50 km cut-off treatment indicator with yearly indicators and were identical to the preferred specification, i.e. including county and year-by-month fixed effects as well as economic and environmental controls, with the exception that the treatment group of air monitor sites was defined by varied cut-off distances as given on the x-axis.

Next, Table 1.5 provides secondary regression results using Equation 1.3, that is, adding the interaction of Z-scored shipping intensity and the IMO regulation indicator variables to Equation 1.2. As in Table 1.2, county fixed effects along with the data availability control are included in all specifications and year-by-month fixed effects are in specifications **(2)** and **(3)**. Economic and environmental controls are included in **(3)**, the preferred specification.

Table 1.5. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration, taking into account the intensity of shipping activity of nearby major ports.

Specification	(1)	(2)	(3)
Transatlantic Partner Limit (β_1)	-0.425 (0.141) ***	-0.420 (0.141) ***	-0.114 (0.151)
Global Limit (β_2)	-0.788 (0.193) ***	-0.780 (0.193) ***	-0.383 (0.231) *
US SECA Limit (β_3)	-1.396 (0.255) ***	-1.367 (0.255) ***	-0.932 (0.297) ***
Transatlantic Partner Limit * Shipping Intensity (β_4)	-0.245 (0.137) *	-0.247 (0.138) *	-0.212 (0.109) *
Global Limit * Shipping Intensity (β_5)	-0.224 (0.167)	-0.225 (0.169)	-0.274 (0.142) *
US SECA Limit * Shipping Intensity (β_6)	-0.206 (0.185)	-0.212 (0.183)	-0.379 (0.196) *
Shipping Intensity (β_7)	1.088 (0.473) ***	1.175 (0.471) ***	0.871 (0.434) **
Observations	57789	57789	32320
Data Availability	Y	Y	Y
County Fixed Effects	Y	Y	Y
Time Fixed Effects	N	Y	Y
Economic & Environmental Controls	N	N	Y

Table 1.5 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level. β_4, β_5 and β_6 are coefficients on the interaction of Z-scored shipping intensity with their respective limit era indicator variables.

Point estimates of the treatment group effects, β_1-β_3, are somewhat smaller in magnitude to those in the preferred specification **(3)** of the original setting. As shipping intensity is Z-scored and centered around the mean for treated counties, these three estimates reflect the impact of the fuel sulfur caps on the “average” treated county with respect to the activity and distance of nearby ports. In the preferred specification **(3)**, estimates on the interacted shipping intensity-limit era variables are on the edge of significance (in order, $p = 0.053$, 0.054 and 0.054) and increasingly large in magnitude, implying that each additional standard deviation of shipping intensity is associated with less and less SO_2 as the IMO policies become stricter. Specifically, an extra standard deviation in shipping intensity on average contributed 0.871 ppb to a county's SO_2 levels in the pre-policy era, about 19.5% of that era's treated county mean, falling to 0.492 ppb or about half by the US SECA era. This is precisely in line with the theoretical basis for the study: all else equal, counties closer to busier ports measure higher levels of SO_2, but the amount of SO_2 resulting from an additional ton of shipping volume in a nearby port drops as fuel sulfur regulations become stronger.

The question of whether there are heterogenous impacts across Census regions is addressed next. Ports in the Northeast and some parts of the South are more likely to be affected by the limits imposed on the Baltic and North Seas, given transatlantic shipping routes. Moreover, ports in the West could be differentially affected due to the implementation of earlier and more strict regulations in California. Table A.2 provides results using the key preferred regression **(3)** of Table 1.2 for each Census region: Northeast **(1)**, the Midwest **(2)**, the South **(3)**, and the West **(4)**. Unfortunately, subsetting the data to such a degree tends to decrease precision substantially and results mostly lose significance, although point estimates for the US SECA limit era do not differ greatly from those determined using the unified data. Overall, these patterns suggest similar impacts across different regions which is consistent with the policy's simultaneous application across the US and strict enforcement.

1.6.2. Regression analysis: mortality rates

Following Equation 1.2, Table 1.6 gives the primary results from regressing all-cause mortality rates measured in counties on the interaction of the treatment indicator defined by the 50 km cut-off distance with the fuel sulfur limit era indicator variables. In parallel with Table 1.2, county fixed effects along with the data availability control are included in all specifications and year-by-month fixed effects are in specifications **(2)** and **(3)**. County-level controls are included in in **(3)**, the preferred specification. Here, county smoking rates as well as the fraction of the county population in each age band[34] are added to the previous list of controls. In all specifications, regressions were weighted by the pre-policy era average population in each county.

Table 1.6. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in all-cause mortality rates (per 100,000 population).

Specification	(1)	(2)	(3)
Transatlantic Partner Limit (β_1)	-2.3 (5.1)	-1.7 (5.2)	0.3 (4.3)
Global Limit (β_2)	-11.0 (7.4)	-10.2 (7.4)	-7.0 (5.4)
US SECA Limit (β_3)	-23.9 (10.4) ***	-23.1 (10.6) **	-19.9 (6.9) ***
Observations	57552	57552	32296
Data Availability	Y	Y	Y
County Fixed Effects	Y	Y	Y
Time Fixed Effects	N	Y	Y
Economic, Environmental & Health Controls	N	N	Y

Table 1.6 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level.

The regression results for the preferred specification in Table 1.6 show a large and significant decline in mortality rates near major ports in the US SECA limit era, but the estimate on the global limit era is insignificant. As with the SO_2 analysis, no decline can be linked to the IMO regulations affecting the Baltic and North Seas. The average decrease of 19.9 per 100,000 population in all-cause mortality rates attributable to the full set of fuel sulfur caps represents a 2.2% decrease in treatment group counties relative to control group counties from the pre-policy era average among treated counties.

---

[34] Age bands consist of 0-4 years, 5-14 years, 15-24 years, 25-34 years, 35-44 years, 45-54 years, 55-64 years, 65-74 years, 75-84 years, and 85 and over.

There is reason to suspect that the measured effect from the all-ages mortality rate aggregate is a composite of effects from different age groups that vary substantially. The impact of air pollution varying with age is well-known in the medical and health economics literature: in a meta-analysis of air pollution and mortality studies, Stieb, Judek, and Burnett (2011) found substantially higher excess mortality rates in the elderly population from a variety of pollutants, including SO_2. Murphy (2017) studied decreases in PM2.5 imposed by the EPA's Clean Air Interstate Rule and found increasingly large impacts to mortality rates after age 55, with no significant effect below that age. Deryugina *et al.* (2019) also found higher mortality impacts from PM2.5 pollution within the 65+ population as ages increased. In addition, a report from the United Kingdom Department of Health (Committee of the Medical Effects of Air Pollutants, 1998) found that unit increases in PM10, SO_2 as well as ozone significantly increased hospital admissions in the 65+ population compared to the 15-64 population, with the rate being doubled for SO_2.

In order to explore the age dependence on mortality rate outcomes from the fuel sulfur limit policies, Table A.3 gives the results from regressing county mortality rates on the interaction of the treatment indicator defined by the 50 km cut-off distance with the fuel sulfur limit era indicator variables. Mortality rates are separated into all ages **(1)**, then the age bands < 1 year **(2)**, 1-4 years **(3)**, 5-14 years **(4)**, 15-24 years **(5)**, 25-34 years **(6)**, 35-44 years **(7)**, 45-54 years **(8)**, 55-64 years **(9)**, 65-74 years **(10)**, 75-84 years **(11)**, and 85+ years **(12)**. All specifications in Table A.3 include county fixed effects, year-by-month fixed effects, and the complete set of controls, consisting of data availability, NO_2 concentrations, temperature and wind speed averages, unemployment rates, per-capita income and population, SO_2 emitted from nearby terrestrial fossil fuel sources, smoking rates, and fraction of the county population in each age band being analyzed. Regressions were additionally weighted by the pre-policy era average age band-specific population in each county.

A clear pattern is evident from the estimates in Table A.3: younger age bands have insignificant and inconclusive results, while several older age bands show impacts that range from small to moderate with much higher precision, stemming from the global limit and US SECA limit eras. In part this is due to the fact that younger age bands have a much higher proportion of missing data, but nonetheless no effect from the fuel sulfur cap policies is significant until well into middle age bands.

Figure 1.10 displays these coefficients and their associated 95% confidence intervals as a percentage of pre-policy era mean treated county mortality rates, since absolute mortality rates steadily increase with age. Error is high but decreases substantially for older age groups, and the significant estimated relative coefficients on the US SECA limit era indicators in these groups range from 1.9-3.2% of pre-policy means. Interestingly, the under one year age group, also regarded as highly susceptible to air pollution (e.g. Chay and Greenstone, 2003; Currie and Neidell, 2005; Currie, Neidell, and Schmieder, 2009; and Currie, Heep Ray, and Neidell, 2011), reports similar relative point estimates of 3.4%, but with very high error. This is nonetheless in line with Hansen-Lewis and Marcus (2023), which use more precise infant health data and find the impact of the SECA to be a reduction of 2.8% in infant mortality.

Figure 1.10. **Regression coefficients and confidence intervals corresponding to the three policy era indicator variables as mortality rate age bands are varied.**

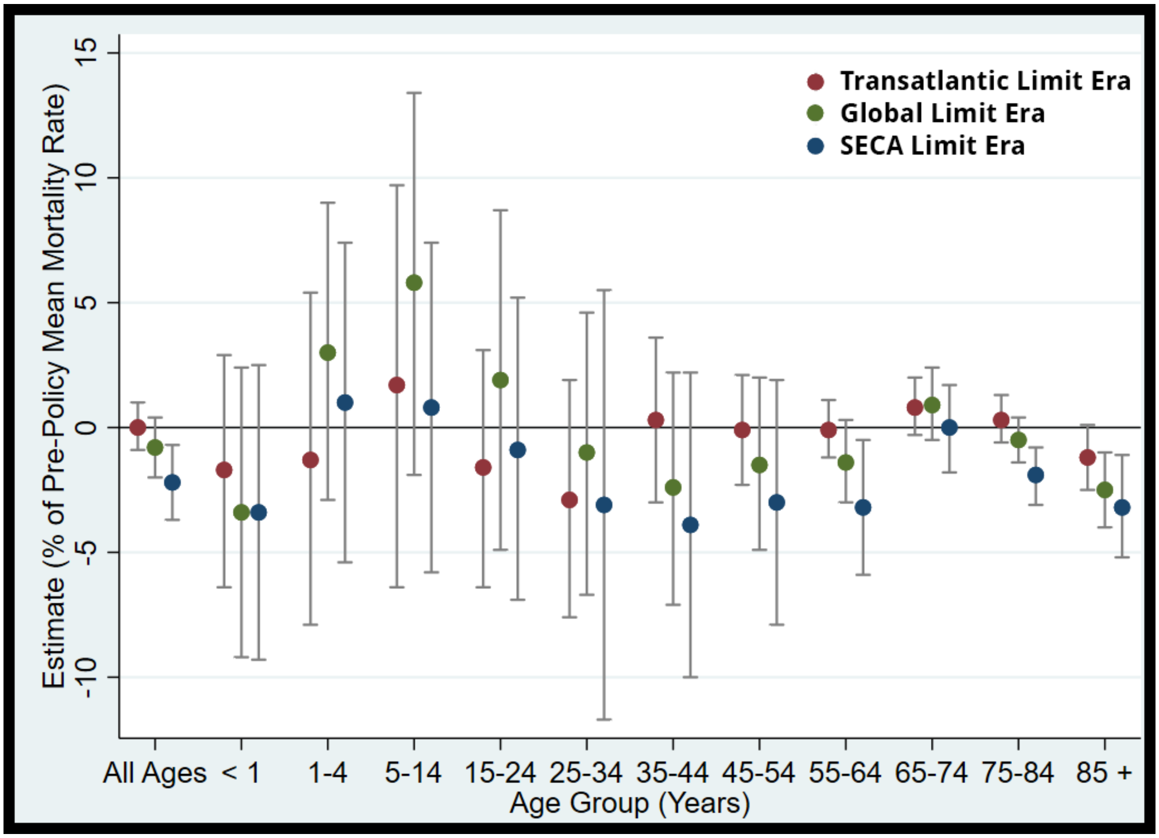

Figure 1.10 Notes: Estimates result from regressions of county mortality rates on the interaction of the 50 km cut-off treatment indicator with yearly indicators. All regressions include county and year-by-month fixed effects as well as economic, environmental and health controls, and are identical except that the regressed age group and age group population fraction control vary as given on the x-axis.

Given the strong age dependence on the mortality rate estimates, this study now contrasts the all-cause mortality rates of two groups: those aged 44 and under, and those 45 and over. For each age group, a model is estimated akin to that shown in Figure 1.8, where year (not policy) indicators are interacted with the indicator of whether a county is within 50 km of a major port. Figure 1.11 then plots the difference in all-cause mortality rates between treatment and control counties relative to the first year of the analysis, 2000, with the three key policy eras shaded and labeled. Panel A uses the under 45 age group, while Panel B uses the 45+ group. Each event study includes the full set of controls, with regressions weighted by age-specific pre-policy county populations.

Mortality rate estimates are in general noisier than those of SO_2, a phenomenon found in similar papers (e.g. Figures 3 and 5 in Barreca, Neidell, and Sanders, 2021). However, supporting this study's identification assumption, trends in SO_2 between treated and untreated counties are similar both before and after the policy shocks in both panels. While no lasting trend is visible in the under 45 group estimates during the introduction of the different fuel sulfur policies and confidence intervals always overlap the 2000 baseline, the global limit and US SECA limit eras create large and persistent differentials between the treatment and control counties in the analysis of the 45+ group, with counties near ports experiencing much larger declines in mortality rates relative to counties not near a port.

With no significant impact detected on measured SO_2 in the transatlantic partner limit era, it is not surprising that there is also a lack of impact found on mortality rates. By contrast, in the 45+ group, mortality rates in port counties show substantial drops during the global limit era (2009-2012) and as the SECA is implemented, these declines continue and are sustained for the remainder of the study period. The 2014-2019 mortality rate differential is large and fully statistically distinguishable from that of 2000.

Figure 1.11. Mortality rate event study coefficients corresponding to the implementation of MARPOL Annex VI fuel sulfur limit eras for the under 45 and 45+ age groups.

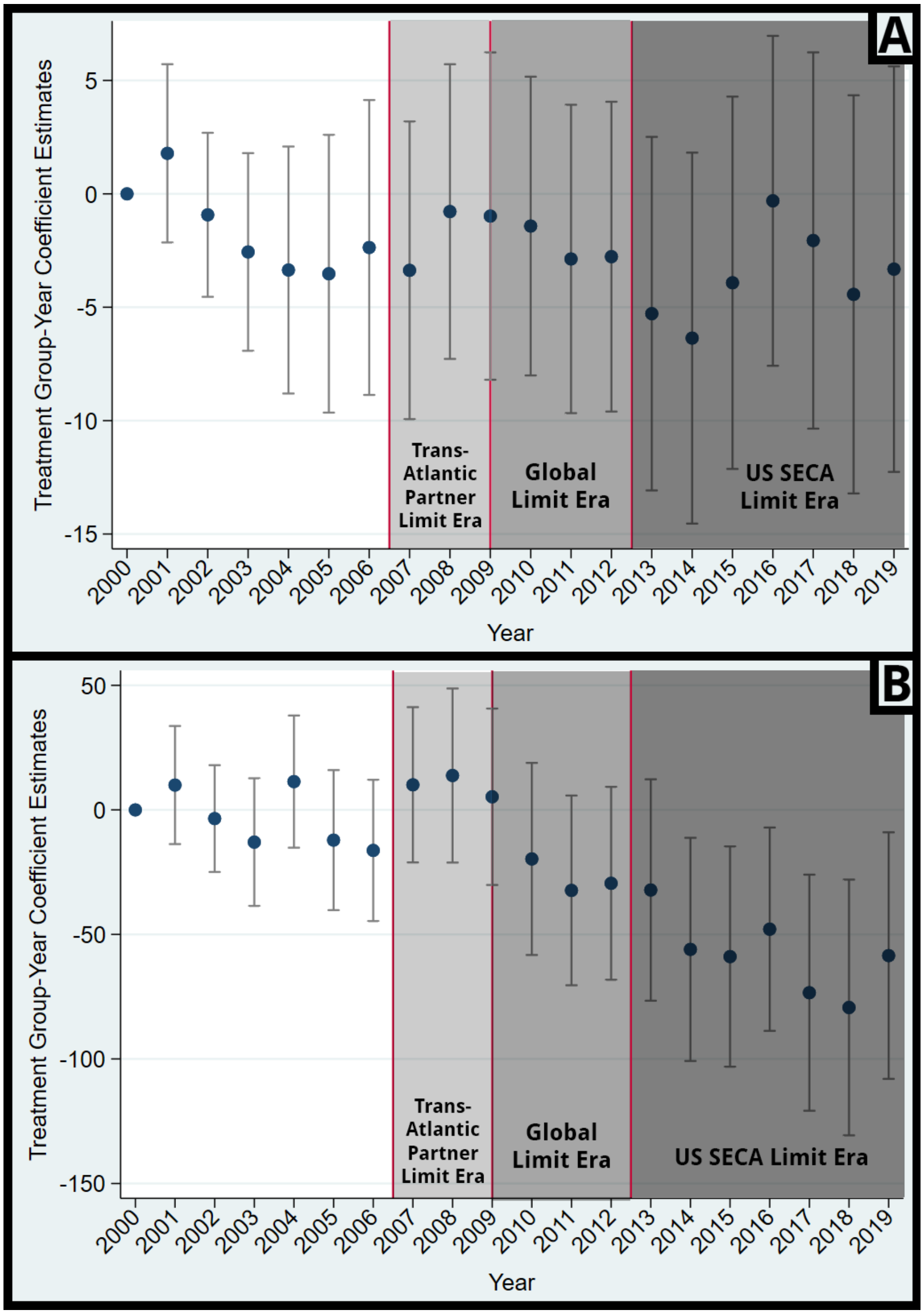

Figure 1.11 Notes: These event studies present the coefficients of regressions of mortality rate concentrations on the interaction of the 50 km cut-off treatment indicator with yearly indicators as well as the full set of county fixed effects and controls given in the preferred specification in Table 1.6. Panel A uses mortality rates from the under 45 age group, while Panel B uses data from the 45+ group. Regressions were weighted by age-specific pre-policy mean county populations, errors were clustered at the county level and the difference estimate for the initial year is set to 0. Error bars represent 95% confidence intervals, and vertical red lines mark the chronological boundaries of the different regulatory eras, labeled near the plotted coefficients.

The impact of the fuel sulfur policies on the all-cause mortality rate for the 45+ age group can be further decomposed into specific-cause mortality rate effects. Table 1.7 provides results from regressing county all- and specific-cause mortality rates on the interaction of the treatment indicator defined by the 50 km cut-off distance with the fuel sulfur limit era indicator variables. Specification **(1)** uses all-cause rates, **(2)** uses diseases of the circulatory system, and **(3)** uses neoplasms or cancers. As diseases of the respiratory system alone make up a significantly smaller portion of the overall mortality rate than other causes, specification **(4)** uses a combined cardio-respiratory rate. Finally, for comparison purposes specification **(5)** uses the remainder of all-cause mortality, where values exist for the previous causes. All specifications in Table 1.7 include the full set of fixed effects and controls as in Table 1.6, with regressions again weighted by each county's 45+ aged pre-policy mean population.

Table 1.7. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in all- and specific-cause mortality rates (per 100,000 population) for the 45+ age group.

Specification	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Mortality Cause	*All-cause*	*Circulatory diseases*	*Neoplasms or cancers*	*Cardio-respiratory diseases*	*All other causes*
Transatlantic Partner Limit (β_1)	6.8 (8.3)	-2.0 (6.3)	4.6 (2.7)	3.9 (6.8)	-1.6 (6.3)
Global Limit (β_2)	-15.8 (12.1)	-18.7 (6.8) ***	3.4 (3.3)	-6.9 (8.7)	-11.2 (8.0)
US SECA Limit (β_3)	-52.8 (16.9) ***	-32.2 (10.2) ***	-6.3 (4.3)	-22.4 (11.9) *	-24.2 (11.0) **
Treated Pre-Policy Mean Rate	2229.4	877.4	556.2	1433.6	575.6
% Decline from Pre-Policy Mean	2.4 (0.8)	3.7 (1.2)	1.1 (0.8)	1.6 (0.8)	4.2 (1.9)
Observations	32269	31649	31355	30330	30317
Data Availability	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y
Economic & Environmental Controls	Y	Y	Y	Y	Y

Table 1.7 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. Each specification uses the full set of fixed effects and controls given in

the preferred specification in Table 1.6. Regressions were weighted by each county's 45+ aged pre-policy mean population, and in all specifications, errors were clustered at the county level.

In Table 1.7, estimates of the impact of the MARPOL Annex VI fuel sulfur policies on the relative difference between treated and control counties in all-cause mortality rates as well as circulatory and other-cause mortality rates were large and significant. The total average drop in all-cause, circulatory and other rates was 2.4%, 3.7% and 4.2% respectively from their pre-policy era means, with all transatlantic partner limit era estimates insignificant and the magnitude of point estimates increasing from the global limit era to the US SECA limit era. The estimate on neoplasms or cancers was moderate but not significant, and the combined cardio-respiratory category had a lower and less significant estimated impact[35].

Diseases of the circulatory system make up about 60% of the total impact in the 45+ age group[36]. Unfortunately, annual county-level CDC data on the remaining specific causes of mortality, dividing about a quarter of the total mortality rate into more than a dozen other subsets, tends to have very high rates of missing data. It is therefore difficult to determine which other specific mortality causes are linked to the fuel sulfur policies, or if reduced air pollution is perhaps acting as a general health factor that lessens the mortality rate of pre-existing health conditions or disorders.

Both the lack of impact for younger age groups and for older groups the 2.4% average decrease in all-cause mortality rates that can be attributed to the total series of fuel sulfur limit regulations align well with similar studies. Ha *et al.* (2003) found that a change in SO_2 exposure from the first to the fourth quartile led to a 2.5% increase in total mortality for those 65 and over in Seoul, South Korea, while there was no significant impact on those ages 2-64. Li *et al.* (2016) found that a 3.8 ppb increase in SO_2 concentrations in Guangzhou, China led to increases in COPD mortality rates (a category representing 8.4% of total mortality) of 3.8% for those over 65, but no significant increase for those under 65. Barreca, Neidell, and Sanders (2021) examined sulfur controls imposed by the US Acid Rain Program and concluded that each unit of

---

[35] Event studies (not shown) of respiratory mortality rates display very high rates of noise, which dilutes the estimates of diseases of the circulatory system when combined.

[36] As specific-cause data was not complete relative to the all-cause data, estimates do not exactly sum to those in the all-cause column.

decreased baseline PM2.5 led to a 1.1% mortality reduction, with effects found in the 35-64 and 65+ age groups but none in the under-35 group.

To complete the analysis, Table A.4 provides secondary mortality rate regression results using Equation 1.3, again adding the interaction of Z-scored shipping intensity and the fuel sulfur limit era indicator variables to the regression. All fixed effects and controls are included and regressions were weighted by each county's specific-age pre-policy mean population. Specifications include all-cause mortality rates for the 44 and under group and 45+ groups as **(1)** and **(2)** respectively, then for the 45+ group mortality rates are divided into **(3)**, diseases of the circulatory system, **(4)**, neoplasms or cancers, **(5)**, combined cardio-respiratory diseases, and **(6)**, the remainder of all-cause mortality where values exist for the previous causes.

As expected, no estimate in the under-45 group is significant or suggestive of any impact from the MARPOL Annex VI regulations. However, results from the 45+ group are more interesting. As was seen in the SO_2 regressions, point estimates of the treatment group effects β_1-β_3 are attenuated somewhat compared to the original setting in Table 1.7. The addition of this Z-scored variable implies β_1-β_3 represent the impact of the fuel sulfur caps on the average treated county with respect to the shipping volume and distance of nearby ports. However, while estimates on the interacted shipping intensity-limit era variables are generally negative, they have high error. The exceptions are those on neoplasms or cancers which become increasingly negative through the transatlantic partner, global limit and US SECA limit eras, as expected. While the regressions suggest that an additional standard deviation of shipping intensity contributes to mortality rates in treated counties, for most mortality causes the change over time in this contribution is inconclusive.

