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Looking Back at Fifty Years of the Clean Air Act

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Abstract

Since 1970, transportation, power generation, and manufacturing have dramatically transformed as air pollutant emissions have fallen significantly. To evaluate the causal impacts of the Clean Air Act on these changes, we synthesize and review retrospective analyses of air quality regulations. The geographic heterogeneity in regulatory stringency common to many regulations has important implications for emissions, public health, compliance costs, and employment. Cap-and-trade programs have delivered greater emission reductions at lower cost than conventional regulatory mandates, but policy practice has fallen short of the cost-effective ideal. Implementing regulations in imperfectly competitive markets have also influenced the Clean Air Act's benefits and costs.

JEL Codes: Q52, Q53, Q58

Keywords: retrospective analysis, quasi-experimental methods, cap-and-trade, performance standards, regulatory performance

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1. Introduction

The 1970 Clean Air Act (CAA), followed by the 1977 and 1990 amendments, is arguably the most important and far reaching environmental statute enacted in the United States. This legislation fundamentally shifted the state-oriented focus of most air quality regulation to the federal government and stimulated a broad-based and costly effort to limit harmful air emissions across the United States. Far more than aspirational, the Act included specific targets and timetables for action, empowered citizens with the right to sue government officials, and regulated entities that failed to perform their duties.

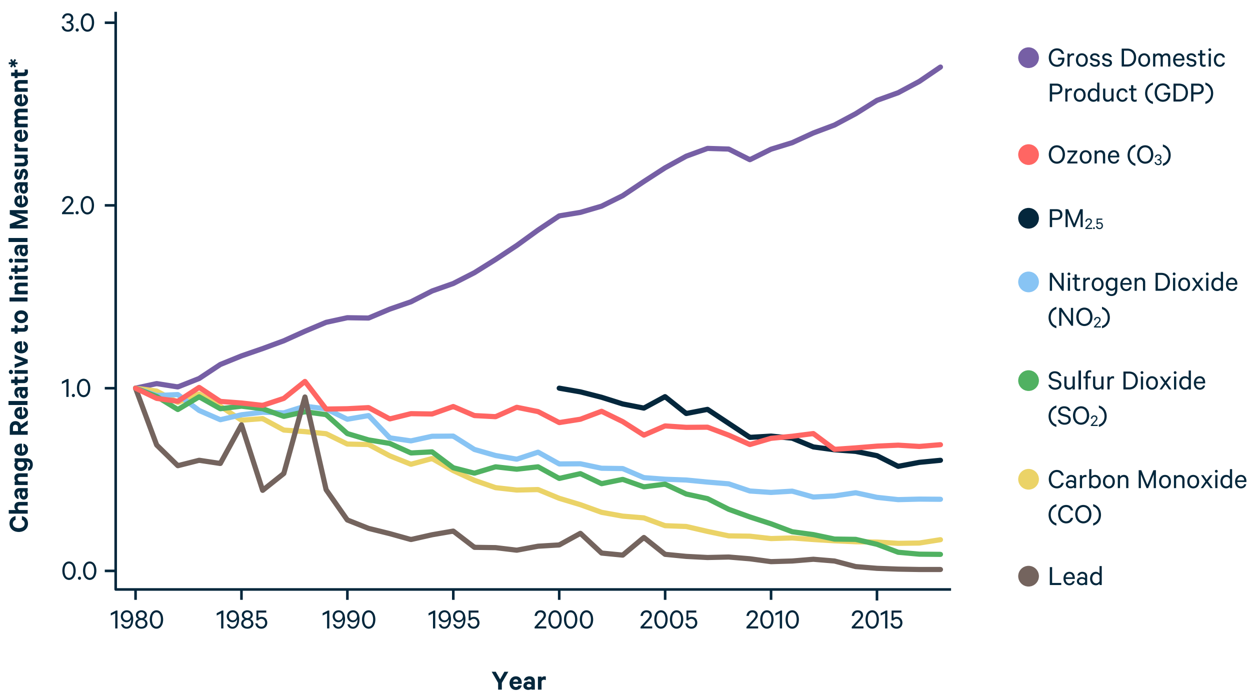
Despite the quadrupling of gross domestic product since 1970 (Figure 1), air quality across the United States has improved substantially. The US Environmental Protection Agency (EPA) reports that emissions of the six most common air pollutants declined an average of 73 percent over 1970–2017. The lower emissions have reduced atmospheric concentrations: fine particles (PM2.5) declined 41 percent since 2000, ozone (O_3) fell 32 percent since 1980, and lead decreased 99 percent since 1970 (EPA, various years). An extensive epidemiological literature associates the contribution of these air quality gains to improved life expectancy and reduced morbidity across the United States.[1] The CAA has delivered clear success stories—removing lead from gasoline, phasing out chlorofluorocarbons and other substances that deplete the stratospheric ozone layer, and dramatically reducing sulfur emissions from power plants and transportation fuels. Emissions of air toxics have also declined substantially. These actions over the past fifty years beg the question of regulatory performance evaluation: what have been the causal economic, environmental, and public health impacts of the Clean Air Act?