1.7. Fuel Market Response and Cost-Benefit Analysis

1.7.1. Fuel market response

Given the cumulative impact of the set of MARPOL Annex VI fuel sulfur limit policies on SO_2 exposure and mortality rates near major US ports, it is worth examining the economic costs and benefits of the policy as well as the response in the shipping fuels market. To begin, this study gives a short overview of developments in fuel price premiums between low- and high-sulfur fuels.

All marine fuel oil prices are highly correlated with that of crude oil, their source, but very low sulfur fuels carry a significant price premium over their higher-sulfur alternatives, tonne for tonne. This premium has varied as regulation has spurred increased demand and, in response, technological development, new investment, and increased production capacity at refineries around the world, leading to the premium's apparent long run decline in percentage terms. In particular, the 2012 implementation of the North American SECA and later 2015 tightening of all existing SECAs forced significant changes in the refining and wholesale markets for low-sulfur fuels, which were less disruptive than earlier predictions by the shipping industry and many studies (Notteboom, 2020) and eventually narrowed the low sulfur fuel premium.

For example, from 1990 to 2008, before IMO fuel sulfur limit policies were enacted in the US, the average annual Rotterdam price premium between IFO380, a standard grade of high-sulfur fuel oil, and 0.1% sulfur marine gas oil (MGO) varied between 52% to 155%, with the average being 93% over that period (Notteboom, 2010). In absolute terms, this generally represented a price difference of $100-200 a tonne, with the largest gap coming in the summer of 2008 where the price differential briefly reached about $600, only to fall to $270 two months later (den Boer, Ahdour, and Meerwaldt, 2016) as the world economy began to slow.

From 2010 to 2016, the MGO-IFO380 price premium stayed relatively constant at about 50%, with absolute differences ranging from $300 per tonne to as low as $128. From 2017 to 2019 the MGO-IFO380 premium in relative terms lowered further to between 30 and 50% or about $150-200 per tonne, a development which can be attributed to IMO fuel sulfur regulations (Notteboom, 2020). These MGO-IFO380 price premiums were graphed in Figure 1.3 alongside averaging shipping volume from the top 25 US ports, showing influence from macroeconomic conditions on both variables but without suggesting that price premiums determined the path of shipping volume.

By contrast to MGO and other acceptable fuels under SECA rules, such as 0.1% ultra low sulfur fuel oil (ULSFO, which trades within a few percentage points of MGO), intermediate sulfur fuels such as 1% sulfur LS380, sufficient for use in SECAs from 2012 through 2014, have a much smaller premium over IFO380. The LS380-IFO380 premium was just $15 per tonne in throughout 2014 and 2015 (den Boer, Ahdour, and Meerwaldt, 2016).

1.7.2. Policy costs: fuel premiums and consumption

In order to estimate the cost of implementing the North American SECA, data on price premiums as well as consumption is necessary. The US Energy Information Administration, in its Annual Energy Outlook reference cases[37], provides data for the amount and type of fuels consumed by marine vessels each year. Distillates like MGO, for use in intermediate and very low sulfur blends and for meeting the 2015 SECA requirements of 0.1% sulfur fuel, rose from 14% of consumption in 2010 to 28% in 2014 and then to 38% by 2019, as shown in Table A.5.

The global limit era did not in general require consuming a new type or grade of fuels but rather avoiding the consumption of the most high-sulfur fuels of standard grades. Given the underlying price dependence on crude oil as well as short term shifts in supply and demand, any cost increases involved in ensuring fuels such as IFO380 were kept under the sulfur cap by e.g. changing wholesale suppliers are difficult to detect. Therefore, with some tolerance for uncertainty, one relatively simple method for calculating the policy cost involves establishing a distillate consumption baseline as a percentage of the fuel oil mix prior to the introduction of the North American SECA. Based on data from 2010 to 2012, a reasonable distillate baseline is around 15%. The counterfactual without the SECA, given the premise that the trend in shipping volume does not appear to be significantly impacted by the introduction of the fuel sulfur caps (Figure 1.3), is that fuel consumption would rise along with shipping volume but with the same distillate-heavy fuel oil mix, that is, distillate fuel consumption should remain at about 15% of total fuel consumption over time. Taking excess distillate consumption as due to the SECA regulations and simply multiplying the resulting additional tonnes of distillate fuel by their annual price premium, a policy cost can be calculated. Ignoring discounting, for example, we get a 2013-2019 total of $4.2 billion in 2014 US dollars, or an average of just under $600 million per year. This cost has been rising as distillate

---

[37] The EIA reference case data can be accessed at https://www.eia.gov/outlooks/aeo/.

consumption increases and the premium does not fall fast enough to compensate, perhaps signifying that returns to scale from distillate production have reached their limit.

1.7.3. Policy benefits: Value of a Statistical Life calculations

While the benefits of reduced SO_2 air pollution are varied, including the amelioration of phenomena like acid raid or damage to wildlife populations, the avoided mortality determined in this study can be used in the standard Value of a Statistical Life (VSL) framework (e.g. Viscusi and Aldy, 2003) to calculate a numerical estimate of benefits. This allows for a direct comparison to the low-sulfur fuel premiums calculated in the previous section.

Taking the limit era estimates resulting from regressions of mortality in Table 1.7, multiplying by era mean 45+ aged county populations in our sample[38] and then summing the annual results over the length of each era yields the number of deaths avoided through implementation of the fuel sulfur policies. As estimates in the transatlantic partner limit era were not significant, only the global limit and US SECA eras are considered. Table 1.8 gives these avoided death totals for both all-cause mortality and circulatory mortality separately as Columns **(1)** and **(2)**, respectively. Next, given the 2010 US Census value of the average age of the 45+ group, 61 years, and the corresponding age-appropriate VSL value from Aldy and Smyth (2014), $7 million, we can calculate a rough estimate of the valuation of the mortality improvements in each era, as Columns **(3)** and **(4)**. Finally, Columns **(5)** and **(6)** give the average annual valuation of the mortality improvements, given the length of each limit era.

Even with large margins for error, it is clear that the estimated valuation of benefits to mortality greatly exceeds that of the costs of low-sulfur premiums. In 2019, the year with the highest total premiums of low-sulfur fuel, the benefit to cost ratio ranged from 90 to 1 for circulatory mortality improvements alone to 147 to 1 using all-cause mortality. Even supposing that *all* distillate fuel consumption in 2019 was due to the US SECA, the benefit to cost ratio would range from 55 to 1 for circulatory mortality

---

[38] Populations are given in units of 100,000 as to match with the CDC mortality rates. In addition, air monitor coverage is not universal and not every county near a major port is in the sample. For example, in 2010 the population of the 45+ age group in the US was about 122 million, whereas the population of the 45+ age group in all sample counties was just 68 million. Therefore, the VSL calculations represent a likely lower bound on benefit values.

to 90 to 1 for all-cause mortality. Such large differences between policy costs and benefits have also been found in other analyses of programs that lowered SO_2 emissions in the US. Shadbegian, Gray, and Morgan (2007) determined that reductions in US emissions caused by Title IV of the 1990 Clean Air Act Amendments created health benefits of $56 billion against costs of $558 million. In addition, Barreca, Neidell, and Sanders (2021) found annual benefits of $51 to $109 billion by 2005 from sulfur controls on US power plants under the Acid Rain Program, with annual costs of just $3 billion.

Table 1.8. Change in mortality in the 45+ age group and total benefits using the VSL framework arising from the implementation of MARPOL Annex VI fuel sulfur policies.

Column	(1)	(2)	(3)	(4)	(5)	(6)
Measure	Avoided Deaths	Avoided Deaths	Mortality Improvement Valuation, billions of $	Mortality Improvement Valuation, billions of $	Annual Average Valuation, billions of $	Annual Average Valuation, billions of $
Mortality Cause	All-cause	Circulatory	All-cause	Circulatory	All-cause	Circulatory
Global Limit Era	22489	26616	157	186	43.9	52.0
US SECA Limit Era	167974	102439	1176	2004	158.5	96.7

Table 1.8 Notes: The average age of the 45+ aged population, 61 years, was calculated from 2010 US Census data and matched with the age-appropriate VSL value from Aldy and Smyth (2014), $7 million. Fractions of years were used in calculations, as each limit era either began or ended in the middle of a calendar year.

1.8. Conclusion

This study examines the implementation of successive, increasingly strict International Maritime Organization limits on the sulfur content of marine fuels consumed near the coastline and rivers of the United States. As fuel sulfur level maxima were introduced, the heterogeneity of their impact resulting from varying distances between major ports and air monitors was exploited in a distance-in-distances framework to conclude that SO_2 concentrations dropped substantially due to these changes, on average 24%, near sources of shipping activity. Over half of this decline could be connected to the establishment of the North American Sulfur Emissions Control Area (SECA) specifically. However, no significant effect was found from the 2015 tightening of the SECA, which suggests that most, if not all, of the reductions in sulfur emissions possible in the US through fuel sulfur limit policies on shipping have been already attained. While this is at odds with the results of investigations into the 2015 changes to the European SECAs, such as Barregard et al. (2019) and Lindgren (2021), it is consistent with the results of Hansen-Lewis and Marcus (2023), who find no impact on PM2.5 concentrations in the US from the lowered fuel sulfur limit in 2015. The divergent results between the US and Europe may be ascribed to varying approaches to regulatory implementation, different vessel compliance rates, or other factors.

Mortality rate impacts were heterogenous by age but among those 45 and older, the total impact of the fuel sulfur limit policies was to lower mortality rates by an average of 2.4%, with diseases of the circulatory system representing most of the change. The magnitude of these estimated SO_2 and mortality impacts are consistent with recent literature on SO_2 air pollution and mortality. Finally, estimates of fuel consumption and price premiums for the low sulfur fuels necessary for compliance with these new regulations suggests that these air quality improvements came at an average cost of $600 million USD per year, rising over time to $1.1 billion in 2019 as increased fuel usage was only partially countered by lower premiums. By contrast, the estimated valuation of avoided mortality was substantially larger at just under $160 billion USD a year.

As previously discussed, results from this study are complementary and consistent with a contemporaneous working paper by Hansen-Lewis and Marcus (2023). Hansen-Lewis and Marcus (2023) cleverly use a prediction model developed by the EPA in 2009 that takes into account shipping routes and meteorological conditions, and estimate the actual impact on PM2.5 and infant health outcomes as related to a predicted unit decrease in PM2.5. This modeling approach yields similar estimates on mortality outcomes as the distance-based approach used by this study, taking into account that the county samples and time period studied did not completely overlap: point estimates for average changes in infant mortality and all-ages mortality were 2.8% and 1% respectively in Hansen-Lewis and Marcus (2023), as opposed to 3.4% and 2.2% here. However, deeper exploration into adult mortality by cause and age group in this study yields more detailed information, with a wide divergence seen between the under-45 and 45+ groups. These complementary tallies of benefits calculated using different methods of analysis add to the overall understanding of this country-wide fuel regulation.

Given the scale, costs and health benefits of these US fuel sulfur limit policies, these results and those of Hansen-Lewis and Marcus (2023) help inform of the potential benefits of ongoing efforts to reduce SO_2 pollution in the US and other regions. Why the initial global fuel sulfur limits and 2012 SECA implementation were so impactful but the 2015 tightening of limits did not lead to detectable changes is also a matter for further research, as marine fuel sulfur limits set under MARPOL Annex VI continue to evolve. Although outside of the scope of this study, on January 1, 2020, the IMO reduced the global fuel sulfur limit to 0.5% by mass. While the new global fuel sulfur limit remains higher than that of existing SECAs at 0.1%, conversation between global policymakers continues about further changes to MARPOL Annex VI, including the creation of new SECAs in regions such as the Mediterranean Sea. In addition, several countries have introduced their own domestically-overseen 0.1% fuel sulfur limit SECAs, such as China and South Korea on January 1, 2022. As marine fuel sulfur regulations become ever more commonplace around the world, it is increasingly important to have reliable estimations of their impacts, costs and benefits where they are or may be implemented.

Chapter 2.

Shipping, Sulfur Dioxide and Hospital Admissions: Evidence from Vancouver[39,40]

2.1. Introduction

A large literature on the environmental, economic and health impacts of air pollution has accumulated over the past fifty years, together with broad demands for public policymaking to address the issue (e.g. Joskow, Schmalensee, and Bailey, 1998; Pope *et al.*, 2002; Sunyer *et al.*, 2003; Chay and Greenstone, 2003; Chen *et al.*, 2007; Currie, Neidell, and Schmieder, 2009; Deschênes, Greenstone, and Shapiro, 2017; Deryugina et al., 2019; and Mailloux et al., 2022). Sulfur dioxide (SO_2) is one of the most prominent air pollutants, blamed not only for the acid rain phenomenon but for causing or worsening diseases of the circulatory and respiratory systems and contributing to adult and infant mortality rates. Recent studies from a variety of countries and settings have also linked SO_2 emissions to such varied ills as higher healthcare costs (Shadbegian, Gray, and Morgan, 2007), lower labour supply (Hanna and Oliva, 2015), and lower infant birth weights (e.g. Rogers et al., 2000; Lin et al., 2004).

Concern in Canada over air pollutants such as SO_2 began to rise in the 1970s, where the acid rain phenomenon was highlighted followed by questions of dangers to human health. This led to a set of new policy regimes implementing controls on emissions of sulfur dioxide, both domestically (e.g. the Eastern Canada Acid Rain Program of 1985), and in partnership with the US and United Nations (e.g. the United Nations Economic Commission for Europe Convention on Long-Range Transboundary Air Pollution of 1979 and the Canada-US Air Quality Agreement of 1991). These programs have been credited with substantial reductions in land-based SO_2 emissions throughout the 1980s and 1990s, even surpassing their initial goals (Environment

---

[39] Parts of this material are based on data and information provided by the Canadian Institute for Health Information. However, the analyses, conclusions, opinions and statements expressed herein are those of the author and not necessarily those of the Canadian Institute for Health Information.

[40] This work is intended to be incorporated into a larger work jointly authored with Dr. Kevin Schnepel, Associate Professor of Economics at SFU.

Canada, 1997; Jeffries *et al*., 2003). By 2011, measured SO_2 concentrations in Canada had decreased by an average of 96% compared to 1970 levels (Health Canada, 2016). However, the shipping industry, which has traditionally consumed marine diesel[41] with a high sulfur content, has recently been estimated to be responsible for 13% of the world's SO_2 emitted by human activity (Smith, T. W. P *et al*., 2014). Regional variations can greatly exceed that average: for example, recent estimates have suggested maritime shipping accounted for two-thirds of sulfur emissions in 2010 in Vancouver (Anastasopolos *et al.,* 2021). Given the health impacts related to these SO_2 emissions and other forms of shipping-linked air pollution, the attention of Canadian policymakers has more recently turned toward the sulfur emissions of the maritime shipping industry.

This study evaluates the impact of shipping fuel sulfur limit policies on nearby SO_2 concentrations and their resultant health impacts in Vancouver, British Columbia, home to the largest port by shipping volume in Canada. Several policies included in the comprehensive International Maritime Organization (IMO) treaty regulating pollution from the shipping industry, MARPOL[42], affected limits on fuel sulfur content for ships within the North American Sulfur Emission Control Area (SECA). However, this paper fucuses on a large reduction to the maximum shipping fuel sulfur content on January 1, 2015, which caused an immediate improvement in local air quality.

A fuzzy regression discontinuity model is implemented employing Vancouver air monitor and hospital admission data around the January 1, 2015 policy change to evaluate the causal impact of SO_2 exposure on adult health outcomes. This study documents a decline of 64% from the four months before to the four months after the January 1, 2015 change in SO_2 exposure. This large decline in SO_2 leads to a substantial decline in admissions to two Vancouver hospital systems for diseases of the circulatory system of around 12% from the average just prior to the Jaunary 1, 2015 reduction in SO_2 exposure.

---

[41] Marine diesel or bunker fuel historically has been the lowest quality, most viscous remnants of the oil refining process. As a result, without further processing they contain substantially higher amounts of impurities like sulfur compared to automobile diesel or other fuels.

[42] MARPOL is short for "Marine Pollution" and is formally known as the International Convention for the Prevention of Pollution from Ships, 1973 as modified by the Protocol of 1978. Annex VI of MARPOL, dealing with SO_2 and other vessel emissions, was adopted in 1997.

This study contributes to the growing literature on environmental quality, regulation and health in two key ways. It is the first to use a regression discontinuity model to study the effects of shipping fuel sulfur reductions on health outcomes. Given the long-standing difficulties with confounding variables in the air pollution and health literature (e.g. Le Tertre et al., 2002), the regression discontinuity approach allows for a more straightforward identification of a casual effect, providing additional evidence for the benefits of reductions in shipping fuel sulfur content. This methodology been used prominently in the economics literature to link various kinds of air pollutants with changes in health outcomes such as life expectancy, mortality rates and hospital admissions (e.g. Neidell, 2009; Chen *et al.*, 2013; Bakolis *et al.*, 2016; and Chen *et al.*, 2018). Second, this is the first analysis of the major shipping-based sulfur regulations on adult health using hospital admissions[43] as an outcome variable rather than focusing on mortality. Previous works, including Chapter 1 of this thesis and a recent paper by Hansen-Lewis and Marcus (2023) use mortality rates as health outcome measures.

This work complements a growing literature quantifying changes in SO_2 concentrations stemming from maritime fuel sulfur restrictions. Anastasopolos *et al.* (2021) found large decreases in measured SO_2 concentrations in five Canadian port cities from both the implementation of the SECA and its tightening in 2015, including a 64.7% decline in the Greater Vancouver area from 2013-2014 to 2015-2016. Zhang et al. (2020) examined the April 2016 implementation of a 0.5% in the Shanghai port region from Chinese Domestic Emissions Control Areas (DECAs)[44] using a regression discontinuity model, finding a significant but small (1.5%) decrease in SO_2 concentrations. Zhang, Liu, and Wan (2022) also studied changes in SO_2 concentrations in four port cities on the Yangtze River Delta in China upon the 2016 enactment and 2018 enlargement of the regional DECA. Their estimated regression discontinuities implied that the policy was effective in two of the cities, but ineffective in two others, although non-shipping industrial emissions were substantially larger in proportion than in other settings. In addition, Song et al. (2022) used the implementation of the 2020 IMO

---

[43] A small existing literature has predicted the effects of proposed sulfur control policies on health outcomes, including hospital admissions, using such tools as exposure-response functions. However, no studies have analyzed realized admissions data.

[44] These are solely implemented and overseen by the Chinese government, and while they are similar in approach and goal to MARPOL Annex VI policy, a distinction should be made between them.

0.5% global limit along with a regression discontinuity model to study changes in SO_2 concentrations in two ports near Busan, South Korea, finding declines of 38% and 57% around the 2020 cut-off date.

Several studies have modeled or estimated the effects of shipping traffic on mortality (Corbett et al., 2007; Broome *et al.*, 2016) or hospital admissions (Tian *et al.*, 2013; Gillingham and Huang, 2021), with an emerging literature focusing specifically on the implementation of the three SECAs under MARPOL Annex VI rules. For example, Barregard et al. (2019) used computational models to examine the effect of a 2015 Baltic Sea SECA fuel sulfur limit decrease on mortality rates, finding a 35% drop in premature mortality as well as non-fatal heart disease and stroke. Geels et al. (2021) modeled the potential impact of future expansions in Nordic SECA areas on regional health outcomes, with stricter regulation yielding significant drops in premature mortality rates. Lindgren (2021) studied the implementation of the 2015 SECA changes on coastal regions of the UK, finding a 7% decrease in the risk of low birth weight. Hansen-Lewis and Marcus (2023) studied the implementation of the US portion of North American SECA, finding a 1.7% decrease in the incidence of low birth weight, and a 2.8% decline in infant mortality. Finally, Chapter 1 of this thesis also studies the implementation of the US portion of the North American SECA and documents a 2.4% decline in mortality among individuals 45 and older in counties near major shipping ports, driven by a 3.7% decline in circulatory-related causes of death. While the hospital admission data used in this study is not broken down by age groups, results from Chapter 1 finding a strong increase in mortality rates with age suggest that the estimated impacts on circulatory admissions for older individuals are larger than the overall estimated decline of 12%.

One open question arising from the analysis in Chapter 1 regarded the lack of detected impact on both SO_2 concentrations and mortality rates from the 2015 SECA change in the US compared to earlier phases of the IMO fuel sulfur policy, despite the magnitude of the 2015 reduction of the fuel sulfur cap, from 1.0% to 0.1%, being roughly comparable to previous reductions[45]. As US enforcement was strict, the answer may lie

---

[45] The 2012 transition from the 3.5% global limit to the initial 1.0% SECA limit was nominally much larger than the 2015 tightening of the SECA to 0.1%, but one previous study (Endresen *et al.*, 2005) estimated the average fuel sulfur content before the implementation of the IMO policy as around 2.5%, suggesting that the actual average drop was smaller than the change in nominal limits.

with behavioral adjustments by shippers, terrestrial polluters and individuals, as suggested by Hansen-Lewis and Marcus (2023) as an explanation for overall underperformance of EPA modeling of the impacts of the SECA on PM2.5 concentrations. Similar to the results presented in Chapter 1, Hansen-Lewis and Marcus (2023) found no change in PM2.5 arising from the 2015 modification of the SECA but large reductions stemming from previous phases of the fuel sulfur policy. However, global shipping firms facing similar policies should make the same profit-maximizing adjustments to routes and vessel speeds in Canada as in the United States, and violations of Canadian Ambient Air Quality Standards (CAAQS) can be difficult and costly for Canadian municipalities and provinces in much the same way that violations of US National Ambient Air Quality Standards (NAAQS) are for American counties and states[46]. It follows that the "regulatory rebound" phenomenon discussed in Hansen-Lewis and Marcus (2023) should in theory operate reasonably similarly in both countries. However, both Anastasopolos *et al.* (2021) and the results here suggest large responses in major Canadian ports as a result of the 2015 reduction.

The results from this study focused on Vancouver expands the scope of possible benefits to the policy. While improved air quality is known to be linked to benefits in multiple health outcomes, different policy tools may vary in their impact, and estimates of mortality or infant birth weight changes stemming from the large-scale implementation of the SECA may not give a full picture of the total benefits. This is particularly important given the recent January 1, 2020 change to the global limit on fuel sulfur content from 3.5% to 0.5%, affecting a much wider region than the territory included in existing SECAs.

---

[46] One complexity is that many CAAQS standards only began enforcement in 2015, and previous National Ambient Air Quality Objectives (NAAQO) had much weaker response mechanisms to violations. However, compliance with NAAQO-level limits has nonetheless been improving Canada-wide for decades.

2.2. Policy Background

2.2.1. MARPOL Annex VI implementation in Canada

Canada has generally sought to harmonize its marine sulfur emission policy with the US under the umbrella of MARPOL Annex VI[47]. While a more detailed accounting of MARPOL's history and sulfur policy changes can be found in Chapter 1, Canadian action has included enforcement of the treaty's specified global limit on fuel sulfur content in two phases, with a maximum of 4.5% sulfur by weight from July 1, 2010 to December 31, 2011 and a maximum of 3.5% starting January 1, 2012. In addition, Canada also joined the North American Sulfur Emission Control Area (SECA) depicted in Figure 1.2, but delayed its enforcement of the 1.0% fuel sulfur cap until May 8, 2013[48], putting it approximately 8 months behind the US. However, the limit was further tightened to 0.1% on January 1, 2015 on schedule, alongside the US portion of the SECA. Given the geographic proximity of the Port of Vancouver to the US, this fact allows for a less complicated analysis, without having to consider possible fuel sulfur content differentials with nearby US shipping traffic. In addition, the nature of the fuzzy regression discontinuity model implies that previous shifts in marine sulfur policy are not relevant to the analysis, as only a few months surrounding the January 1, 2015 SECA fuel sulfur cap reduction are considered.

2.2.2. Regulation enforcement

In Canada, enforcement of MARPOL Annex VI and the North American SECA is carried out by Transport Canada, who maintain a team of inspectors with portable fuel analyzers that test vessel fuels for compliance[49]. While sulfur scrubbers are allowed

---

[47] The MARPOL Convention in Canada, including regulation implementing the SECA, was primarily implemented through the 2001 Canada Shipping Act and its later modifications, although some domestic legislation maintains stronger standards in certain aspects, e.g. the Arctic Waters Pollution Prevention Act's complete prohibition on maritime waste disposal in the Canadian Arctic.

[48] According to Transport Canada, the delay was due to "significant additional discussions required with the domestic marine industry". See Transport Canada Ship Safety Bulletin No. 03/2012, accessible at https://tc.canada.ca/en/marine-transportation/marine-safety/ship-safety-bulletins/interim-measures-vessel-air-emissions-ssb-no-03-2012.

[49] More details can be found in Transport Canada Ship Safety Bulletin No. 08/2016, accessible at https://tc.canada.ca/en/marine-transportation/marine-safety/ship-safety-bulletins/regulations-vessel-air-emissions-sulphur-fuel-content-verification-process-ssb-no-08-2016.

under Annex VI as an alternative to burning low-sulfur fuels, by 2015 only a fraction of a percent of shipping vessels in the global fleet had been equipped with such equipment.[50] By law, Transport Canada Marine Safety and Security can respond to violators of the 2001 Canada Shipping Act, the law incorporating MARPOL Annex VI, with fines, suspensions of maritime operating documents, detainment of vessels and criminal prosecution.

2.3. Data Description

2.3.1. Air monitor and meteorological measurements

Hourly air pollutant concentration data recorded by four air monitors in the Greater Vancouver area was collected from the BC Air Data Archive for the years 2012 to 2017. The primary analysis was conducted using SO_2 data aggregated to the daily level from the Vancouver Robson Square station, located in downtown Vancouver. However, three other stations, located in North Vancouver’s Mahon Park (“North Vancouver Mahon Park”), adjacent to the north side of Vancouver’s Second Narrows Bridge (“North Vancouver Second Narrows”), and in Burnaby’s McGill Park (“Burnaby North Eton”) respectively, recorded hourly wind speed and direction in addition to SO_2 measurements for use in plotting the source locations of SO_2. Figure 2.1. gives the locations of all four air monitors in the Greater Vancouver area.

---

[50] See Footnote 8 of Chapter 1 for details.

Figure 2.1. Locations of the four SO_2 air monitors in Greater Vancouver.

The use of air monitor SO_2 data as a proxy for population exposure comes with some drawbacks, as explained in Moretti and Neidell (2011). While the Robson Square air monitor location is centrally located in downtown Vancouver, quelling concerns about possible rural-urban population density disparities in an air monitor network, individuals may control their time outdoors in order to be less exposed on higher pollution days. However, this is more likely to be the case with public air quality advisories, such as episodes of heavy wildfire smoke, and less likely to be a factor with day-to-day changes of SO_2 well under air advisory guidelines. Until 2020, the National Ambient Air Quality Objectives (NAAQO) "Maximum Desirable Level" for SO_2 concentrations was an *annual* average of 11 ppb[51], a threshold surpassed in Vancouver Robson Square only for three days in 2012 and not since.

In addition, as this chapter's focus remains on the regulation of SO_2 emissions from maritime transport, the analysis studies changes in SO_2 concentrations and their impact on hospital admissions, and does not use the concentration of sulfate particles or other atmospheric SO_2 products formed over time, directly or indirectly through

---

[51] In 2020, NAAQO standards for SO_2 were replaced with Canadian Ambient Air Quality Standards (CAAQS), with guidelines updated to include a one-hour limit of 70 ppb and an annual average of 5 ppb. For comparison, since 2012 the highest one-hour SO_2 recording by the Robson Square air monitor was 50.4 ppb on January 30, 2012, and the highest annual average was 3.55 ppb, also in 2012.

measures like PM2.5. However, any impact on hospital admissions may be related to changes in both the parent gas and its particulate reaction products.

2.3.2. Hospital admissions

Daily all-category (total) and specific-category hospital admissions aggregated from two Vancouver medical providers, Providence Health Care's St. Paul's Hospital and Mount Saint Joseph Hospital along with Vancouver Coastal Health's Vancouver General Hospital and UBC Hospital, were obtained from the Canadian Institute for Health Information (CIHI) for the years 2012-2017. No individual or demographic information was included in the data. For any given category, daily admissions in the 1-4 range were suppressed by CIHI and for analysis purposes replaced with the average of 2.5.[52] Of the specific causes for admission, diseases of the respiratory system and diseases of the circulatory system were selected due to their potential links with SO_2, including results in Chapter 1 of this thesis.

2.4. Empirical Strategy

2.4.1. Summary statistics

Table 2.1 gives summary statistics of Vancouver Robson Square SO_2 concentrations, those recorded by the remaining three Greater Vancouver air monitor locations, and hospital admission data separated into total, respiratory and circulatory categories. Statistics are presented from 2012 to 2014 as well as from 2015 to 2017. Means, standard deviations and percent changes from 2012 to 2017 averages were calculated.

---

[52] Second stage fuzzy regression discontinuity results are not materially changed when suppressed data is dropped or replaced with 0 instead of 2.5.

Table 2.1. Summary statistics for air monitor SO_2 concentrations and hospital admissions by category.

	Mean	Standard Deviation	Mean	Standard Deviation	Percent Change
	2012-2014		2015-2017		2012-2017
Vancouver Robson Square SO_2	2.47	1.90	0.53	0.38	-85.2
Other Monitor SO_2	1.49	1.11	0.61	0.37	-65.3
Hospital Admissions, Total	107.72	43.48	115.84	42.26	0
Hospital Admissions, Respiratory	6.93	3.67	8.25	4.01	17.6
Hospital Admissions, Circulatory	14.88	8.49	14.13	8.10	-3.8

Table 2.1 Notes: Air monitor SO_2 concentrations are given in parts per billion and hospital admissions in absolute values. Percentage changes from 2012 to 2017 are calculated using annual averages of all existing daily data in both years.

2.4.2. Linking reductions in SO_2 to shipping activity

Figure 2.2 shows three pairs of plots, one for each of the Greater Vancouver air monitors combining SO_2 concentrations and meteorological readings, produced using the "openair" R package (Carslaw and Ropkins, 2012)[53]. These figures combine wind direction with wind speed in meters per second (in the plots, drawn as radial distance) and are based on the concept of Conditional Bivariate Probability Functions (CBPF). In CBPF analysis, all available hourly SO_2 data is placed into joint wind speed-wind direction bins, and the probability is then calculated of a given bin's SO_2 readings meeting a set threshold of the overall SO_2 distribution (Uria-Tellaetxe and Carslaw, 2014). In Figure 2.2, the threshold is the 90th percentile of all available 2012-2017 data for each monitor, listed in each panel, and various CBPF values are represented by the displayed colour scheme.

In this way, both the direction and relative proximity of multiple SO_2 sources can be determined from a single monitor, and changes over time can be observed directly. For example, in Panel C, the Burnaby North Eton monitor, the large reduction in CBPF probabilities in the northwest quadrant from 2012-2014 to 2015-2017 represents much lower post-2015 SO_2 exposure from Vancouver's Inner Harbour and Central Harbour, an

---

[53] This section takes a similar approach to Anastasopolos *et al.* (2021).

area frequented by shipping traffic. However, heavy sulfur emissions after 2015 from the Burnaby Refinery to the east and northeast can also be seen, as SO_2 measurements during periods of moderate and high winds from those directions remain likely to surpass the 90th percentile threshold. Similar observations can be made about the two North Vancouver air monitors when comparing the plots with their locations in Figure 2.1, adding strong supporting evidence for the impact of the January 1, 2015 decrease in the SECA fuel sulfur limit on regional SO_2 concentrations[54]. During periods when moderate to high winds are blowing from the direction of Vancouver's Inner Harbour (south-southwest in Panel A, west-southwest in Panel B), the likelihood of measurements surpassing the 90th percentile of the overall SO_2 distribution becomes substantially smaller.

---

[54] For concision and to increase the number of plotted bins in each figure, three years are aggregated in each plot in Figure 2.2. However, a sharp drop in CBPF scores in bins representing wind from the harbour is also apparent when moving from 2014 to 2015 for all three monitors.

Figure 2.2. SO_2 Conditional Bivariate Probability Function plots for three Greater Vancouver air monitors, from 2012 to 2014 and from 2015 to 2017.

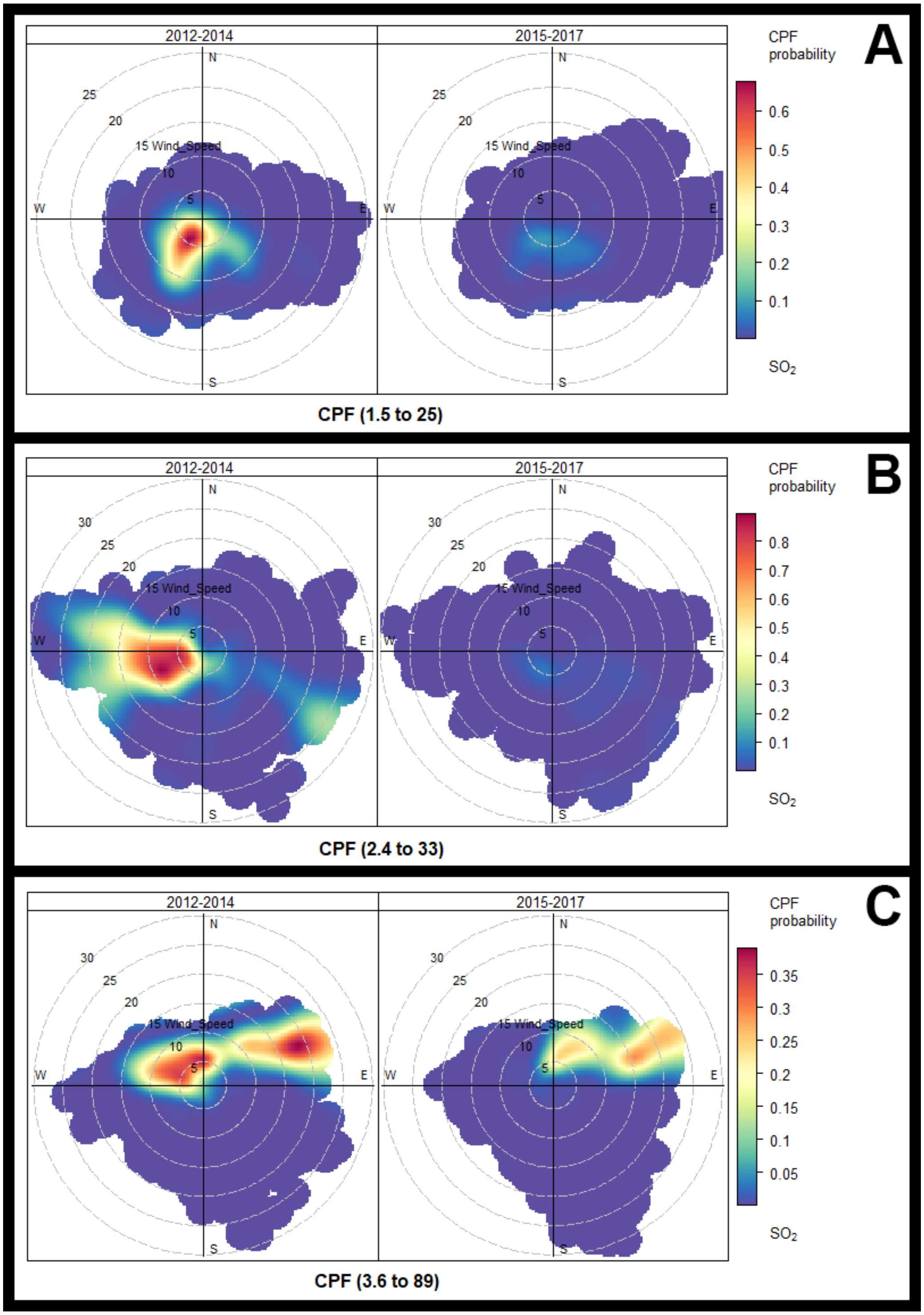

Figure 2.2 Notes: Panel A represents the North Vancouver Mahon Park air monitor, Panel B represents the North Vancouver Second Narrows air monitor, and Panel C represents the Burnaby North Eton monitor. The range of SO_2 values above the 90th percentile of all 2012-2017 data is given below each pair of plots.

2.4.3. Model specification

This study estimates the impact of the January 1, 2015 decrease in the SECA fuel sulfur content limit on SO_2 concentrations and hospital admissions in the Vancouver area using a fuzzy regression discontinuity model with local linear slopes on either side of the cut-off date. For the first stage, the following equation is estimated:

$$Y_t = \alpha + \tau D_t + \beta_1(t - c) + D_t\beta_2(c - t) + \varepsilon_t, \tag{2.1}$$

where Y_t represents the outcome variable, Vancouver Robson Square SO_2 concentrations, t represents the date (in days), τ represents the discontinuity at the January 1, 2015 cut-off date, given as c, D_t indicates whether the date is on or after the cut-off, and β_1 and β_2 are the slope before and after the cut-off, respectively. A triangular kernel was used in estimation and regressions were carried out using the Stata package "rdrobust".

As the model is a fuzzy regression discontinuity design, the second stage then uses a variant of Equation 2.1 where the variability in SO_2 induced by the policy change is exploited to estimate changes in hospital admission rates in each category. This second-stage result can then be scaled by the observed first stage estimate to measure the total impact of the strengthened SECA policy.

2.4.4. Identification strategy and potential threats to causal identification

In a fuzzy regression discontinuity model like the one used in this study, the primary requirement is that all variables potentially impacting the outcomes (SO_2 concentrations and hospital admissions) are continuous around the cut-off date, i.e. that there were no other sharp changes in factors that lead to different levels of SO_2 emissions or cause people to seek hospital admission. While regional economic development, population growth, demographic changes and shifts in the relative incidence of various illnesses and disorders are all relatively smooth processes[55], perhaps the main factor that might challenge this assumption is calendar-based: January

---

[55] One exception would be if a major polluting plant akin to the Burnaby Refinery began operation in the Vancouver area around January 2015, but that was not the case.

1, 2015 is itself a holiday and is also adjacent to the Christmas holidays, which can impact the operation of polluting industries (including shipping) as well as hospital visits. For this reason, in most model specifications a regression was first run on the SO_2 and hospital admission data from 2012 to 2017, including week of year, day of week, and British Columbia statutory holiday indicators to obtain residuals of key variables that have effects from seasonal variation or other calendar-related factors removed. These residuals from 2014 to 2015 were used in the regression discontinuity analysis in order to isolate variation due to the policy but not due to factors that might coincide with the beginning of the year.

Since the fuzzy regression discontinuity specification uses the discontinuous change in SO_2 as an instrument to quantify the causal impact of variation in SO_2 on health, the instrumental variable must satisfy the exclusion restriction. This requires that the outcome (hospital admissions) can only be affected through the change in SO_2 and not through other factors affected by the policy. Potential threats to this causal identification assumption lie in the impact of the policy on shipping volume since other pollutants, such as NO_2, are emitted based on volume, but could also affect the health outcomes evaluated. In addition, changes in shipping volume could directly impact emissions from other pollutant sources related to the shipping industry, such as transport trucks visiting ports. In this way, the regression discontinuity methodology could wrongly attribute an improvement in health from a reduction in other air pollutant emissions to reductions in SO_2.

With respect to changes in NO_2 emissions, three tiers of engine controls progressively limiting NO_2 emissions were gradually phased in under MARPOL Annex VI, according to the date of a vessel's construction. Canada's implementation of these controls was largely harmonized with the US, with Tier I enacted for vessels built in January 2000 onward[56], Tier II for vessels built in January 2011 onward, and Tier III for vessels built in January 2016 onward and operating in a SECA. As none of these changes are expected to result in discontinuous shifts in pollution around January 1, 2015, the primary question is whether shipping activity changed as a result of the policy in such a way that emissions were sharply reduced around the cut-off date.

---

[56] In the US, Tier I requirements for newly constructed ships began in January 2004, the only timing difference between the two countries.

While data was not readily available for daily shipping traffic patterns, annual measurements of shipping volume in the Port of Vancouver are presented in Figure 2.3. These numbers, given in millions of tonnes, were retrieved from the Port of Vancouver's annual Statistics Overview. While a counterfactual trend is difficult to construct, the year-on-year change in volume in 2015 (as well as 2013, the implementation year of the 1.0% SECA limit) and deviation from the line of best fit are well within the 2008 to 2019 range of variation. However, small changes in volume near the January 1, 2015 cut-off date are possible in addition to unobserved differences in shipping routes, and so possible effects of the policy shift on NO_2 and other sources of pollution remain a limitation of the research design. Nonetheless, later results presenting reduced form estimates suggest that the increased strictness of the SECA policy in 2015 caused a significant reduction in hospital admissions for disorders of the circulatory system, through reductions in SO_2 concentrations and potentially NO_2 or other factors.

Figure 2.3. Annual shipping volume in millions of tonnes at the Port of Vancouver, from 2008 to 2019.

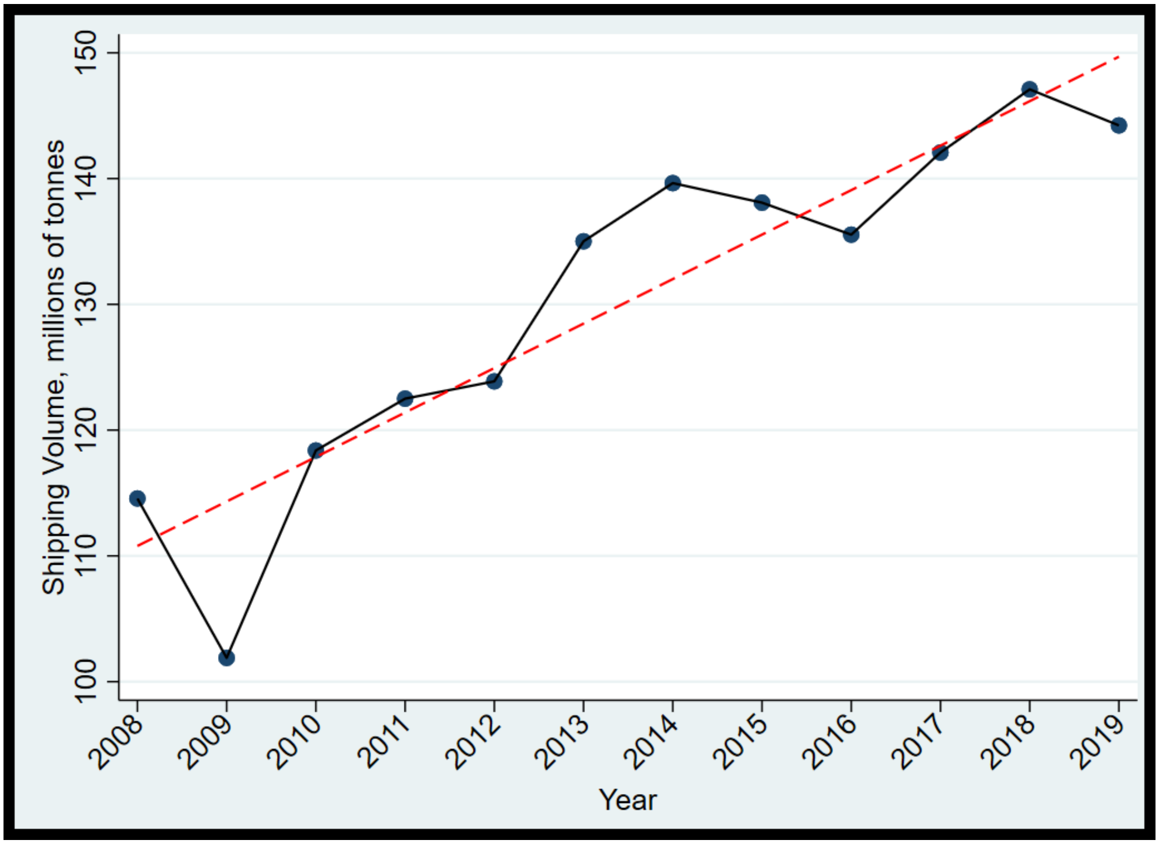

Figure 2.3 Notes: Volume measurements were retrieved from Port of Vancouver's annual Statistics Overview and includes the total tonnage from all categories of cargo. The dashed line of best fit was calculated using all values from 2008 to 2019.

2.5. Results and Discussion

Analysis of the effects of the January 1, 2015 decrease in the SECA fuel sulfur content limit from 1.0% to 0.1% begins with the estimation of a first stage regression discontinuity model using daily SO_2 residualized from a regression including calendar controls[57]. All SO_2 data in the fuzzy regression discontinuity analysis was recorded by the Vancouver Robson Square air monitor with Figure 2.1 giving its central location in downtown Vancouver. Figure 2.4 shows the results of this analysis, using a cut-off date of January 1, 2015 and local linear regressions using a symmetric bandwidth, optimally chosen by the “rdrobust” Stata package, plotted alongside weekly binned SO_2 data from 2014 to 2015. The drop in SO_2 is immediate and substantial in size, and the regression slope is very similar on both sides of the cut-off, suggesting that the changes to the SECA limit took effect within a very short period.

---

[57] These included indicators for the day of the week, British Columbia statutory holidays (some of which vary by date), and the numerical week of the year, starting with January 1 through 7 as Week 1 and with Week 52 potentially having 8 or 9 days depending on whether or not it is a leap year.

Figure 2.4. **First stage (Vancouver Robson Square SO_2) regression discontinuity analysis for the January 1, 2015 cut-off date, based on residuals from a one-way fixed effects regression including calendar controls.**

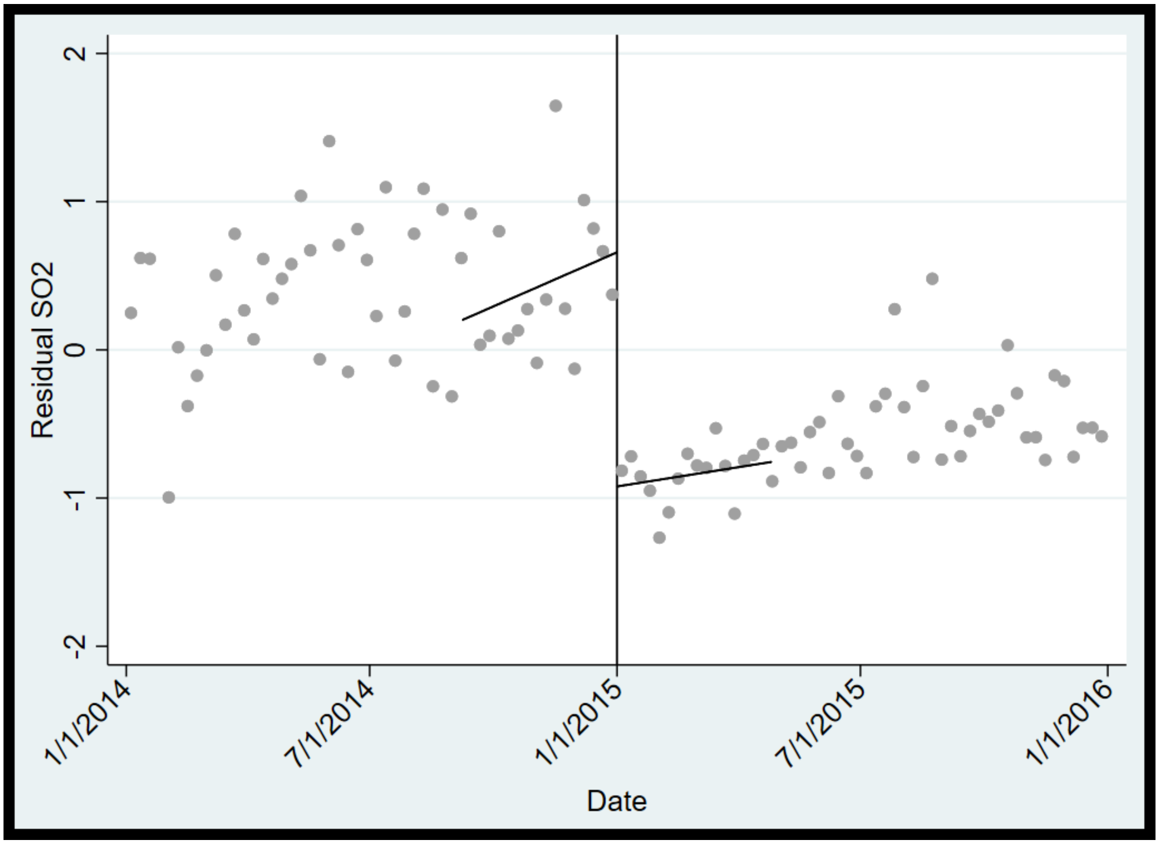

Figure 2.4 Notes: To incorporate calendar controls, a one-way fixed effects regression was first run including indicators for day of week, week of year, and BC holidays for daily SO_2 data from 2012-2017, and the residuals from 2014-2015 were used for the first stage discontinuity analysis. The discontinuity regression used local linear regressions on either side of the cut-off date, with symmetrical bandwidths of 115 days optimally chosen by the rdrobust Stata package. Data points were aggregated into weekly bins for plotting purposes.

Next, Table 2.2 gives the primary fuzzy regression discontinuity estimates for the January 1, 2015 cut-off date, including results for SO_2 (first stage), the three categories of hospital admissions (second stage) and reduced form estimates for hospital admissions. As before, local linear regressions with a symmetric and optimally chosen bandwidth were used. Estimates on SO_2 and circulatory admissions show a significant and sizeable treatment effect, while no effect is visible on total and respiratory admissions.

Table 2.2. First stage (SO_2), second stage (hospital admissions) and reduced form fuzzy regression discontinuity estimates for the January 1, 2015 cut-off date, both with and without calendar controls.

Specification	**(1)**	**(2)**	**(3)**	**(4)**	**(5)**
Effect Size	-0.979 (0.092) ***	-1.583 (0.151) ***	0.642 (2.635)	-0.156 (0.676)	1.737 (0.738) ***
Outcome Variable	SO_2	SO_2	Total admissions	Respiratory admissions	Circulatory admissions
Estimate Type	First Stage	First Stage	Second Stage	Second Stage	Second Stage
Bandwidth (Days)	306	115	137	80	142
Calendar Controls Included	No	Yes	Yes	Yes	Yes
2012-2014 Mean Value	2.474	2.474	144.57	9.63	22.78
% Decline from 2012-2014 Mean	39.6 (3.7)	64.0 (6.1)	0.1 (3.8)	-2.6 (12.3)	12.1 (6.7)
Specification			**(6)**	**(7)**	**(8)**
Effect Size			-0.765 (4.694)	0.647 (0.984)	-2.898 (1.253) ***
Outcome Variable			Total admissions	Respiratory admissions	Circulatory admissions
Estimate Type			Reduced Form	Reduced Form	Reduced Form
Bandwidth (Days)			124	99	140
Calendar Controls Included			No	Yes	Yes

Table 2.2 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. If calendar controls were used, an ordinary regression was first run including indicators for day of week, week of year, and BC holidays for SO_2 and hospital admissions data from 2012 to 2017, and the residuals from 2014 to 2015 were used for the first stage, second stage or reduced form discontinuity analysis. All discontinuity regressions used local linear regressions on either side of the cut-off date, with symmetrical bandwidths optimally chosen by the rdrobust Stata package. For second stage (hospital admission) variables, percent declines from the 2012 to 2014 mean are calculated as the estimated effect size multiplied by the magnitude of the first stage effect size.

Taking into account seasonal variation, the estimated effect of the SECA changes on SO_2 represented a 64% decline from the trend of the four months preceding January 1, 2015. This number is consistent with Anastasopolos *et al.* (2021), who used other regional Vancouver air monitor data in a model using seasonal Mann-Kendall tests of trends with Sen’s slope, finding that the effect of the 2015 changes was to reduce SO_2

concentrations by an average of 64.7%[58], almost identical to the results here. In addition, supplementary data in Anastasopolos *et al.* (2021) suggest that non-shipping industrial sources of SO_2 were roughly constant throughout 2010 to 2017 and responsible for about one third of total emissions in 2010, with shipping contributing the remaining two thirds. Although the effect of the 2013 implementation of the SECA is not estimated here, the magnitude of the 2015 decrease is consistent with almost all shipping-related sulfur emissions being eliminated, implying that compliance with the regulation was very high from its enactment. This has also been found in the European context: Kattner *et al.* (2015) studied the individual exhaust plumes of ships transiting Hamburg harbour and found that compliance with the 0.1% rule in early 2015 was at over 95% of vessels. Yang *et al.* (2016) also measured SO_2 plumes from ships near Plymouth in the United Kingdom and estimated the same 95+% compliance rate.

Other papers comparing the 2015 shift from the 1.0% to the 0.1% SECA fuel sulfur limits in Europe have found varying estimates. Lindgren (2021) found that the 0.1% limit produced an average 22% decrease in SO_2 concentrations in areas near the North Sea coast in the United Kingdom. However, this study examined a wide region instead of a single port area with monitors close to ship traffic, as is the case in Vancouver. Kattner *et al.* (2015) reported an approximately 50% reduction in measured SO_2 in Hamburg from 2014 to 2015, and Yang *et al.* (2016) found a two thirds reduction in measured SO_2 in Plymouth during the same time period, more in line with this chapter's results. However, these findings only add to the mystery of why the 2015 changes to the SECA in the US were not estimated to have any effect, either in Chapter 1 or in Hansen-Lewis and Marcus (2023). As, Canada, the US, Germany and the UK are all wealthy, developed countries with robust regulatory apparatuses and enforcement agencies as well as environmental monitoring networks, adaptations by shipping firms or other individuals should not by themselves cause such a large discrepancy in the effects of the same policy. Further research on this question is essential for uncovering why an enforced reduction in the sulfur content of fuel used in the course of maritime shipping improved air quality so much near port areas in Canada and Europe as well as in the US in 2012-2013, but not in the US in 2015.

---

[58] This can be calculated from their Table 3 results.

Turning to the second stage results, estimates suggest that each unit (part per billion) of reduced SO_2 can be linked to a 1.737 decrease in daily hospital admissions for diseases of the circulatory system. Given the magnitude of the observed decrease in SO_2, the total effect represents a 12% decline from the 2012-2014 circulatory admissions average, or a 19% decline from the mean of the 142 days preceding the January 1, 2015 cut-off date. This is a substantially higher estimate than found in Sunyer et al. (2003), which found that a 1 ppb increase in SO_2 exposure in a given two-day period corresponded with a roughly 0.2% increase in hospital admissions for cardiovascular disorders. However, in this setting, the decrease in SO_2 is sustained over the long run and not just a daily variation, which suggests that the impact would be much larger as a cumulative benefit to cardiovascular health.

These results are also consistent with Chapter 1 of this thesis in terms of the category of illness most impacted by the fuel sulfur policies. Estimates found that the overall effect of the different phases of MARPOL Annex VI fuel sulfur policies was to reduce US mortality rates among the 45+ age group by 2.4%, with the majority of the effect contributed by lowered mortality from diseases of the circulatory system. Here, however, hospital admissions are affected at a much higher rate, suggesting that improved air quality from reductions in SO_2 emissions may have led to benefits for those suffering a variety of disorders of the circulatory system, both critical and not critical. Alternatively, those with the highest repeated admissions for such illnesses may have benefitted disproportionately. Unfortunately, data limitations make it impossible to examine these two possibilities in detail.

As one additional point of comparison between the US and Canadian results, the short-term nature of the fuzzy regression discontinuity model, optimally chosen as a five-month bandwidth centered around the January 1, 2015 cut-off date, suggests a more immediate effect of the policy on hospital admissions compared with mortality rates in the US. Panel B of Figure 1.11 in Chapter 1 of this thesis shows a much more drawn-out process of reductions in mortality rates in the treated group of counties compared to the control group, as the IMO policies are put into effect.

Next, plots of estimated second-stage effects from the SECA policy change are given in Figure 2.5, with Panel A showing total admissions, Panel B showing respiratory admissions, and Panel C showing circulatory admissions. In Panels A and B, there are no apparent deviations from the trend around the SECA changes. However, in Panel C, there is a clear break in the trend in the months around the cut-off date, with regression discontinuity plotted for the 142 days before and after January 1, 2015.

Figure 2.5. **Second stage (hospital admissions) fuzzy regression discontinuity analysis for the January 1, 2015 cut-off date.**

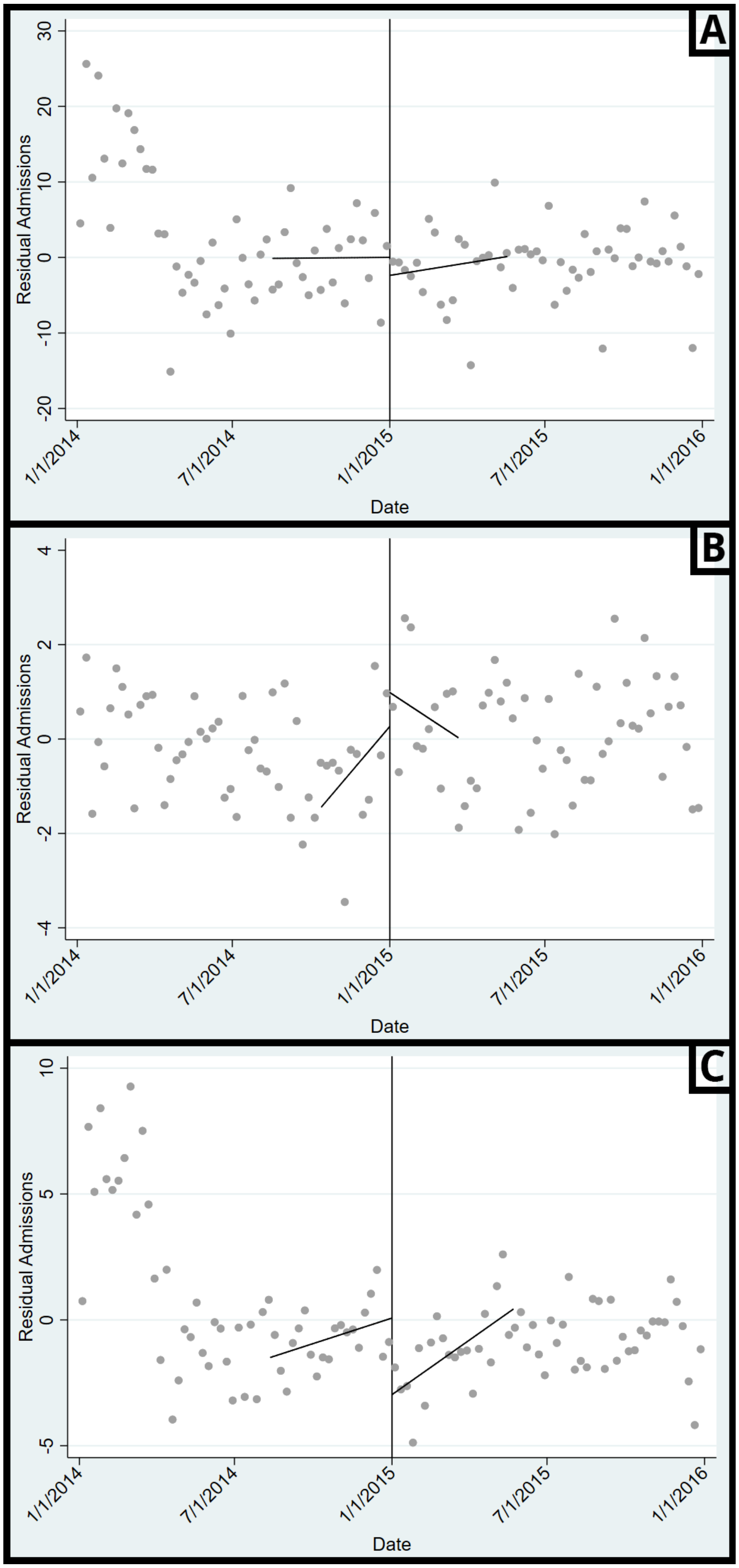

Figure 2.5 Notes: Panel A uses total admissions, B uses admissions for diseases of the respiratory system, and C uses admissions for diseases of the circulatory system. Calendar controls are incorporated by first regressing SO_2 and hospital admission data on indicators for day of week, week of year, and BC holidays from 2012 to 2017, and the residuals from 2014 to 2015 were used for the second stage discontinuity analyses. Treatment effect magnitudes and error are given in Table 2.2. Each discontinuity regression used local linear regressions on either side of the cut-off date, with symmetrical bandwidths of 137 days (total admissions), 80 (respiratory) and 142 (circulatory) optimally chosen by the rdrobust Stata package. Data points were aggregated into weekly bins for plotting purposes.

As a robustness check, Table 2.3 gives regression discontinuity treatment estimates for January 1 of placebo years 2014 and 2016, when no MARPOL Annex VI changes to sulfur limits were implemented. Given the insignificant first stage, only reduced-form effects on the circulatory hospital admission outcome variable are presented[59]. Overall, Table 2.3 provides no evidence of changes in January 1 of 2014 or 2016, which supports the key identification assumptions and alleviates concerns about any other unobserved determinants of health outcomes changing discontinuously at the beginning of each year.

Table 2.3. First stage (SO_2) and reduced form (circulatory admissions) regression discontinuity estimates for placebo cut-off dates January 1st, 2014 and January 1st, 2016, including calendar controls.

Specification	(1)	(2)	(3)	(4)
Effect Size	-0.554 (0.374)	-0.066 (0.078)	-1.556 (2.435)	1.745 (1.464)
Cut-off Date	January 1 2014	January 1 2016	January 1 2014	January 1 2016
Available Data	2013-2014	2015-2016	2013-2014	2015-2016
Outcome Variable	SO_2	SO_2	Circulatory admissions	Circulatory admissions
Bandwidth (Days)	79	43	59	118
Calendar Controls Included	Yes	Yes	Yes	Yes

Table 2.3 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. Circulatory admission estimates are given in reduced form only, as first stage estimates are not significant. To incorporate calendar controls, a regression was first run including indicators for day of week, week of year, and BC holidays for both daily SO_2 and hospital admission data from 2012 to 2017, and the residuals from either 2013 to 2014 or 2015 to 2016 were used for the first stage and reduced form discontinuity analyses, depending on the cut-off date. All discontinuity regressions used local linear regressions on either side of the cut-off date, with symmetrical bandwidths optimally chosen by the rdrobust Stata package.

---

[59] Reduced form estimates on the other two admissions categories are not presented in Table 2.3, but are not significant for either 2014 or 2016.

Finally, Figures 2.6 and 2.7 present first stage (SO_2) and second stage (circulatory hospital admissions) regression discontinuity results as the bandwidth is manually varied by 30 day increments, from 30 to 240 days. In both plots, estimate magnitudes stabilize for bandwidths above 60-90 days and error decreases as the bandwidth gets larger, although SO_2 estimates are significant even with a 30 day bandwidth and second stage circulatory admission estimates are only significant with bandwidths above 90 days. Nonetheless, the stability of the treatment effect as the period of time around the cut-off date is increased is strong evidence that January 1, 2015 represents a break in the trend of both SO_2 and circulatory hospital admissions due to the SECA changes.

Figure 2.6. First stage (SO_2) regression discontinuity effect estimates for the January 1, 2015 cut-off date as bandwidth is varied.

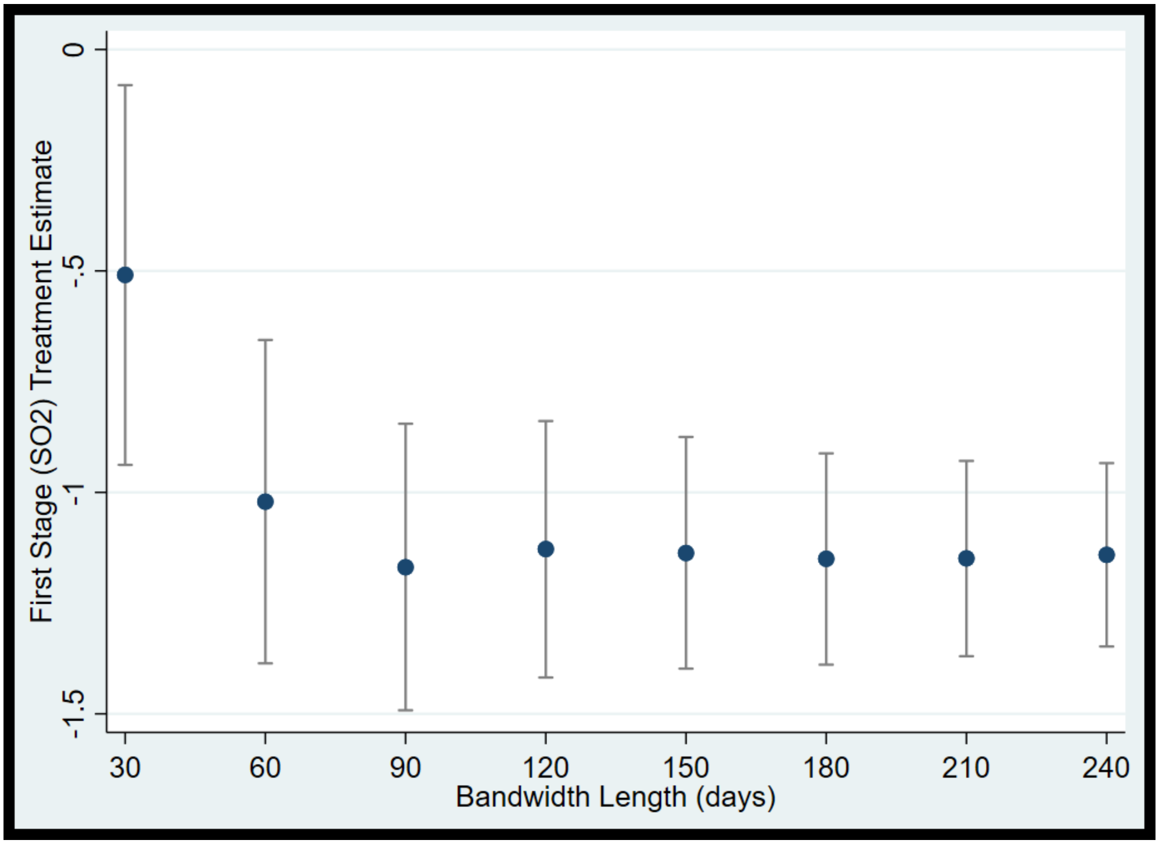

Figure 2.6 Notes: Calendar controls are incorporated by first regressing SO_2 concentrations on indicators for day of week, week of year, and BC holidays from 2012 to 2017, and the residuals from 2014 to 2015 were used for the first stage discontinuity analysis. The discontinuity regression used local linear regressions on either side of the cut-off date, with symmetrical bandwidths varying by 30 days. Data points were aggregated into weekly bins for plotting purposes.

Figure 2.7. **Second stage (hospital admissions for diseases of the circulatory system) fuzzy regression discontinuity effect estimates for the January 1, 2015 cut-off date as bandwidth is varied.**

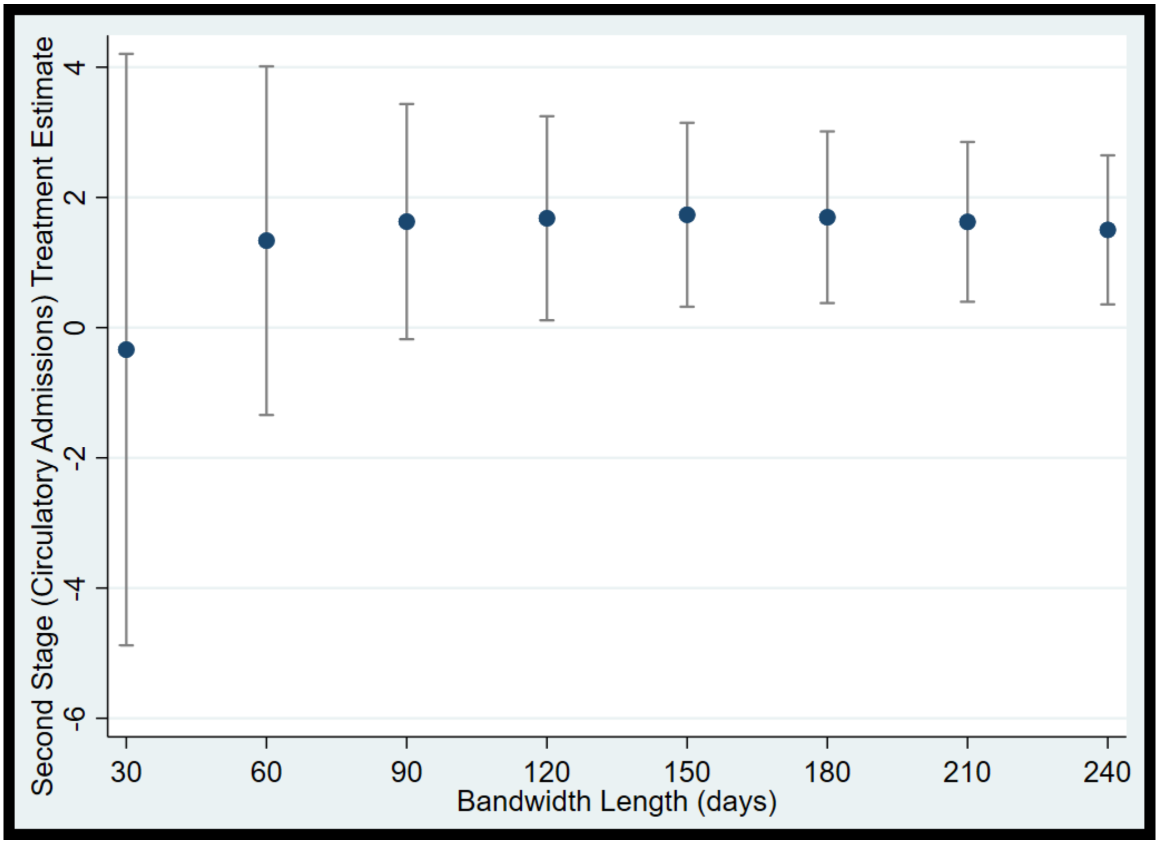

Figure 2.7 Notes: Calendar controls are incorporated by first regressing SO_2 and hospital admission data on indicators for day of week, week of year, and BC holidays from 2012 to 2017, and the residuals from 2014 to 2015 were used for the second stage discontinuity analysis. The discontinuity regression used local linear regressions on either side of the cut-off date, with symmetrical bandwidths varying by 30 days. Data points were aggregated into weekly bins for plotting purposes.

2.6. Conclusion

This study examines the implementation of the January 1, 2015 reduction in shipping fuel sulfur content from 1.0% to 0.1% in the port city of Vancouver, Canada. Using a fuzzy regression discontinuity design, a significant drop of about two thirds in SO_2 concentrations was found to cause a 12% drop in local hospital admissions for disorders of the circulatory system relative to the 2012 to 2014 mean. While the magnitude of the decrease in SO_2 was consistent with European studies into the parallel fuel sulfur decrease there, a difficult-to-explain discrepancy remains with US sulfur and health outcome results around 2015 which requires further investigation.

The broad scope and scale of the realized 2015 changes to the North American SECA were prefaced by long debate and discussion among government, industry and regulatory agencies. These results add substantially to the available information on their environmental and health benefits, which can inform future changes to fuel sulfur policies in Canada and around the world.

Chapter 3.

Exploring the Link Between Childhood Lead Exposure and Criminal Activity in Canada

3.1. Introduction

In the last twenty years, a broad set of studies have assessed the connections between population lead exposure and socioeconomic outcomes including education and occupation (Reuben *et al.*, 2017), poverty (Aelion *et al.*, 2013), and most prominently, crime.[60] Although this field has some roots in the medical and psychology literatures, which established the many harmful impacts of lead poisoning over several decades, it was motived in large part by a large observed drop in crime rates in the United States and Canada throughout the 1990s and 2000s. Many factors have been linked to this decrease, such as abortion access, trends in drug and alcohol use, police tactics, incarceration rates, demographic shifts and more nebulous hypotheses about societal values.[61]

An emerging literature, primarily using American data, finds a strong link between lead exposure during early childhood and a variety of criminal activity later in life (e.g. Nevin, 2000; Reyes, 2007; and Mielke and Zahran, 2012). While lead is not safe at any age, even low levels of exposure within the first few years of life can increase the probability of developing various neurological, behavioral and personality problems.

---

[60] The link between lead exposure and criminal or delinquent activity is explored in Needleman *et al.* (1996), Nevin (2000, 2007), Reyes (2007), Mielke and Zahran (2012), and Aizer and Currie (2019), among others.

[61] Donohue (1998), Donohue and Levitt (2001), Ouimet (2004), Sen (2007) and Farrell (2013) all argue for various factors having an influence on this crime drop. While the literature on this topic is quite large, some explanations have attracted more debate than others. Arguments about the validity of the measured impact of legalized abortion in particular have continued in papers such as Foote and Goetz (2008) and Donohue and Levitt (2019).

These range from attention deficit disorder and impulsiveness to aggressiveness and to lowered intelligence,[62] and many are in turn connected to criminal behavior.[63]

A set of papers have linked the large drop in lead pollution stemming from the United States Clean Air Act in the 1970s and 1980s to sharp decreases in crime around twenty years later. Exploiting differential variation in the decline of lead exposure across US states, Reyes (2007) finds that 56% of the decline in violent crime in the US could be attributed to the reduction in lead exposure. Nevin (2000) matches both the 1960s-70s rise and 1990s decline in murder and other violent crime in the US using national-level lead exposure data, showing that the lead-crime link is an especially powerful explanation for changes in crime rates compared to many other factors which explain the later reduction alone. Similarly, Mielke and Zahran (2012) use lead and crime data starting from 1972 in six major US cities and find that a 1% increase in air lead exposure twenty two years earlier increases the assault rate by 0.46%. This relationship holds for both the 1970s increase and 1990s-2000s decrease in assault rates, and they are able to attribute 60% to 90% of the observed decline in assaults to the previous drop in lead exposure.

The sources and quality of data in these recent lead and crime papers varies: some use proxies for lead exposure like the amount of leaded gasoline burned in a region by year or annual air lead levels as measured by monitors, then look at how broader crime rates evolved, as in Reyes (2007) and Mielke and Zahran (2012). Other contributions to the literature use limited sets of blood tests done on specific cohorts of children and follow their education paths and delinquency rates over time, as in Nevin (2000, 2007) and Aizer and Currie (2019).

The primary sources of lead exposure for children have varied over the last century. In the US, the consumption of water from lead pipes and connectors as well as leaded paint was the main route to lead poisoning from the late 1800s to the 1940s

---

[62] Smith *et al.* (1989), Needleman (1985), Banks *et al.* (1997) and Shah-Kulkarni *et al.* (2016) detail some of the long-held knowledge and newer discoveries about lead's impact on young children.

[63] See, for example, Needleman (1996) and Nevin (2000). The theorized mechanisms of such developmental issues involve both the increased uptake rate of lead in young children including its circulation to the brain, and its ability to bind to specific proteins there, disrupting the action of neurotransmitters and their receptors. Lidsky and Schneider (2003) report on these mechanisms as well as a set of social and genetic exacerbating factors for lead's impact.

(National Research Council, 1993), by which time non-leaded paint began to dominate the market and older plumbing was gradually being phased out of use.[64] The first use of tetra-ethyl lead for automotive purposes was in the 1920s, but its adoption rapidly increased along with the development of highway systems and more widespread ownership of motor vehicles. From the 1940s until the 1980s, children's exposure to lead came mainly from the burning of leaded gasoline, until Clean Air Acts in Canada and the US introduced increasingly strict restrictions on its lead content and eventually enacted bans, in 1990 and 1996 respectively. Thus, over the time period of interest in this study (1974 to 1996) and many others in the literature, atmospheric particulates are the predominant lead source of concern.

To evaluate the potential causal link between lead exposure and crime, historical air monitor data from major urban areas provided by Environment and Climate Change Canada is combined with counts of criminal incidents in these areas available through the Uniform Crime Reporting survey. Exploiting heterogeneity in the rate of air lead decline between cities, the difference-in-difference empirical strategy used here uncovers the relationship between declines in lead exposure and crime eighteen years later, while controlling for aggregate shocks (e.g. recessions), any unobserved time-invariant factors within cities, as well as other important time-varying factors such as demographic changes and abortion rates. Overall, a 10% decline from the average city's initially measured air-in-lead exposure levels taking place eighteen years prior is found to be associated with an approximately 0.8% decrease in property and violent crime rates.

The results suggest that in the fourteen cities studied, almost one tenth of the observed property crime decrease over that period, and one sixth of the violent crime decrease, can be attributed to the decline in lead exposure faced by inhabitants in the mid-1970s through the mid-1990s. These estimates strongly suggest that Canadian

---

[64] Canadian data on the historical impact of leaded paint is largely unavailable. As O'Grady and Perron (2011) point out, cases of paint-related lead poisoning were reported in medical journals in the 1930s and public health officials began to educate the public about the risks of lead in paint, but Canada did not legally restrict the lead content of interior paint until 1976 and the number of mildly or severely affected children before then is unknown. It is, however, a reasonably safe assumption that Canadians did not depart too far from American market trends in this respect.

efforts to reduce lead pollution had an unexpected benefit in the form of lower rates of criminal activity of multiple types.

This paper contributes to the literature by offering novel evidence on the link between childhood lead exposure and crime in Canada. While Nevin (2007) documents a strong national-level correlation between lead and crime, to the author's knowledge this is the first paper that exploits variation between cities in Canada, allowing for estimates of causal impact. Examining the impact of changes in air lead concentrations in the Canadian context allows for a wider perspective about the benefits to lead reductions, as key country characteristics differ from the US: Canada is a more sparsely populated country with criminal justice laws and policies that vary between it and its neighbour to the south. However, the decline of air lead concentrations occurred on a similar timeline with the advent of environmental legislation and regulation[65] as well as technological advances in automobiles[66], allowing for a useful comparison of the two experiences.

Air lead exposure is very low in developed countries today, but legacy sources of lead remain in plumbing, paint and other household materials, and public policy efforts to eradicate them are ongoing, often at great expense. For example, the 2021 US Infrastructure Investment and Jobs Act included 15 billion USD over five years to replace lead pipes and service lines. Additional evidence on lead exposure's indirect costs, such as its relationship with crime, helps to improve estimates of the net benefits of such policies where they are considered.

3.2. Data Description

3.2.1. Lead exposure

The independent variable of interest, lead exposure during early childhood development, was not directly measurable at a large scale or over a significant stretch of

---

[65] The strength and timing of the 1963 US Clean Air Act implementation varied by state, and according to Powell and Wharton (1982), in Canada various environmental laws began to be implemented on a provincial level by the late 1960s, culminating in the federal Clean Air Act in 1971.

[66] Particularly important was the standardization and widespread use of the catalytic converter, which does not function with leaded gasoline

time.[67] Instead, since lead is reliably taken into the body through respiration, following similar studies in the US a proxy variable was used for lead exposure: data from air monitors placed in cities across Canada by a joint federal and provincial/territorial initiative founded in 1969, the National Air Pollution Surveillance Program (NAPS).[68] Starting in 1970 and increasingly through that decade, monitoring devices were installed in major urban areas to detect the concentration of various metals and pollutants in air, with devices moving offline and online throughout the years and later being upgraded to detect lower concentrations of elements.

The specific dataset used contains annual average air lead concentrations (in micrograms per cubic metre) detected by the instruments at various sites across the country, with some cities hosting multiple instruments.[69] The data ranges from 1974-1998, however, not all sites (or cities) have complete measurements in that range: just under half of the cities in this study began measurements one to five years after 1974, most ended somewhat earlier in the 1990s, and a handful were missing some annual values. Column **(1)** of Table 3.1 gives the range of years of available air lead data for each city selected for the study. Where multiple active sites existed in a given city and year, data from each was averaged to record the final value.[70] For missing values in between years of data, located primarily near the end of the dataset where measured data in every city was close to the lower instrument detection limit (i.e., two to three percent of the peak recorded values in the 1970s), linear interpolation between neighbouring values was used.

Panel A of Figure 3.1 shows the Canada-wide trend of lead from 1970 to 1993, taken from aggregated NAPS data provided separately from the site-level statistics. The

---

[67] Although various blood sampling programs have existed in Canada over the years, most have involved a single city or region and collected measurements at just one point in time, e.g. in relation to concern about a large community polluter. Tsekrekos and Buka (2005) give an overview of the available data; Rhainds *et al.* (1999) is a representative study of child blood lead levels in Quebec. In the period of interest there is just one year of nationally representative data, collected as part of the 1978-79 Canada Health Survey as described by Stephens and Jones (1981).

[68] Kelley (1979) gives an overview of the goals and early progress of the NAPS program.

[69] This data was obtained from the Environment and Climate Change Canada agency following an e-mail inquiry.

[70] Cities with multiple sites (minimum ten years overlap) included Halifax, Montreal, Ottawa, Hamilton, Windsor, Winnipeg, Regina, and Vancouver.

trend is immediately apparent: from the beginning of the measurements, lead levels in air decrease steadily and rapidly to minimal levels by the 1990s. Although the peak year for air lead cannot be determined from this data, various pieces of provincial and then federal clean air legislation in the late 1960s and early 1970s (Powell and Wharton, 1982) were almost certainly the main driving factor for this decrease, along with various technological developments in industry and transportation. However, this Canada-wide trend does mask substantial heterogeneity within cities, as the remaining panels of Figure 3.1 make clear. Larger urban areas like Toronto and Montreal, as well as cities in urban corridors like London, tend to have higher initial lead levels and steeper drops compared to the smaller Atlantic and Prairie cities. This holds up to the 1990s, when all sites recorded values at or near the monitor technology's lower detection limit. Deviations from the smooth Canada-wide decreasing trend are also apparent, with some cities showing temporary increases in air lead levels, particularly around the late 1970s.

Figure 3.1. Canada-wide and individual city trends in air lead concentrations.

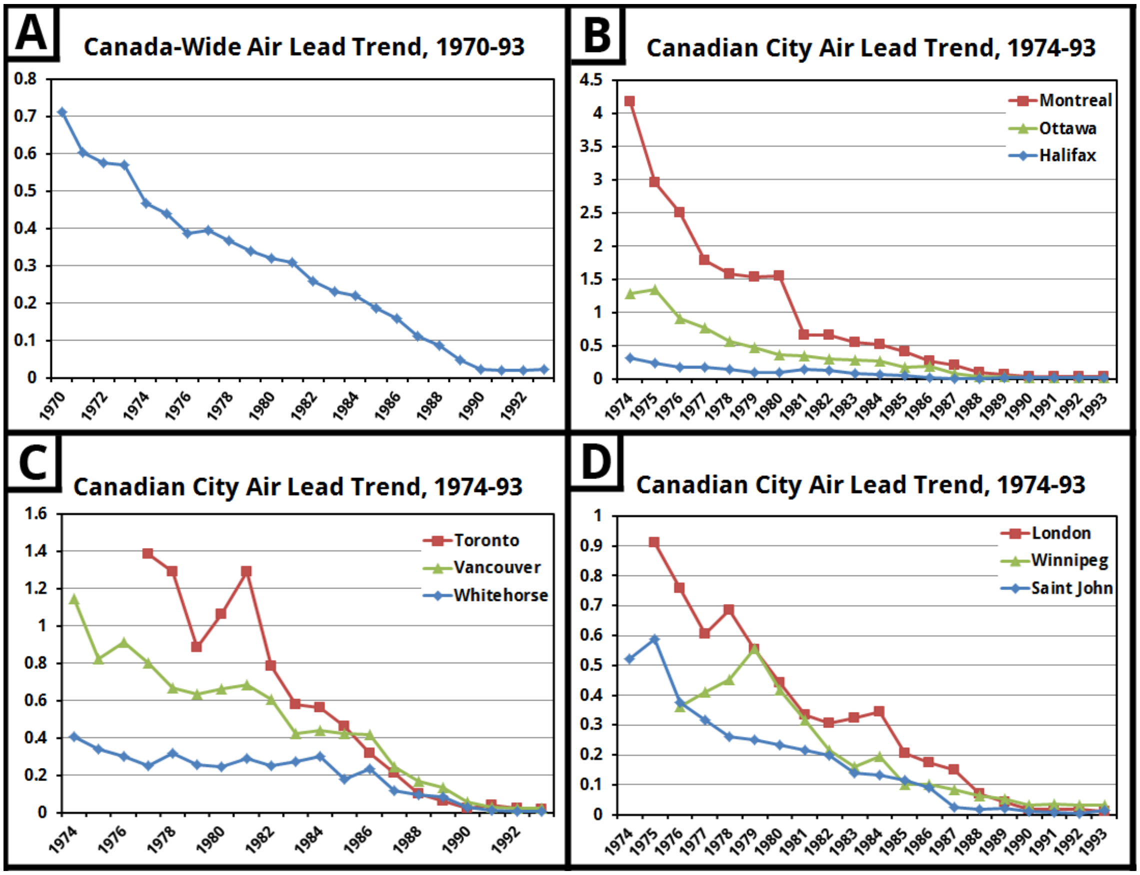

Figure 3.1 Notes: Air lead concentrations are given in micrograms per cubic metre. Available data past 1993 approaches the technology's lower limit of detection and is not shown. Y-axes differ in scale between panels.

3.2.2. Crime statistics

Crime statistics were collected to match cities where NAPS air monitor data was available. The source of this data was the Uniform Crime Reporting Survey (UCR)[71], administered by a joint federal and provincial/territorial organization, the Canadian Centre for Justice Statistics (CCJS). Begun in 1962, this survey goes out to all police forces across Canada and collects detailed information on substantiated incidences of reported crime on a monthly basis, with an almost 100% response rate. Data is then checked for consistency and errors, aggregated across regions and made available online for various public policy and research purposes.

There are two major versions of the UCR survey, both running simultaneously. The first is UCR, sometimes called UCR 1.0, which has been ongoing since 1962, although CMA level data is only consistently available to 2003 and national-level data to 2007. The second is UCR2, which started in 1988 as UCR 2.0 and was revised in 1998, 2004 and 2017 to UCR 2.1, 2.2 and 2.3 respectively in order to add various reporting efficiencies, information on modern crimes like cybercrime, and name information about victims and accusers. While UCR is an “aggregate” survey which focuses on summary information, UCR2 is labeled an “incident-based” survey and includes more detailed information about crimes committed, victims, and accusers. In addition, the coverage of UCR2 is somewhat lower than UCR and has varied from its inception, going from just 50% coverage in 1998 to nearly 100% by 2008.[72]

In addition to those broad differences, UCR2 also adopts methodological changes from UCR. One is that UCR2 includes updated criminal violations created by law as noted above, with UCR respondents previously having to code these new crimes as “Other Criminal Code”. UCR2 also includes mischief and arson as property crimes, and a set of crimes such as kidnapping and criminal harassment has been newly categorized as violent crime. Table B.1 gives the list of specific crimes grouped into

---

[71] A detailed description of the survey and its methodology can be found at the Statistics Canada website: https://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=3302

[72] More details on this point can be found in Babyak (2009) and Canadian Centre for Justice Statistics (2013).

violent or property crime, with the differences between UCR and UCR2 marked in bold text[73].

However, the key change included in the newer version of the survey is that each offense up to four in an “incident” is counted separately, compared to UCR where, with some exceptions in the violent crime category, only the highest Criminal Code punishment offence committed during an incident is reported, or when multiple identical offences occur simultaneously, only one is stated on the survey. To illustrate this, as the UCR reporting manual[74] states, “theft of four vehicles at the same time from a new or used car lot would involve one offence only” – under UCR2 this would be four offences of theft. This has the effect of increasing reported crime rates in the UCR2 survey compared to UCR.

Arguably, a priori the differences between the two surveys may not substantially change crime *trends* in the period after 1998. The main cases where a differential trend might exist are where the type of crimes committed rapidly shifts to either single or multiple simultaneous offences in a way that increasingly separates the two methodologies over time, and where the proportions of the various crimes coded as “Other Criminal Code” in UCR change with the effect of inflating or deflating property and violent crime rates in UCR2 relative to UCR.

To test this, Figure 3.2 shows trends in Canada-wide crime rates (per 100,000 inhabitants) from UCR and UCR2, with UCR data ranging from 1991 to 2007 and UCR2 ranging from 1998 to 2016. Panel A details the trend in property crime and panel B shows that of violent crime. In the range of years from 1998 to 2007, where available data from the two surveys overlap, the annual differences are shown. In Panel A, it is clear that property crime rate data from the two surveys is consistently offset by a fixed amount – good evidence that the primary changes imposed by UCR2 for property crime were unbiased with respect to the trend, and that the two datasets can be relatively seamlessly combined if that difference is taken into account. In Panel B, the difference in violent crime rates is somewhat less constant, with a substantial shift occurring after the

---

[73] Survey version crime differences were sourced from Statistics Canada (2009) and Government of British Columbia Ministry of Public Safety and Solicitor General Policing and Security Branch (2019).

[74] The manual, published by the Canadian Centre for Justice Statistics Policing Services Program in 2002, can be found online.

first two years of overlap and then stabilizing. This changing difference is due to an increase in UCR2-measured violent crime rates relative to UCR and specifically, according to Statistics Canada (2009), the “result of large increases in uttering threats and criminal harassment” newly coded by UCR2 for those two years. For that reason, in this study, crime datasets were combined by an indexing process that takes effect in the year 2000, as described later. While the small inconsistency in crime sets is unfortunate, combining them allows for a substantial thirteen year extension of the study to 2016.

Figure 3.2. Measurements of property and violent crime in Canada from UCR and UCR2 datasets.

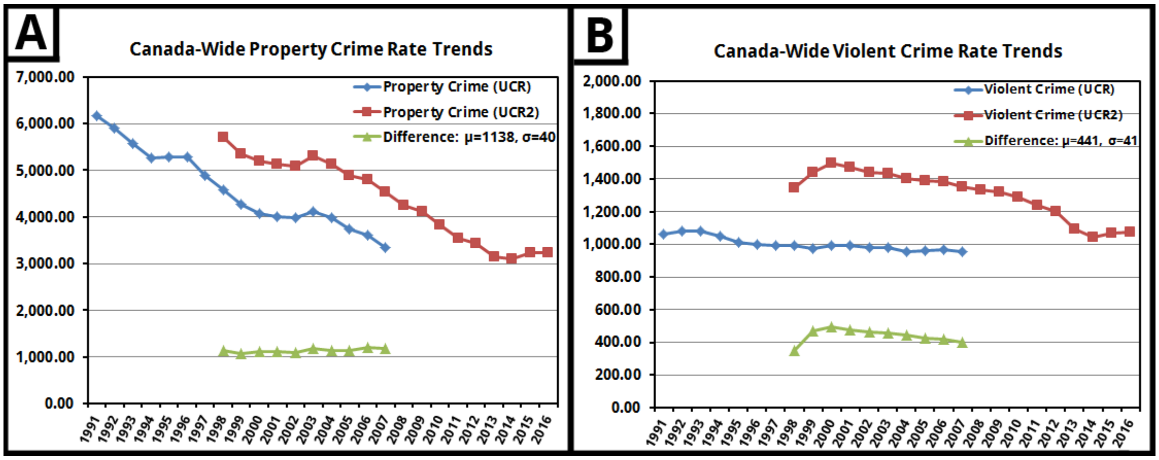

Figure 3.2 Notes: Crime rates are given as offenses per 100,000 inhabitants. Differences between the two datasets where they overlap are included, along with means and standard deviations of difference lines.

As with the city-level lead exposure trends, Figure 3.3 displays some degree of heterogeneity between a selection of cities in terms of how both property and violent crime rates evolve over time. Using UCR data (not combined), panels A and B illustrate property crime trends, and panels C and D show violent crime, with the same six cities followed for each category. Once again, the urban centres tend to follow the general characteristics of slope and direction of the national trend much more closely, albeit with different initial crime rates, while the smaller cities are less consistent. Whitehorse (Yukon statistics, as explained later) and Halifax actually see *increases* in crime rates for a range of years, something not present in the Canada-level data, while Toronto, Vancouver and Montreal hew much more closely to the national trend.

Figure 3.3. Canada-wide and individual city trends in both property and violent crime rates.

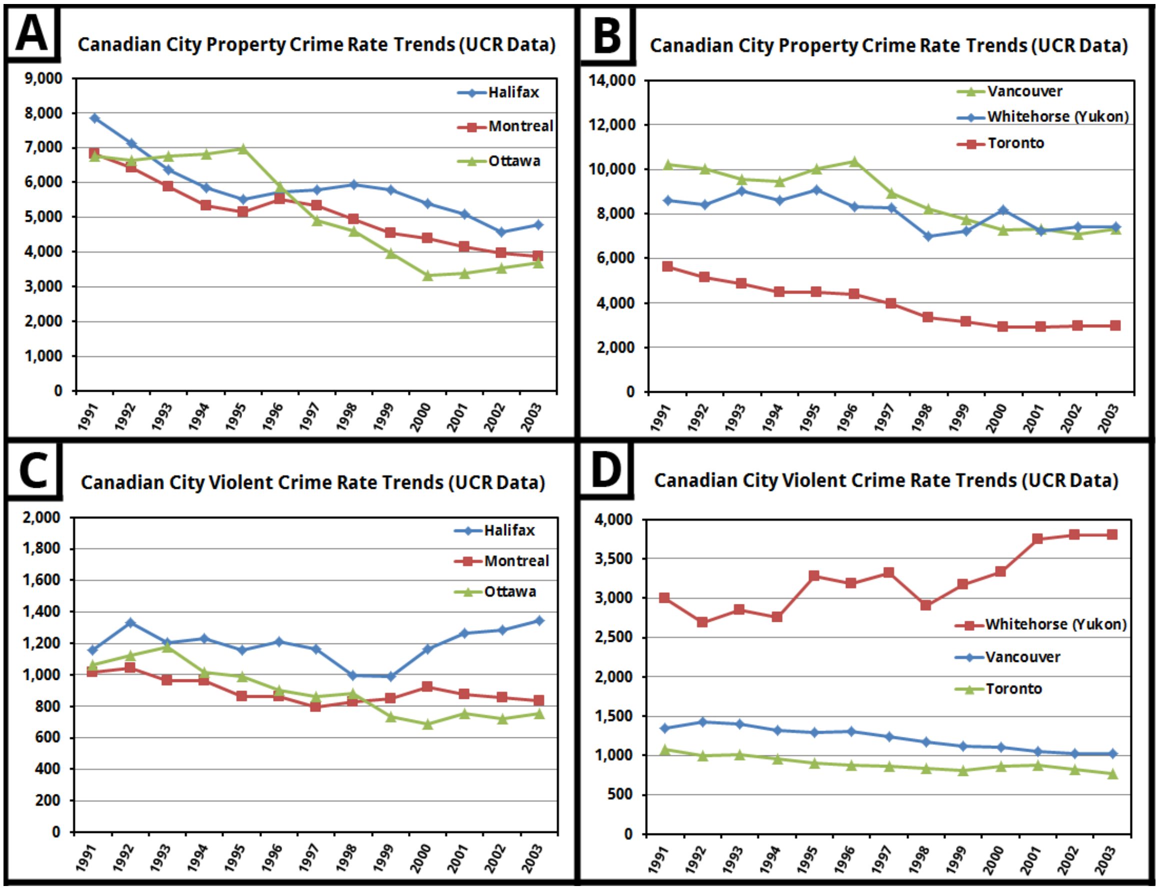

Figure 3.3 Notes: Crime rates are given as offenses per 100,000 inhabitants. Data is sourced from the Uniform Crime Reporting Survey, revision 1.0, and displayed for 1991 to 2003. Y-axes differ in scale between panels.

One difficulty in connecting lead exposure in childhood to criminal activity committed in adulthood is that exposure and crime need not happen in the same location: Canada sees inter-city and inter-provincial migration on a sizeable scale. As with other developed countries, the tendency is toward urbanization[75]. This in turn implies that on the whole, the measured impact of lead exposure on crime on a major city level (not the national level) could be stronger than it actually is, as city crime rates would be lowered by the addition of those inhabitants who grew up in more rural areas with lesser exposure levels, but counted as having higher exposure from the within-city lead trend. Previous iterations of the UCR survey did not include names or other information such as place of birth, and UCR 2.3 data is kept strictly confidential in terms

---

[75] Statistics Canada (2015).

of information “that may identify a particular victim or suspect by the specifics of an offence”. To get around this problem, future work will need to examine other sources of criminal data such as court records to more directly connect lead exposure levels to criminal activity, although such alternate sources come with their own complications such as significantly smaller sample size. While Reyes (2007) was able to use US Census information on state-of-birth distributions by age, year, and state of residence to correct for this issue, such records are unavailable in Canada.

UCR crime datasets were taken from various Statistics Canada tables and publications available online. UCR2 is only compiled from 1998 onwards but is straightforwardly available.[76] UCR1 data is available directly only from 1991 to 1997,[77] but annual issues of Juristat magazine, a product of the CCJS, contain CMA level breakdowns by crime category to 2003.[78] The crime data was aggregated by major CMAs as a rate per 100,000 inhabitants. Violent and property crime statistics were used, excluding other criminal categories such as traffic violations, bank fraud, etc. Crime rate datasets were combined by the use of an indexing process: first, UCR2 was normalized as “1” in the year 2000 and followed the relative changes in each non-indexed series to 2016. For example, the national UCR2 index for property crime rates in 2016 is 0.62 and for violent crime, 0.72. Each combined crime dataset includes UCR values to the year 2000, and from then, the combined dataset value is UCR’s value in 2000 multiplied by the created UCR2 index for each year to 2016. The outcome of this process is a smooth crime series from 1991 to 2016, which nonetheless takes into account the more modern UCR2 survey’s reporting from 2000 onward.

Since some air lead monitors were located in smaller Canadian CMAs, not every city with a NAPS air monitor could be paired with crime statistics, and not every CMA with reported crime statistics could be linked to NAPS air monitor data. The final list of cities with paired lead and crime data was a set of fourteen: Halifax, Nova Scotia; Saint John, New Brunswick; Saguenay, Trois-Rivières, and Montréal, Quebec; Ottawa (Ontario section), Toronto, Hamilton, London, and Windsor, Ontario; Winnipeg, Manitoba; Regina, Saskatchewan; Vancouver, British Columbia; and Whitehorse,

---

[76] Statistics Canada Table 35-10-0177-01: “Incident-Based Crime Statistics, by Detailed Violations, Canada, Provinces, Territories and Census Metropolitan Areas”.

[77] Statistics Canada Table 35-10-0133-01: “Crime Statistics, by Detailed Offences”.

[78] Statistics Canada, Publication 85-002-X: “Juristat”.

Yukon. The final city on the list, Whitehorse, makes up 70% of the population of the Yukon, and as Whitehorse CMA crime statistics were unavailable, its lead data was paired with Yukon-wide crime statistics instead. Columns **(2)** and **(3)** of Table 3.1 gives the collected range of years of crime data for each city selected for the study, and Figure 3.4 shows a map of selected cities in the study.

Table 3.1. Data availability for each variable in years, given for each of the fourteen cities examined as well as Canada overall.

	(1)	**(2)**	**(3)**
Variable	NAPS Lead	UCR1 Crime	UCR2 Crime
Halifax, NS	1974-98	1991-2003	1998-2016
Saint John, NB	1974-95	1991-2003	1998-2016
Saguenay, QC	1978-94	1991-2003	1998-2016
Trois-Rivières, QC	1978-94	1991-2003	1998-2016
Montréal, QC	1974-96	1991-2003	1998-2016
Ottawa, ON	1974-98	1991-2003	1998-2016
Toronto, ON	1977-93	1991-2003	1998-2016
Hamilton, ON	1979-98	1991-2003	1998-2016
London, ON	1975-94	1991-2003	1998-2016
Windsor, ON	1974-97	1991-2003	1998-2016
Winnipeg, MB	1976-96	1991-2003	1998-2016
Regina, SK	1974-98	1991-2003	1998-2016
Vancouver, BC	1974-98	1991-2003	1998-2016
Whitehorse, YT	1974-94	1991-2003	1998-2016
Canada	1970-93	1991-2007	1998-2016

Figure 3.4. **The locations within Canada of each of the fourteen cities examined.**

One motivation for this study is the interesting similarity in trends between air lead levels and criminal activity, with a roughly twenty-year lag. As the most damaging lead exposure occurs during early childhood according to Smith *et al.* (1989), and criminal activity peaks (with small differences in crime categories) from the late teenage years to the early twenties,[79] lag times of approximately twenty years are often used in other studies to examine the link between lead and crime.[80] Figure 3.5 shows this in detail in the Canadian context, by combining the Canada-wide UCR and UCR2 datasets with the index method in 2000, moving national average lead data ahead by twenty years, and normalizing initial year values to 1. Remarkably, the three trends have some broad characteristics in common: lagged decline in lead exposure is consistent with declines in crime rates (albeit with different rates of decline by category, with lead falling the fastest), and the lagged decline to minimal levels of lead exposure is consistent with a leveling of crime rates. While the match is not identical, it is not just lead exposure but many complicated time-varying factors including legislation and social policy that impact

---

[79] Farrington (1986) and Allen and Superle (2016).

[80] Nevin (2000, 2007), Reyes (2007), and Mielke and Zahran (2012) all use a lag time for lead exposure between eighteen and twenty one years.

rates of criminal offenses, and information gleaned quantitatively from the long-term trend is more valuable than a qualitative comparison of any one or two years.

Figure 3.5. A comparison of Canadian-average trends of violent and property crime rates from a combined UCR-UCR2 dataset, alongside air lead levels with a twenty year lag.

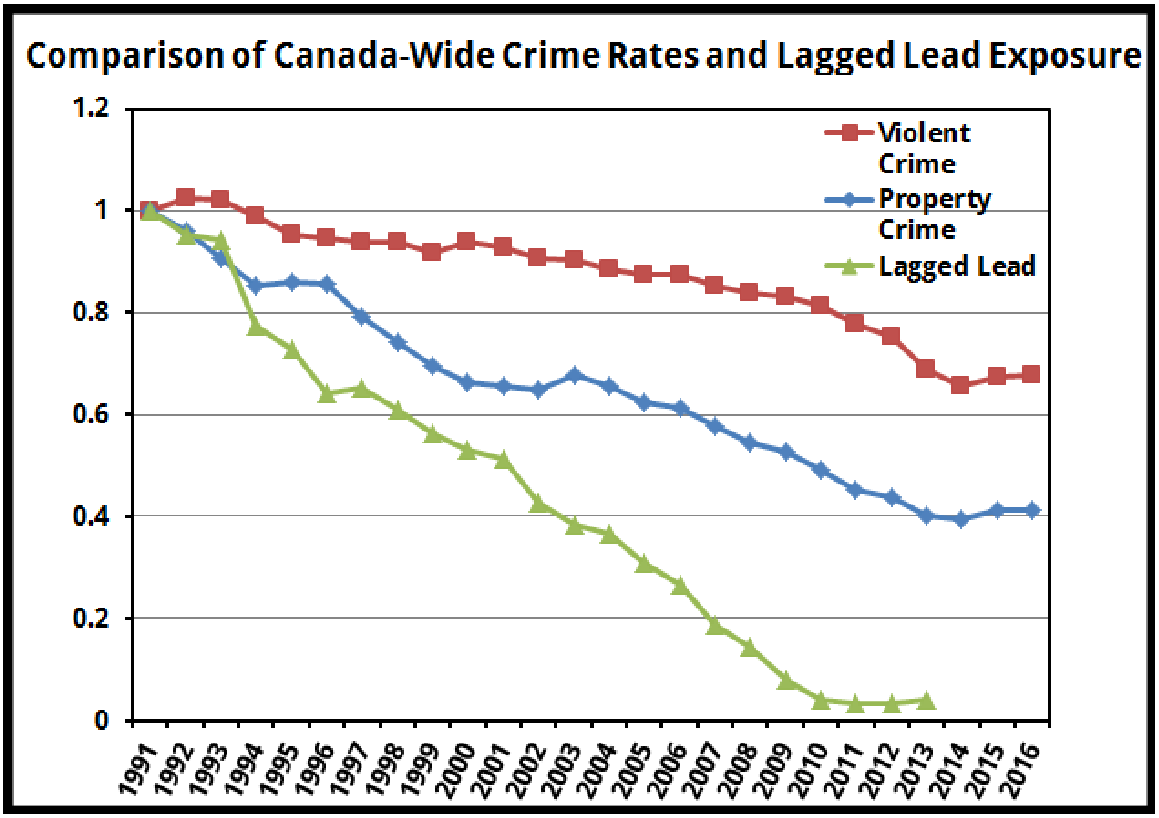

Figure 3.5 Notes: Crimes rates per 100,000 inhabitants as well as twenty year lagged air lead concentrations in micrograms per cubic metre are each normalized to 1991 levels.

3.2.3. Controls

Six controls were collected for each of the fourteen CMAs. With one exception, these were taken from Canadian Census data, tabulated every five years between 1991 and 2016, and values were linearly interpolated between Census years. Controls included average household income, male fraction of the population, fraction of the population aged 15 to 29, a calculated ethnicity value, a calculated education attainment value, and provincial induced abortion rate at the time of lead exposure. The ethnicity variable was defined as the combined fractions of the population that reported Indigenous ancestry and were categorized as a visible minority, and educational attainment was defined as a weighted average of a one to three point scale within CMA populations aged 15 and over, corresponding to census categories of education. One point corresponded to no certificate, diploma or degree, two points to a secondary (high) school diploma or equivalency certificate, and three points to a postsecondary certificate, diploma or degree.

Abortion rates per 1000 women aged 15 to 44 during 1973-1998 and by province of residence (not procedure) were retrieved from Statistics Canada. The link between abortion availability and crime is well-studied in the American context, although it remains highly controversial as evidenced by Foote and Goetz (2008) and Donohue and Levitt (2019). In Canada, abortion in Canada was legalized for health reasons by doctor's order in 1969, with more broad legalization coming in 1988.[81] While recorded Canadian abortion rates remain fairly steady outside of Quebec from the early 1970s to the early 1990s, provincial variability is high. Unfortunately, data on a CMA level is unavailable for the years coinciding with air lead data (and is inconsistently available even for later years), so provincial rates are used here as an approximation for the city level rates. This is likely to be more reasonable for the highly urbanized provinces than the more rural ones, as according to Norman *et al.* (2013), abortion rates tend to be lower in regions with lower population density and will make the provincial number less accurate as a stand-in for particular cities. In addition, as a general caveat, Statistics Canada (2008) warns that abortion has been under-reported to various extents by province over the years.

For the remaining controls, data limitations and availabilities necessitated some minor adjustments. In 2011, National Household Survey (NHS) data was used for variables where Census data did not exist. Income is always reported for the year previous to the census, so for 2016 income values the linear 2010-2015 trend was extended. Before 1996 visible minority status was imputed by Statistics Canada from ethnic origin and immigration questions, and was not available on a CMA level, so values were extrapolated backward from the 1996-2001 trends. Finally, two CMAs underwent name changes (Chicoutimi-Jonquière to Saguenay, Ottawa-Hull to Ottawa-Gatineau, both reflected in the 2006 Census) and while it's unlikely it impacted the data

---

[81] The Criminal Law Amendment Act, 1968–69 allowed a medical committee to prescribe an abortion for health reasons. In 1988, the Supreme Court case R v. Morgentaler struck down the abortion provision in the Criminal Code of Canada and the resulting state of legalization has remained since.

in any significant way, minor border shifts occurred for many CMAs over the years surveyed for the controls.

Figures 3.6 and 3.7 give summary statistics of crime rates and air lead levels for Canada as well as the fourteen cities of interest. Means and percent declines from the initial to the final value were calculated over the primary (eighteen year lag) city-level regression timeline, i.e. from 1992 to 2016 for crime data, and over the years available from 1974 to 1998 for lead data. Table B.2 gives a table of these summary statistics for the set of controls used, with the addition of standard deviation. CMA population is included there for reference.

Of interest is the uniformly steep decline in lead levels in each city, independent of the initial year of data, as well as significant declines in both property and violent crime rates in most cities. The smaller cities tended to see the lowest mean air lead levels as well as the lowest declines in crime in the combined UCR dataset. There were three outliers with respect to violent crime. The first two were Saguenay and Trois-Rivières, which had moderate lead levels but the lowest mean violent crime rates. While Saguenay showed very little decrease in violent crime rates from 1992 to 2016, Trois-Rivières saw a small increase. The third, Saint John, also showed a relatively low decline in violent crime over the full time period, primarily because the starting year, 1992, recorded an unusually low rate compared to the value in 1991 and 1993. The 1993 to 2016 decline was 20.3%, far more than the 5.7% for 1992 to 2016 displayed in Figure 3.7. However, the remaining thirteen cities were much less sensitive to the choice in starting year for their crime rate summary statistics.

Figure 3.6. Mean value of property and violent crime rates (combined datasets) as well as air lead levels, for Canada as well as the fourteen cities studied.

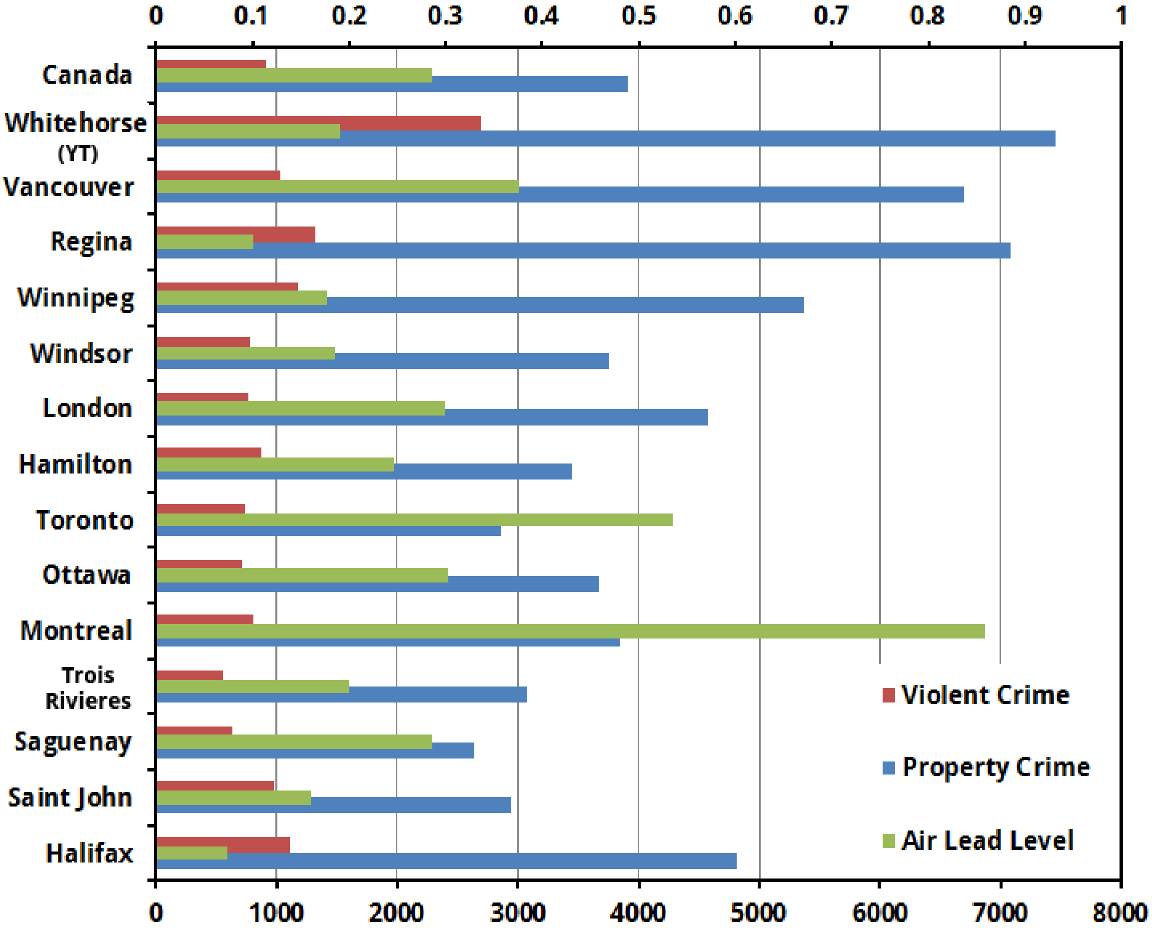

Figure 3.6 Notes: The top axis corresponds to lead, in micrograms per cubic metre, while the bottom axis gives both crime rates, in rates per 100,000 inhabitants. Mean values were calculated using all available years of data. The range of years for crime rates was 1992 to 2016, and given by city for lead levels in Table 3.1.

Figure 3.7. Percent decline of property and violent crime rates (combined datasets) as well as air lead levels, for Canada as well as the fourteen cities studied.

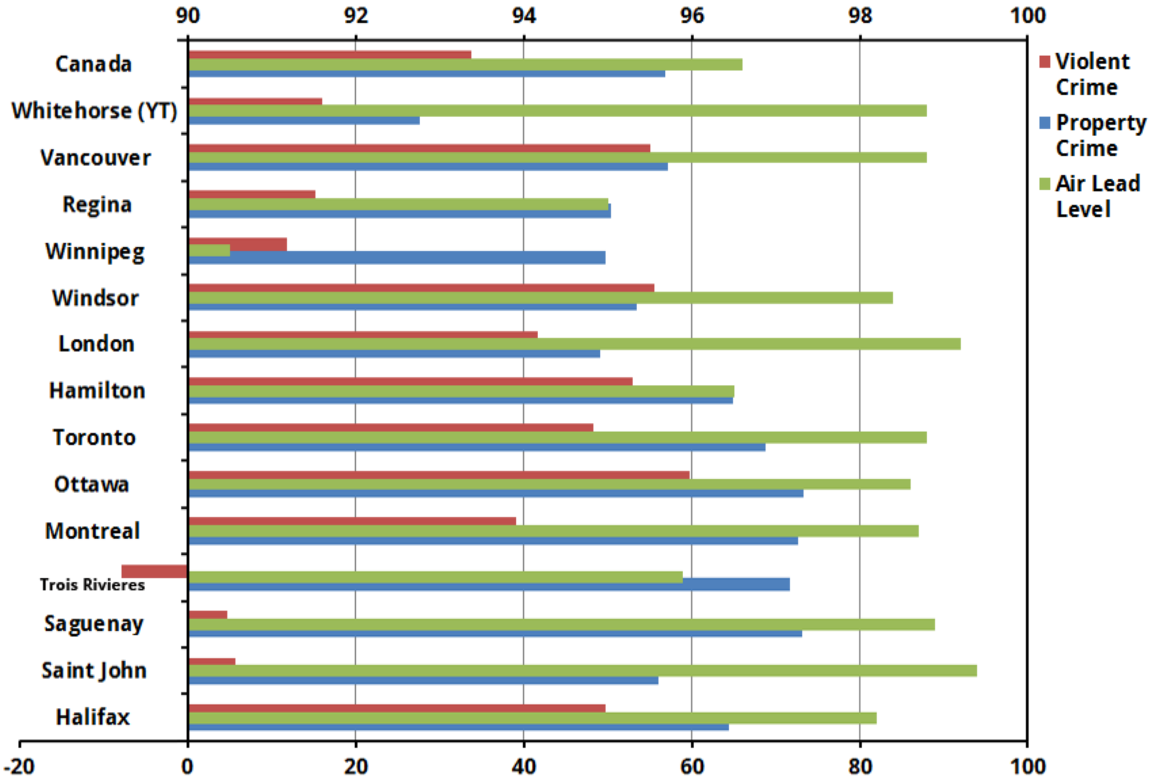

Figure 3.7 Notes: The top axis corresponds to lead, in micrograms per cubic metre, while the bottom axis gives both crime rates, in rates per 100,000 inhabitants. The percent decline was calculated using the values of the variable in its initial and final years of availability. The negative decline in violent crime for Trois-Rivières indicates a rise in that city's violent crime rate. The range of years for crime rates was 1992 to 2016, and given by city for lead levels in Table 3.1.

3.3. Empirical Methodology

A simple regression of crime rates on lagged lead exposure will run into issues of omitted variables bias, and a national regression will be unable to exploit the city-level variation that this new data set provides. As seen in Figures 3.6 and 3.7, the fourteen cities vary substantially in terms of the mean and percentage decline in their lead and crime rates, although there is no particularly informative pattern visible from the summary statistics alone. The Canadian Clean Air Act of 1971 and the provincial legislation of the late 1960s undoubtedly spurred on the rapid decline in air lead levels that can be seen in the data presented here. However, the actual trend of the decline was not identical from city to city, except that by around 1990 each locale had reached a stable minimum.

Following Reyes (2007), the link between childhood lead exposure and criminal offenses is explored in the Canadian context with the following regression equation:

$$\ln\left(crime\ rate\right)_{c,y} = \beta lead\ exposure_{c,y-18} + \gamma X_{c,y} + \mu_c + \mu_y + \varepsilon_{c,y}, \tag{3.1}$$

where c is the city studied, y is the year, and $X_{c,y}$ represents a vector of time-varying city-level control variables[82]. City (μ_c) and year (μ_y) fixed effects are included in order to control for location-specific time-invariant factors that might impact lead levels such as local population density or vehicle use, in addition to common shocks to lead levels across Canadian cities. β, the coefficient of interest, measures the effect of the treatment (lead exposure) which is lagged by eighteen to twenty years, depending on the specification. Unlike Reyes (2007), here abortion was folded into the city-level controls, also with an eighteen to twenty year lag, but coefficients are reported where relevant in the analysis. Standard errors are clustered at the city level.

In order to interpret β as representing a causal relationship between changes in lagged lead exposure and crime rates, the key regressor, lead exposure, needs to be exogenous conditional on the included fixed effects and controls. The assumption that air lead exposure is uncorrelated with other unobserved factors influencing crime rates is a strong one, but there are multiple factors supporting this key identifying assumption.

First, it is unlikely that individuals strongly responded to changes in exposure risk from air lead concentrations. In general, air lead is difficult to avoid in an urban environment: during the regression timeframe, its creation was tied to the consumption of leaded gasoline in cities, and anyone living in an urban environment would be exposed to it each time they breathed the outside air. Furthermore, early public information and guidelines on air lead specifically were weak and so even pollution-conscious individuals would have problems determining exposure levels which might change their behavior[83]. The first Canadian air pollution guidelines created in the 1970s,

---

[82] These included average household income, male fraction of the population, fraction of the population aged 15 to 29, ethnicity, education attainment, and in some specifications, the lagged abortion rate.

[83] Air lead was primarily produced through burning leaded fuels in automobiles, an activity typically taking place during daytime hours and closer to individuals than other major sources of general air pollution such as heavy industry. As such, even common heuristics, e.g. staying indoors when regional atmospheric conditions or industrial activity produced a highly polluted or

the National Ambient Air Quality Objectives (NAAQO), included lead as one component of the total suspended particulate matter category. However, at that time standards had few mechanisms for enforcement, and inter-provincial cooperation on air pollution was often poor until reforms in the late 1990s. In addition, until 2000, the suspended particulate matter standards were based upon the 1960s-era assumption that low ambient concentrations of particular matter measured in developed nation cities were not harmful to human health or the environment, now known to be false (CEPA/FPAC Working Group on Air Quality Objectives and Guidelines, 1999). For these reasons, strong individual responses to variations in air lead levels in the 1970s and 1980s are not expected, after which time lead levels fell to a minimal level. In addition, the robustness of results to the inclusion of a set of city-level controls and city-specific linear trends mitigates concerns that results are confounded by time-varying determinants of crime specific to certain cities that are correlated with the decline in lead exposure decades earlier.

3.4. Results & Analysis

3.4.1. Regression estimates and discussion

Following Equation 3.1, the primary results from regressing crime rates on eighteen year lagged lead levels are presented, including city and year fixed effects in some specifications as well as city-level controls. Regressions with city-specific linear trends and additional lag times are presented as a robustness check. The data is an unbalanced panel from 1992 to 2016, as while crime and controls were complete over that time period, lead data was not complete from 1974 to 1998 as can be seen in Table 3.1.

Tables 3.2 and 3.3 show the results of each regression specification, with the first table giving details of property crime regressions and the second, violent crime. There are seven city-level specifications in both sets of regressions. Specification **(1)** is the raw correlation between crime on lead in the panel without any controls and specification **(2)** adds city and year fixed effects. Specification **(3)** adds all city-level controls except lagged abortion rates, which are included in **(4)**. Specification **(5)**, the preferred

---

low-visibility environment, would not have been sufficient to consistently avoid lead exposure in the absence of ready access to local air lead data or warnings.

specification, adds city-specific linear trends. Specifications **(6)** and **(7)** modify specification **(5)** by using nineteen and twenty year lag times, respectively, both using lead data starting from 1974 and including up to 1997 and 1996 instead of 1998.

Table 3.2. Estimates on the effect of lagged lead exposure on Canadian city property crime.

Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lead Exposure (Pb)	0.298 (0.126) **	0.123 (0.055) **	0.093 (0.024) ***	0.082 (0.025) ***	0.084 (0.021) ***	0.065 (0.022) ***	0.084 (0.021) ***
Lag Time, years	18	18	18	18	18	19	20
Observations	302	302	302	302	302	297	291
City and Year Fixed Effects	N	Y	Y	Y	Y	Y	Y
City Linear Trends	N	N	N	N	Y	Y	Y
Controls	N	N	Y	Y	Y	Y	Y
Abortion Rates	N	N	N	Y	Y	Y	Y

Table 3.2 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the city level.

Table 3.3. Estimates on the effect of lagged lead exposure on Canadian city violent crime.

Specification	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Lead Exposure (Pb)	0.056 (0.073)	0.083 (0.060)	0.077 (0.042) *	0.089 (0.036) ***	0.097 (0.032) ***	0.068 (0.022) ***	0.069 (0.025) ***
Lag Time, years	18	18	18	18	18	19	20
Observations	302	302	302	302	302	297	291
City and Year Fixed Effects	N	Y	Y	Y	Y	Y	Y
City Linear Trends	N	N	N	N	Y	Y	Y
Controls	N	N	Y	Y	Y	Y	Y
Abortion Rates	N	N	N	Y	Y	Y	Y

Table 3.3 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the city level.

Lead exposure is estimated to have a positive relationship with future crime levels on an eighteen year lag. The effect of progressively adding fixed effects and controls to the property crime regression is to lower the estimated effect size from the raw correlation, although estimates are highly significant throughout. For violent crime, the addition of the fixed effects and controls do not substantially change the point estimate but increase the significance of the results. The inclusion of city-specific linear trends does not meaningfully change either the estimate or the significance. Interestingly, increasing the lag time by one or two years tends to lower the coefficient on lead exposure, although a sizeable effect is still detectable.

3.4.2. Impact of lead decline on Canadian crime rates

What do the estimated coefficients suggest about the impact of lower lead levels? Taking the 0.08 to 0.1 value from specification **(5)** of each table, a 10% decrease in the average city's initially measured air lead levels can be examined, i.e. a drop of 0.095 μg/m^3, which corresponds to an approximately 0.8% to 0.9% decrease in crime rates. Since lead levels declined almost completely from their peak in each city where measurements exist (ten of the fourteen cities had decreases of more than 98% and none had a decrease of less than 90%) and cities varied substantially in initial lead levels, this implies that decreases of about 4% to 10% in each crime rate from the early to mid-1990s onward were due to lower lead exposure during childhood, with the larger, more polluted cities tending to experience the higher end of that range.

With an average fall of about 60% in property crime rates and 30% in violent crime rates across the fourteen cities from 1992 to 2016, this in turn means that a substantial fraction of these observed lowered crime rates can be linked to the abatement of lead pollution in the 1970s and 80s. Figure 3.8 shows this in more detail. While the absolute levels of impact on property and violent crime rates are similar, the relative impact on violent crime rates is almost doubled (22% compared to 11.5% for property crime rates), as violent crime declined substantially less than property crime over this range of time.

These estimates are substantially lower than others in the literature. Reyes (2007) estimated that the decline in lead in the US, proxied by leaded gasoline consumption, could explain 56% of the US decline in violent crime from 1985 to 2002, an era with significant overlap to this study. Mielke and Zahran (2012), also working from US data from 1972 to 2007, estimated an impact of lead on aggravated assault rates from between 66% and 89%. One possible explanation for this is the fact that Canada is a much more sparsely populated country than the US, with less dense cities[84]. Most air lead pollution in the 1970s and 1980s was emitted from vehicles and lower population (and thus vehicle) density would decrease the amount of lead that inhabitants were exposed to. A comparison of the US Environmental Protection Agency's national air lead trend[85] with Figure 3.1 suggests that American lead levels were substantially higher, in turn implying that lead's impact on crime would be greater than the host of other possible explanatory variables compared to the results of this study.

Additionally, Reyes (2007) found significant impacts only on violent crime, and Nevin (2007) connected lead to declines in both property and violent crime rates. This study agrees with the latter's findings in that the coefficients associated with lead exposure for both property and violent crime are significant and indeed similar in magnitude. This discrepancy may relate to the different categorization of criminal acts in the Canadian UCR survey compared to the United States FBI's own UCR survey, or it may simply be evidence in favor of the suggestion that lead exposure impacts more than the commission of violent crimes like homicide and assault.

---

[84] Filipowicz (2018).

[85] EPA air lead levels by decade can be examined at the EPA's website: https://www.epa.gov/air-trends/lead-trends.

Figure 3.8. **Average 1992-2016 crime rate declines in percentages attributable to 1974-1998 lead level decline, by type of crime (property or violent).**

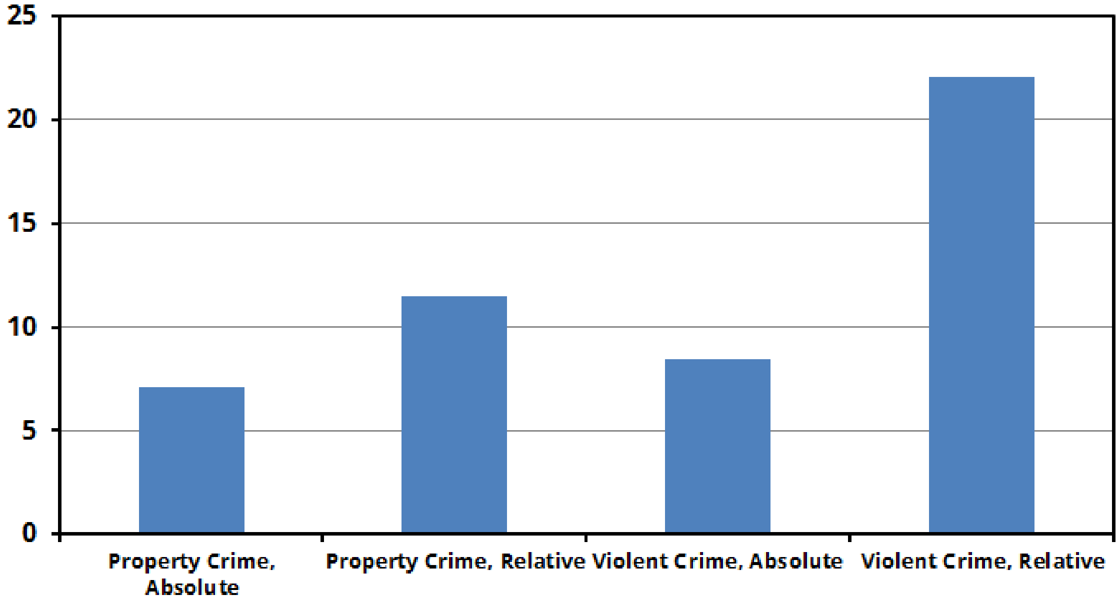

Figure 3.8 Notes: Since Saguenay and Trois-Rivières showed a small net decrease and increase respectively in violent crime from 1992 to 2016, and Saint John's initial 1992 violent crime rate is an apparent outlier, impacting the 1992-2016 percentage decline as discussed earlier, those three cities were dropped from the average in that category.

3.5. Conclusion

Overall, these results imply a significant relationship between reductions in childhood lead exposure in Canadian cities and later decreases in both violent and property crime rates. Regressions on CMA-level crime data, including city and year fixed effects and a variety of controls, estimate that reduced lead exposure contributed over a tenth of the observed decrease in property crime rates and a fifth of the lowered violent crime rates over the period 1992 to 2016.

While a relatively small estimate compared to similar studies in the US literature, the result shows that crime reduction in multiple categories was an unintended but significant benefit of lead pollution control policies in Canada throughout the 1970s and 80s. While the problem of air lead has since receded, these results also help to inform ongoing efforts to eradicate legacy sources of lead exposure.

Productive avenues for future work include quantifying the size of this benefit relative to the cost of pollution control measures as well as exploring alternative sources of both lead exposure data and crime rate data. City-level leaded gasoline consumption data from before 1974 can extend the study period and look at the previous increases in lead and crime. Additional crime rate data, such as appearances and convictions in youth courts, may allow the more close following of a specific age cohort (e.g. fifteen and sixteen year olds). This would help avoid the effect of migration on the results and reduce any composition effect in overall crime rates, and focus more on the impact of changes in lead exposure.

References

Aelion, C. Marjorie et al. Associations Between Soil Lead Concentrations and Populations by Race/Ethnicity and Income-to-Poverty Ratio in Urban and Rural Areas. Environmental Geochemistry and Health (2013), Vol. 35, pp. 1-12.

Aizer, Anna, and Currie, Janet. Lead and Juvenile Delinquency: New Evidence from Linked Birth, School, and Juvenile Detention Records. Review of Economics and Statistics (2019), Vol. 101 (4), pp. 575-87.

Aldy, Joseph E. and Smyth, Seamus J. Heterogeneity in the Value of Life. NBER Working Paper 20206 (2014).

Allen, Mary K. and Superle, Tamy. Youth Crime in Canada, 2014. Juristat (2016).

Anastasopolos, Angelos T. et al. Air Quality in Canadian Port Cities After Regulation of Low-Sulphur Marine Fuel in the North American Emissions Control Area. Science of The Total Environment (2021), Vol. 791 (15), pp. 147949-60.

Babyak, Colin et al. The Methodology of the Police-Reported Crime Severity Index. Proceedings of the Survey Methods Section, 2009 Statistical Society of Canada Annual Meeting.

Bakolis, Ioannis et al. Protective Effects of Smoke-free Legislation on Birth Outcomes in England: A Regression Discontinuity Design. Epidemiology (2016), Vol. 27 (6), pp. 810-8.

Banks, E.C., Ferretti, L.E., and Shucard, D.W. Effects of Low Level Lead Exposure on Cognitive Function in Children: A Review of Behavioral, Neuropsychological and Biological Evidence. Neurotoxicology (1997), Vol. 18 (1), pp. 237-81.

Barnett, Adrian G. et al. Air Pollution and Child Respiratory Health: A Case-Crossover Study in Australia and New Zealand. American Journal of Respiratory and Critical Care (2005), Vol. 171 (11), pp. 1272–8.

Barreca, Alan I., Neidell, Matthew, and Sanders, Nicholas J. Long-run Pollution Exposure and Mortality: Evidence from the Acid Rain Program. Journal of Public Economics (2021), Vol. 200, pp. 104440.

Barregard, Lars et al. Impact on Population Health of Baltic Shipping Emissions. International Journal of Environmental Research and Public Health (2019), Vol. 16 (11), pp. 1954-64.

Becker, Randy A. Air Pollution Abatement Costs Under the Clean Air Act: Evidence from the PACE Survey. Journal of Environmental Economics and Management (2005), Vol. 50 (1), pp. 144-69.

Borgschulte, Mark, Molitor, David, and Zou, Eric Yongchen. Air Pollution and the Labor Market: Evidence from Wildfire Smoke. The Review of Economics and Statistics (2022), pp. 1-46.

Bourque, C. P.-A. and Arp, P. A. Simulating Sulfur Dioxide Plume Dispersion and Subsequent Deposition Downwind from a Stationary Point Source: A Model. Environmental Pollution (1996), Vol. 91 (3), pp. 363-80.

Broome, Richard A., et al. The Mortality Effect of Ship-Related Fine Particulate Matter in the Sydney Greater Metropolitan Region of NSW, Australia. Environment International (2016), Vol. 87, pp. 85-93.

Uniform Crime Reporting Version 1.0 Reporting Manual. Canadian Centre for Justice Statistics Policing Services Program (2002).

Uniform Crime Reporting Incident-Based Survey User Manual. Canadian Centre for Justice Statistics (2013).

Carslaw, David C. and Ropkins, Karl. Openair - An R Package for Air Quality Data Analysis. Environmental Modelling and Software (2012), Vol. 27-28, pp. 52-61.

Carson, Richard T., Jeon, Yongil, and McCubbin, Donald R. The Relationship Between Air Pollution Emissions and Income: US Data. Environmental and Development Economics (1997), Vol. 2 (4), pp. 433-50.

CEPA/FPAC Working Group on Air Quality Objectives and Guidelines. National Ambient Air Quality Objectives for Particulate Matter. Part 1, Science Assessment Document. Health Canada (1999), Publication H46-2/98-220-1E.

Chan, H. Ron et al. The Impact of Trading on the Costs and Benefits of the Acid Rain Program. Journal of Environmental Economics and Management (2018), Vol. 88, pp. 180-209.

Chay, Kenneth Y. and Greenstone, Michael. Impact of Air Pollution on Infant Mortality: Evidence from Geographic Variation in Pollution Shocks Induced by a Recession. The Quarterly Journal of Economics (2003), Vol. 118 (3), pp. 1121-67.

Chen, Hong et al. Effect of Air Quality Alerts on Human Health: A Regression Discontinuity Analysis in Toronto, Canada. The Lancet Planetary Health (2018), Vol. 2 (1), pp. e19-26.

Chen, Shuo, Li, Yiran, and Yao, Qin. The Health Costs of the Industrial Leap Forward in China: Evidence from the Sulfur Dioxide Emissions of Coal-Fired Power Stations. China Economic Review (2018), Vol. 49, pp. 68-83.

Chen, Tze-Ming et al. Outdoor Air Pollution: Nitrogen Dioxide, Sulfur Dioxide, and Carbon Monoxide Health Effects. The American Journal of the Medical Sciences (2007), Vol. 333 (4), pp. 249-56.

Chen, Yuyu, et al. Evidence on the Impact of Sustained Exposure to Air Pollution on Life Expectancy from China's Huai River Policy. Proceedings of the National Academy of Sciences (2013), Vol. 110 (32), pp. 12936-41.

Committee of the Environmental and Occupational Health Assembly of the American Thoracic Society. Health Effects of Outdoor Air Pollution. American Journal of Respiratory and Critical Care Medicine (1996), Vol. 153 (1), pp. 3-50.

Committee of the Medical Effects of Air Pollutants. Quantification of the Effects of Air Pollution on Health in the United Kingdom. United Kingdom Department of Health (1998).

Corbett, James J. et al. Mortality from Ship Emissions: A Global Assessment. Environmental Science & Technology (2007), Vol. 41 (24), pp. 8512-18.

Cullinane, Kevin and Bergqvist, Rickard. Emission Control Areas and Their Impact on Maritime Transport. Transportation Research Part D (2014), Vol. 28, pp. 1-5.

Currie, Janet and Neidell, Matthew. Air Pollution and Infant Health: What Can We Learn from California's Recent Experience? The Quarterly Journal of Economics (2005), Vol. 120 (3), pp. 1003-30.

Currie, Janet, Neidell, Matthew, and Schmieder, Johannes F. Air Pollution and Infant Health: Lessons from New Jersey. Journal of Health Economics (2009), Vol. 28 (3), pp. 688-703.

Currie, Janet, Heep Ray, Samantha, and Neidell, Matthew. Quasi-Experimental Studies Suggest That Lowering Air Pollution Levels Benefits Infants' and Children's Health. Health Affairs (2011), Vol. 30 (12), pp. 2391-99.

Curtis, Luke et al. Adverse Health Effects of Outdoor Air Pollutants. Environment International (2006), Vol. 32 (6), pp. 815-30.

den Boer, Eelco, Ahdour, Saliha, and Meerwaldt, Harold. SECA Assessment: Impacts of 2015 SECA Marine Fuel Sulphur Limits. CE Delft (2016), Publication 16.7H83.43.

Deryugina, Tatyana et al. The Mortality and Medical Costs of Air Pollution: Evidence from Changes in Wind Direction. American Economic Review (2019), Vol. 109 (12), pp. 4178–219.

Deschênes, Olivier, Greenstone, Michael, and Shapiro, Joseph S. Defensive Investments and the Demand for Air Quality: Evidence from the NO_x Budget Program. American Economic Review (2017), Vol. 107 (10), pp. 2958-89.

Donohue, John T. Understanding the Time Path of Crime. The Journal of Criminal Law and Criminology (1998), Vol. 88 (4), pp. 1423-52.

Donohue, John T. and Levitt, Steven D. The Impact of Legalized Abortion on Crime. Quarterly Journal of Economics (2001), Vol. 116 (2), pp. 379-420.

Donohue, John T. and Levitt, Steven D. The Impact of Legalized Abortion on Crime over the Last Two Decades. National Bureau of Economic Research (2019), Working Paper No. 25863.

Endresen, Øyvind et al. Improved Modelling of Ship SO_2 Emissions — A Fuel-Based Approach. Atmospheric Environment (2005), Vol. 39 (20), pp. 3621–28.

1997 Annual Report on the Federal-Provincial Agreements for the Eastern Canada Acid Rain Program. Environment Canada (1997), Publication En40-11/29E.

Integrated Science Assessment (ISA) for Sulfur Oxides – Health Criteria. Environmental Protection Agency (2017), Publication EPA/600/R-17/451.

Eyring, Veronica et al. Transport Impacts on Atmosphere and Climate: Shipping. Atmospheric Environment (2010), Vol. 44 (37), pp. 4735–71.

Farrell, Graham. Five Tests for a Theory of the Crime Drop. Crime Science (2013), Vol 2 (5).

Farrington, David P. Age and Crime. Crime and Justice (1986), Vol. 7, pp. 189-250.

Filipowicz, Josef. Room to Grow: Comparing Urban Density in Canada and Abroad. Fraser Institute (2018), Research Bulletin Series.

Fioletov, V. E. et al. Estimation of SO_2 Emissions Using OMI Retrievals. Geophysical Research Letters (2011), Vol. 38 (21).

Foote, Christopher L. and Goetz, Christopher F. The Impact of Legalized Abortion on Crime: Comment. The Quarterly Journal of Economics (2008), Vol. 123 (1), pp. 407–23.

Geels, Camilla et al. Projections of Shipping Emissions and the Related Impact on Air Pollution and Human Health in the Nordic Region. Atmospheric Chemistry and Physics (2021), Vol. 21 (16), pp. 12495–519.

Gillingham, Kenneth and Huang, Pei. Racial Disparities in the Health Effects from Air Pollution: Evidence from Ports. NBER Working Paper 29108 (2021).

Overview of Crime Data Collection in British Columbia, 2018. Government of British Columbia Ministry of Public Safety and Solicitor General Policing and Security Branch (2019).

Greenberg, N. et al. Modeling Long Term Effects Attributed to Nitrogen Dioxide (NO_2) and Sulfur Dioxide (SO_2) Exposure on Asthma Morbidity in a Nationwide Cohort in Israel. Journal of Toxicology and Environmental Health, Part A (2017), Vol. 80 (6), pp. 327-37.

Ha, Eun-Hee et al. Infant Susceptibility of Mortality to Air Pollution in Seoul, South Korea. Pediatrics (2003), Vol. 111 (2), pp. 284-90.

Haines, Douglas A. et al. An Overview of Human Biomonitoring of Environmental Chemicals in the Canadian Health Measures Survey: 2007–2019. International Journal of Hygiene and Environmental Health (2017), Vol. 220 (2) Part A, pp. 13-28.

Halliday, Timothy J., Lynham, John, and de Paula, Aureo. Vog: Using Volcanic Eruptions to Estimate the Health Costs of Particulates. The Economic Journal (2018).

Hanna, Rema and Oliva, Paulina. The Effect of Pollution on Labor Supply: Evidence from a Natural Experiment in Mexico City. Journal of Public Economics (2015), Vol. 122, pp. 168-79.

Hansen-Lewis, Jamie and Marcus, Michelle M. Uncharted Waters: Effects of Maritime Emission Regulation. NBER Working Paper 30181 (2023).

Human Health Risk Assessment for Sulfur Dioxide. Health Canada (2016), Publication H144-29/2016E.

Jeffries, D. S. et al. Monitoring the Results of Canada/U.S.A Acid Rain Control Programs: Some Lake Responses. Environmental Monitoring and Assessment (2003), Vol. 88 (1-3), pp. 3-19.

Johansson, L. et al. The Evolution of Shipping Emissions and the Costs of Regulation. Atmospheric Chemistry and Physics (2013), Vol. 13 (22), pp. 11375-89.

Jonson, J. E. et al. Impact of Excess NO_x Emissions from Diesel Cars on Air Quality, Public Health and Eutrophication in Europe. Environmental Research Letters (2017), Vol. 12 (9).

Jonson, Jan Eiof et al. Effects of Strengthening the Baltic Sea ECA Regulations. Atmospheric Chemistry and Physics (2019), Vol. 19 (21), pp. 13469-87.

Joskow, Paul L., Schmalensee, Richard, and Bailey, Elizabeth M. The Market for Sulfur Dioxide Emissions. The American Economic Review (1998), Vol. 88 (4), pp. 669-85.

Kattner, L. et al. Monitoring Compliance with Sulfur Content Regulations of Shipping Fuel by In Situ Measurements of Ship Emissions. Atmospheric Chemistry and Physics (2015), Vol. 15 (17), pp. 10087-92.

Kelley, Danford G. The National Air Pollution Surveillance Network in Canada. Journal of the Air Pollution Control Association (1979), Vol. 29 (8), pp. 794-5.

Klotz, Richard and Berazneva, Julia. Local Standards, Behavioral Adjustments, and Welfare: Evaluating California's Ocean-Going Vessel Fuel Rule. Journal of the Association of Environmental and Resource Economists (2022), Vol. 9 (3), pp. 383-424.

Le Tertre, A. et al. Short-Term Effects of Particulate Air Pollution on Cardiovascular Diseases in Eight European Cities. Journal of Epidemiology and Community Health (2002), Vol. 56 (10), pp. 773–9.

Lidsky, Theodore I. and Schneider, Jay S. Lead Neurotoxicity in Children: Basic Mechanisms and Clinical Correlates. Brain (2003), Vol. 126 (1), pp. 5-19.

Likens, Gene E. and Bormann, F. Herbert. Acid Rain: A Serious Regional Environmental Problem. Science (1974), Vol. 184 (4142), pp. 1176-79.

Li, Li et al. The Burden of COPD Mortality Due to Ambient Air Pollution in Guangzhou, China. Scientific Reports (2016), Vol. 6 (1).

Lin, Chih-Ming et al. Association Between Maternal Exposure to Elevated Ambient Sulfur Dioxide During Pregnancy and Term Low Birth Weight. Environmental Research (2004), Vol. 96 (1), pp. 41-50.

Liu, Huan et al. Health and Climate Impacts of Ocean-Going Vessels in East Asia. Nature Climate Change (2016), Vol. 6 (11), pp. 1037-41.

Lindgren, Samuel. The Coast is Clear: Shipping Emission Standards, Air Quality and Infant Health. Transportation Research Part D (2021), Vol. 100, No. 103067.

Luechinger, Simon. Air Pollution and Infant Mortality: A Natural Experiment from Power Plant Desulfurization. Journal of Health Economics (2014), Vol. 37, pp. 219-31.

Mailloux, Nicholas A. et al. Nationwide and Regional PM2.5-Related Air Quality Health Benefits from the Removal of Energy-Related Emissions in the United States. GeoHealth (2022), Vol. 6 (5).

McLinden, Chris A. et al. Space-based Detection of Missing Sulfur Dioxide Sources of Global Air Pollution. Nature Geoscience (2016), Vol. 9, pp. 496-500.

Mielke, Howard W. and Zahran, Sammy. The Urban Rise and Fall of Air Lead (Pb) and the Latent Surge and Retreat of Societal Violence. Environment International (2012), Vol. 43, pp. 48-55.

Moretti, Enrico and Neidell, Matthew. Pollution, Health, and Avoidance Behavior: Evidence from the Ports of Los Angeles. The Journal of Human Resources (2011), Vol. 46 (1), pp. 154-75.

Murphy, Joshua Dennis. The Costs, Benefits, and Efficiency of Air Quality Regulation. Doctoral Dissertation, University of Toronto (2017).

National Research Council Committee on Measuring Lead in Critical Populations. Measuring Lead Exposure in Infants, Children, and Other Sensitive Populations. The National Academies Press (1993).

Needleman, Herbert L. The Neurobehavioral Effects of Low-Level Exposure to Lead in Childhood. International Journal of Mental Health (1985), Vol. 14 (3), pp. 64-77.

Needleman, Herbert L. et al. Bone Lead Levels and Delinquent Behavior. Journal of the American Medical Association (1996), Vol. 275 (5), pp. 363-69.

Neidell, Matthew. Information, Avoidance Behavior, and Health: The Effect of Ozone on Asthma Hospitalizations. Journal of Human Resources (2009), Vol. 44 (2), pp. 450-78.

Nevin, Rick. How Lead Exposure Relates to Temporal Changes in IQ, Violent Crime, and Unwed Pregnancy. Environmental Research (2000), Vol. 83 (1), pp. 1-22.

Nevin, Rick. Understanding International Crime Trends: The Legacy of Preschool Lead Exposure. Environmental Research (2007), Vol. 104, pp. 315–36.

Newbery, David M., Siebert, Horst, and Vickers, John. Acid Rain. Economic Policy (1990), Vol. 5 (11), pp. 297-346.

Norman, Wendy V. et al. Barriers to Rural Induced Abortion Services in Canada: Findings of the British Columbia Abortion Providers Survey (BCAPS). PLOS One (2013), Vol. 8 (6).

Notteboom, Theo. The Impact of Low Sulphur Fuel Requirements in Shipping on the Competitiveness of Roro Shipping in Northern Europe. WMU Journal of Maritime Affairs (2010), Vol. 10, pp. 63-95.

Notteboom, Theo. Roro Shipping vs. Trucking: Revisiting the Impact of Low-Sulphur Marine Fuel Use on Cost Competitiveness of Routing Options in North Europe. WMU Journal of Maritime Affairs (2020), Vol. 19, pp. 399-426.

O’Grady, Kelly and Perron, Amélie. Reformulating Lead-Based Paint as a Problem in Canada. American Journal of Public Health (2011), Vol. 101 Supplement 1, pp. 5176-87.

Ouimet, Marc. Explaining the American and Canadian Crime Drop in the 1990s. Penal Field [Online] (2004), Vol. 1.

Pope, C. Arden III et al. Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. The Journal of the American Medical Association (2002), Vol. 287 (9), pp. 1132-41.

Powell, R. J. and Wharton, L. M. Development of the Canadian Clean Air Act. Journal of the Air Pollution Control Association (1982), Vol. 32 (1), pp. 62-5.

Reuben, Aaron et al. Association of Childhood Blood Lead Levels with Cognitive Function and Socioeconomic Status at Age 38 Years and with IQ Change and Socioeconomic Mobility Between Childhood and Adulthood. Journal of the American Medical Association (2017), Vol. 317 (12), pp. 1244-51.

Reyes, Jessica Wolpaw. Environmental Policy as Social Policy? The Impact of Childhood Lead Exposure on Crime. The B.E. Journal of Economic Analysis & Policy (2007), Vol. 7 (1).

Rhainds, Marc et al. Lead, Mercury, and Organochlorine Compound Levels in Cord Blood in Quebec, Canada. Archives of Environmental Health: An International Journal (1999), Vol. 54 (1), pp. 40-7.

Rogers, J. Felix et al. Association of Very Low Birth Weight with Exposures to Environmental Sulfur Dioxide and Total Suspended Particulates. American Journal of Epidemiology (2000), Vol. 141 (6), pp. 602-13.

Schindler, D. W. Effects of Acid Rain on Freshwater Ecosystems. Science (1988), Vol. 239 (4836), pp. 149-57.

Sen, Anindya. Does Increased Abortion Lead to Lower Crime? Evaluating the Relationship between Crime, Abortion, and Fertility. The B.E. Journal of Economic Analysis & Policy (2007), Vol. 7 (1).

Shadbegian, Ronald J., Gray, Wayne, and Morgan, Cynthia. Benefits and Costs from Sulfur Dioxide Trading: A Distributional Analysis. In Visgilio, Gerald R. and Whitelaw, Diana M. (Eds.), Acid in the Environment (2007), pp. 241-59. Springer, Boston, United States.

Shah-Kulkarni, Surabhi et al. Neurodevelopment in Early Childhood Affected by Prenatal Lead Exposure and Iron Intake. Medicine (Baltimore) (2016), Vol. 96 (4).

Smith, M., Grant, L., and Sors, A.I. (Eds). Lead Exposure and Child Development: An International Assessment. Springer Netherlands (1989).

Smith, T. W. P et al. Third IMO GHG Study 2014. International Maritime Organization (2014), Publication MEPC 67/INF.3.

Song, Sang-Keun et al. Impact of International Maritime Organization 2020 Sulfur Content Regulations on Port Air Quality at International Hub Port. Journal of Cleaner Production (2022), Vol. 347, pp. 131298.

Stavins, Robert N. What Can We Learn from the Grand Policy Experiment? Lessons from SO_2 Allowance Trading. Journal of Economic Perspectives (1998), Vol. 12 (3), pp. 69-88.

Stieb, David M., Judek, Stan, and Burnett, Richard T. Meta-Analysis of Time-Series Studies of Air Pollution and Mortality: Effects of Gases and Particles and the Influence of Cause of Death, Age, and Season. Journal of the Air and Waste Management Association (2011), Vol. 52 (4), pp. 470-84.

Strumpf, Erin C. et al. Did the Great Recession Affect Mortality Rates in the Metropolitan United States? Effects on Mortality by Age, Gender and Cause of Death. Social Science & Medicine (2017), Vol. 189, pp. 11-16.

Report on the Demographic Situation in Canada, 2005 and 2006: Fertility and Induced Abortions. Statistics Canada (2008), Publication 91-209-X.

Measuring Crime in Canada: Introducing the Crime Severity Index and Improvements to the Uniform Crime Reporting Survey. Statistics Canada (2009), Publication 85-004-X.

Canadian Megatrends: Canada Goes Urban. Statistics Canada (2015), Publication 11-630-X.

Stephens, Thomas and Jones, Gareth. The Health of Canadians: Report of the Canada Health Survey. Canadian Journal of Public Health (1981), Vol. 72 (4), pp. 230-2.

Sunyer, Jordi et al. The Association of Daily Sulfur Dioxide Air Pollution Levels with Hospital Admissions for Cardiovascular Diseases in Europe (The Aphea-II Study). European Heart Journal (2003), Vol. 24 (8), pp.752-60.

Tao, Ling et al. Effects of Switching to Lower Sulfur Marine Fuel Oil on Air Quality in the San Francisco Bay Area. Environmental Science & Technology (2013), Vol. 47 (18), pp. 10171-8.

Tian, Linwei et al. Shipping Emissions Associated with Increased Cardiovascular Hospitalizations. Atmospheric Environment (2013), Vol. 74, pp. 320-5.

Tsekrekos, Stephen N. and Buka, Irena. Lead Levels in Canadian Children: Do We Have to Review the Standard? Paediatrics & Child Health (2005), Vol. 10 (4), pp. 215–20.

Uria-Tellaetxe, Iratxe and Carslaw, David C. Conditional Bivariate Probability Function for Source Identification. Environmental Modelling and Software (2014), Vol. 59, pp. 1-9.

Viscusi, W. Kip and Aldy, Joseph E. The Value of a Statistical Life: A Critical Review of Market Estimates Throughout the World. Journal of Risk and Uncertainty (2003), Vol. 27 (1), pp. 5-76.

Vutukuru, Satish and Dabdub, Donald. Modeling the Effects of Ship Emissions on Coastal Air Quality: A Case Study of Southern California. Atmospheric Environment (2008), Vol. 42 (16), pp. 3751-64.

Yang, Mingxi et al. Attribution of Atmospheric Sulfur Dioxide over the English Channel to Dimethyl Sulfide and Changing Ship Emissions. Atmospheric Chemistry and Physics (2016), Vol. 16 (8), pp. 4771-83.

Zhang, Qiang et al. Does Emission Control Area Policy Reduce Sulfur Dioxides Concentration in Shanghai? Transportation Research Part D (2020), Vol. 81, pp. 102289.

Zhang, Qiang, Liu, Huiyun, and Wan, Zheng. Evaluation on the Effectiveness of Ship Emission Control Area Policy: Heterogeneity Detection with the Regression Discontinuity Method. Environmental Impact Assessment Review (2022), Vol. 94, pp. 106747.

Zhang, Xu et al. Changes in the SO_2 Level and $PM_{2.5}$ Components in Shanghai Driven by Implementing the Ship Emission Control Policy. Environmental Science & Technology (2019), Vol. 53 (19), pp. 11580-7.

Appendix A.

Supplementary Tables for Chapter 1

Table A.1. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration, comparing results from site- and county-level analysis.

Specification	(1)	(2)
Level of Analysis	Site	County
Transatlantic Partner Limit (β_1)	-0.333 (0.125) ***	-0.159 (0.149)
Global Limit (β_2)	-0.895 (0.191) ***	-0.496 (0.221) **
US SECA Limit (β_3)	-1.543 (0.261) ***	-1.064 (0.284) ***
Treated Pre-Policy Mean SO_2	4.863	4.462
% Decline from Pre-Policy Mean	31.7	23.8
Observations	70435	32320
Data Availability	Y	Y
Site/County Fixed Effects	Y	Y
Time Fixed Effects	Y	Y
Economic & Environmental Controls	Y	Y

Table A.1 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. Mean SO_2 levels are given in parts per billion, calculated as the treated site or county average from January 2000 to April 2006. In both specifications, errors were clustered at the site or county level. Both regressions were completed using the preferred specification from Table 1.2, including site/county and year-by-month fixed effects and all controls, but the second column uses only county-aggregated data.

Table A.2. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in SO_2 concentration, using regional subsets of the data.

Specification	**(1)**	**(2)**	**(3)**	**(4)**
Region	Northeast	Midwest	South	West
Transatlantic Partner Limit (β_1)	0.238 (0.265)	-0.268 (0.345)	-0.275 (0.236)	-0.390 (0.342)
Global Limit (β_2)	-0.200 (0.342)	-0.354 (0.460)	-0.248 (0.319)	-0.579 (0.364)
US SECA Limit (β_3)	-0.792 (0.496)	-0.777 (0.584)	-0.861 (0.390) **	-0.854 (0.448) *
Observations	8754	7454	11245	4867
Data Availability	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y
Economic & Environmental Controls	Y	Y	Y	Y

Table A.2 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, errors were clustered at the county level. All regressions were completed using the preferred specification from Table 1.2, including site/county and year-by-month fixed effects and all controls, but the data is subset by named Census region in each column.

Table A.3. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in all-ages and age-grouped all-cause mortality.

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Age Band (years)	All Ages	< 1	1-4	5-14	15-24	25-34
Transatlantic Partner Limit (β_1)	0.3 (4.3)	-13.5 (18.2)	-0.4 (1.1)	0.3 (0.7)	-1.3 (1.9)	-3.2 (2.6)
Global Limit (β_2)	-7.0 (5.4)	-26.6 (22.7)	1.0 (1.0)	1.0 (0.7)	1.5 (2.8)	-1.1 (3.1)
US SECA Limit (β_3)	-19.9 (6.9) ***	-26.7 (23.2)	0.3 (1.1)	0.1 (0.6)	-0.7 (2.5)	-3.4 (4.8)
Treated Pre-Policy Era Mean Rate	900.5	777.8	34.1	17.1	80.4	109.8
% Decline from Pre-Policy Era Mean	2.2 (0.8)	3.4 (3.0)	-0.9 (3.2)	-0.6 (3.5)	0.9 (3.1)	3.1 (4.4)
Observations	32296	24163	10350	12997	25551	27311
Data Availability	Y	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y	Y
Economic, Environmental & Health Controls	Y	Y	Y	Y	Y	Y

Specification	(7)	(8)	(9)	(10)	(11)	(12)
Age Band	35-44	45-54	55-64	65-74	75-84	85+
Transatlantic Partner Limit (β_1)	0.7 (3.5)	-0.4 (5.1)	-0.8 (5.8)	19.9 (13.7)	19.0 (26.9)	-186.1 (100.5) *
Global Limit (β_2)	-5.2 (5.0)	-6.7 (7.9)	-13.4 (8.5)	22.4 (17.8)	-28.8 (26.0)	-394.7 (119.2) ***
US SECA Limit (β_3)	-8.3 (6.6)	-13.7 (11.3)	-31.3 (13.4) ***	-1.0 (21.0)	-110.2 (34.3) ***	-495.7 (161.8) ***
Treated Pre-Policy Mean Rate	213.1	454.1	987.3	2356.8	5668.9	15662.8
% Decline from Pre-Policy Mean	3.9 (3.1)	3.0 (2.5)	3.2 (1.4)	0 (0.9)	1.9 (0.6)	3.2 (1.0)
Observations	28696	29702	30490	31139	31464	31599
Data Availability	Y	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y	Y
Economic, Environmental & Health Controls	Y	Y	Y	Y	Y	Y

Table A.3 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. Mortality rates are given per 100,000 population. In all specifications, regressions were weighted by age band-specific pre-policy mean county population and errors were clustered at the county level. All regressions were completed using the preferred specification from Table 1.6, including county and year-by-month fixed effects and all controls.

Table A.4. Impact of the implementation of MARPOL Annex VI fuel sulfur limit eras on changes in county mortality rates (per 100,000 population), taking into account the intensity of shipping activity of nearby major ports.

Specification	(1)	(2)	(3)	(4)	(5)	(6)
Age Group	*< 45*	*45+*	*45+*	*45+*	*45+*	*45+*
Mortality Cause	All-cause	All-cause	Circulatory diseases	Neoplasms or cancers	Cardio-respiratory	All other causes
Transatlantic Partner Limit (β_1)	-1.1 (1.6)	4.3 (8.2)	-2.6 (6.5)	4.6 (2.6) *	0.3 (6.8)	-0.5 (6.5)
Global Limit (β_2)	-0.8 (2.1)	-15.9 (11.8)	-17.7 (6.9) ***	3.4 (3.0)	-9.7 (8.4)	-9.5 (8.4)
US SECA Limit (β_3)	-2.9 (2.9)	-55.9 (15.6) ***	-32.1 (9.5) ***	-5.5 (3.9)	-27.1 (10.8) ***	-23.5 (11.6) **
Transatlantic Partner Limit * Shipping Intensity (β_4)	0.1 (0.8)	-6.9 (3.8) *	-3.0 (2.0)	-2.6 (0.9) ***	-0.7 (2.1)	-3.6 (3.4)
Global Limit * Shipping Intensity (β_5)	0.1 (1.0)	-9.3 (5.0) *	-5.1 (3.1)	-3.8 (1.2) ***	-0.9 (3.4)	-4.5 (3.8)
US SECA Limit * Shipping Intensity (β_6)	0 (1.3)	-5.6 (7.4)	-4.6 (4.1)	-4.3 (1.8) ***	1.3 (4.3)	-2.5 (4.4)
Shipping Intensity (β_7)	3.9 (4.6)	48.8 (19.5) ***	22.6 (11.9) *	16.4 (6.7) ***	24.9 (11.3) **	7.0 (11.6)
Observations	29956	32269	31649	31355	30330	30317
Data Availability	Y	Y	Y	Y	Y	Y
County Fixed Effects	Y	Y	Y	Y	Y	Y
Time Fixed Effects	Y	Y	Y	Y	Y	Y
Economic, Environmental & Health Controls	Y	Y	Y	Y	Y	Y

Table A.4 Notes: Asterisks represent levels of statistical significance: * = significant at the 10% level, ** = significant at the 5% level, *** = significant at the 2.5% level. In all specifications, regressions were weighted by age group-specific pre-policy mean county population, and errors were clustered at the county level. All regressions were completed with the inclusion of the full set of fixed effects and controls. β_4, β_5 and β_6 are coefficients on the interaction of Z-scored shipping intensity with their respective limit era indicator variables.

Table A.5. Consumption of distillate fuels in absolute and relative terms and its estimated price premium over high-sulfur fuels.

Year	Distillate Consumption, %	Distillate Consumption, million tonnes/year	Additional Distillate Consumption, million tonnes/year	Distillate Premium, $/tonne
2010	14	3.2	-	225
2011	15	3.0	-	320
2012	14	2.3	-	320
2013	17	2.7	0.4	330
2014	28	3.8	1.8	310
2015	33	4.9	2.7	205
2016	27	5.4	2.5	210
2017	30	6.7	3.4	175
2018	31	6.7	3.6	200
2019	38	8.8	5.4	200

Table A.5 Notes: Distillate consumption as percentage of overall marine fuel as well as in tonnes per year were retrieved from the EIA. Distillate premiums over IFO380 grade bunker fuel were calculated in 2014 dollars based on den Boer, Ahdour, and Meerwaldt, 2016; Notteboom, 2020; and Ship & Bunker data.

Appendix B.

Supplementary Tables for Chapter 3

Table B.1. List of crimes included in the UCR system, given by category.

Violent Crime	Violent Crime (cont.)	Property Crime
Murder 1st degree	Unlawfully causing bodily harm	Breaking and entering
Murder 2nd degree	Trap, likely to or causing bodily harm	Theft over $5,000 (non-motor vehicle)
Manslaughter	Discharge firearm with intent	Theft under $5,000 (non-motor vehicle)
Infanticide	**Using firearm or imitation in commission of offence**	Motor vehicle theft
Criminal negligence causing death	**Pointing a firearm**	Possession of stolen property
Other related violations causing death	Assault against peace or public officer	Trafficking in stolen goods
Attempted murder	**Criminal negligence causing bodily harm**	Fraud
Conspiracy to commit murder	Assaults - other	Mischief
Sexual asssault - level 3	**Forcible confinement or kidnapping**	**Identity theft (Fraud before 2010)**
Sexual asssault - level 2	**Hostage-taking**	**Identity fraud (Fraud before 2010)**
Sexual asssault - level 1	**Trafficking in persons**	**Arson**
Other sexual violations	Abduction under 14, not parent or guardian	**Altering/removing/destroying a vehicle identification number (Criminalized in 2011)**
Sexual interference	Abduction under 16	
Invitation to sexual touching	Removal of children from Canada	
Sexual exploitation	Abduction under 14, contravening custody order	
Incest	Abduction under 14, by parent or guardian	
Anal intercourse	Robbery	
Bestiality - commit or compel or incite	**Robbery of firearms**	
Corrupting morals of a child	**Extortion**	
Luring a person under 18 via computer	**Intimidation of justice system participant or a journalist**	

Violent Crime	Violent Crime (cont.)	Property Crime
Voyeurism	**Intimidation - other**	
Assault - level 3	**Criminal harassment**	
Assault - level 2	**Harassing phone calls**	
Assault - level 1	**Uttering threat to person**	

Table B.1 Notes: Crimes in bold represent new additions in UCR2.

Table B.2. Summary statistics of controls, 1992 to 2016.

	Halifax						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	367114	65210	0.483	8.1	0.216	0.094	2.31
St. Dev.	23011	13380	0.0017	1.4	0.011	0.026	0.11
% Change	24.1	88	-0.4	88.2	-18.7	140.6	15

	Saint John						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	124849	60228	0.481	3	0.196	0.04	2.17
St. Dev.	1704	12752	0.001	1.4	0.015	0.0148	0.13
% Change	0.9	89.4	0	364.3	-26	247.4	19.9

	Saguenay						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	157155	55038	0.493	9.39	0.191	0.025	2.26
St. Dev.	3058	10872	0.002	4.6	0.014	0.014	0.14
% Change	0.09	80.7	0.4	770	-23.6	450	19.5

	Trois-Rivieres						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	143782	50976	0.481	9.39	0.188	0.024	2.2
St. Dev.	6482	9658	0.002	4.6	0.009	0.011	0.1
% Change	13.9	81.7	0.8	770	-18.2	228.6	19.8

Montreal

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	3589509	61368	0.485	9.39	0.2	0.164	2.25
St. Dev.	266345	12733	0.001	4.6	0.008	0.04	0.14
% Change	29.4	93.8	0.8	770	-16.1	105	20.3

Ottawa (Ontario)

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	847634	84524	0.487	14.4	0.208	0.193	2.4
St. Dev.	81066	14620	0.002	2.13	0.008	0.057	0.12
% Change	40	72.4	-0.8	58.6	-14	239.5	14.6

Toronto

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	4951384	83945	0.486	14.4	0.208	0.403	2.26
St. Dev.	609320	16356	0.0012	2.13	0.009	0.076	0.13
% Change	50	88.1	-0.8	58.6	-14	89.8	18

Hamilton

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	677831	73407	0.487	14.4	0.195	0.127	2.2
St. Dev.	44340	14945	0.001	2.13	0.008	0.037	0.13
% Change	20	93	-0.4	58.6	-15.5	181.4	19.7

London

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	446111	66051	0.484	14.4	0.21	0.118	2.23
St. Dev.	30400	11528	0.0006	2.13	0.008	0.035	0.11
% Change	27.2	74.4	0.4	58.6	-15	177.6	16.1

Windsor

	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	307917	68741	0.49	14.4	0.205	0.156	2.17
St. Dev.	18420	10450	0.001	2.13	0.012	0.045	0.14
% Change	23.3	77.5	0.6	58.6	-16.5	212.2	21.2

	Winnipeg						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	698240	64039	0.487	9.4	0.209	0.244	2.17
St. Dev.	36650	15042	0.002	3	0.007	0.067	0.14
% Change	18.8	112	1	156.1	-12	143.9	20.4

	Regina						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	202110	71034	0.487	6.77	0.222	0.163	2.19
St. Dev.	13300	19729	0.003	1.19	0.007	0.047	0.13
% Change	23.1	128.9	1.4	51.7	-13	143.2	18.4

	Vancouver						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	2073520	72321	0.49	17.4	0.208	0.406	2.3
St. Dev.	236900	14603	0.002	1.5	0.007	0.071	0.13
% Change	49.4	90.5	-0.8	5.4	-12	84.9	16.7

	Whitehorse						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	23251	79057	0.5	17.1	0.207	0.231	2.46
St. Dev.	2622	17284	0.006	2.7	0.01	0.019	0.05
% Change	50.9	87.7	-2.5	105.8	-19.7	7.48	4.7

	Canada						
	Population	*Average Income*	*Male Pop. Share*	*Abortion Rate*	*15 to 29 Share*	*Ethnicity*	*Education*
Mean	31190644	67890	0.491	12.3	0.199	0.19	2.19
St. Dev.	2269825	15066	0.0008	2.1	0.0085	0.046	0.14
% Change	27.3	103	-0.4	76.3	-16.2	129.7	20.3

Table B.2 Notes: Population is given in absolute counts, average income is in Canadian dollars, the abortion rate is per 1000 women aged 15 to 44, ethnicity as a fraction of the population reporting Indigenous ancestry or are a visible minority, and educational attainment is given as a weighted average of a one to three point scale corresponding to census categories of education. Percentage changes are calculated using the 1992 and 2016 values, except abortion rates, which are lagged by eighteen years.