Pursuant to Executive Orders issued by Presidents Reagan and Clinton, EPA has developed more than a hundred ex ante studies of major CAA rules, known as Regulatory Impact Analyses (RIAs), designed to measure the benefits, costs and (sometimes) the distributional consequences of major new rules before they are promulgated.[2] However, as Michael Greenstone (2009) noted a decade ago, RIAs are developed at the "point when the least is known and any analysis must rest on many unverifiable and potentially controversial assumptions" (p. 113). As required by the 1990 CAA amendments, EPA has also conducted three aggregate analyses of the Act, also largely ex ante in nature (EPA 1997, 1999, 2011). Most of the RIAs and all three of the aggregate studies demonstrate monetized benefits in excess of costs, although several of the latter have been criticized for the baseline assumption that all post 1970 air

1 Although the causal literature doesn't necessarily attribute all the gains to the CAA, there is substantial evidence on the issue. See Deryugina et al. (2019).

2 A "major rule" is one likely to result in "an annual effect on the economy of $100 million or more." **https://www.archives.gov/files/federal-register/executive-orders/pdf/12866.pdf**.

Figure 1. Changes in Gross Domestic Product and Six Common Air Pollutants, 1980-2018



*The index begins at 1 in 1980, with the exception of PM2.5, which was measured beginning in 2000. The index for each year is the actual value divided by the initial value. Source: Federal Reserve Economic Data | Federal Reserve Bank of St. Louis

quality improvements are attributable to the CAA, and for the failure to disaggregate the analysis sufficiently by rule to determine if even larger net benefits could have been achieved with the same resources.[3]

Ideally, a retrospective or ex post analysis of the CAA would involve a comprehensive assessment of its contribution to the observed air quality improvements, along with the associated changes in human health and welfare. Such an analysis would focus on the realized benefits and costs of major regulations, and it would consider the role of economic incentive mechanisms in achieving emissions reductions. It would also consider the unintended (adverse or beneficial) consequences of CAA rules (e.g., on employment, plant location, and expansion of market power) as well as the distributional impacts of the rules (e.g., on specific locations, industries, occupations or subpopulations). Further, a retrospective review might examine whether alternative rule designs could yield more effective or efficient outcomes with fewer adverse consequences.[4]

3 For a detailed review of the EPA 1997 and 1999 studies, see Krupnick and Morgenstern (2002). More recently, EPA has attempted to address concerns about the aggregate studies by conducting retrospective analysis of several individual rules and developing credible counterfactuals instead of arbitrarily attributing all improvements in air quality to regulatory actions (e.g., Kopits et al. 2014). This work, however, is still in its infancy.

The present review is best understood as a launching point towards a comprehensive ex post assessment of the CAA. Fortunately, economic research on environmental regulation has advanced considerably in the past two decades, and at least partial answers to these questions can be found in the published literature. Arguably, the focus in this literature is on the effectiveness of the regulation in achieving the stated benefits, measured as changes in emissions, concentrations, or health outcomes. An additional focus of this paper is on the costs and unintended consequences of the rules, often expressed as adverse economic impacts.

As randomized controlled trials are not possible looking backward in time, the preferred approach for examining regulatory performance is to use quasi-experimental methods to establish a realistic counterfactual.[5] While these methods share similarities with randomized controlled trials, they generally do not involve strictly random assignment to treatment or control groups.[6] Structural econometric approaches can also be used to establish counterfactuals.

This review is based on a detailed analysis of more than three dozen published economics studies of federal air quality rules, including those covering both stationary and mobile sources. With one important exception, the focus is on published papers that develop realistic baselines via quasi-experimental methods or structural approaches to examine responses to specific regulations as opposed to broad programs. The exception is the relatively large and important body of research that has used non-attainment (NA) status, a spatial designation embodied in the CAA, as an exogenous source of variation in regulatory stringency.

The emphasis on published retrospective studies of individual rules based on quasi-experimental or structural approaches limits the review to what has been studied as opposed to the full set of regulations issued under authority of the CAA. Importantly, entire categories of regulation, including national level new source performance standards, the new source review program, and mobile source standards limiting tailpipe emissions have not been examined retrospectively in a rigorous manner.[7] While this emphasis limits the ability of the present review to make broad statements about the contribution of the CAA to improving societal health and welfare, it does strengthen the basis for ascertaining the causal effects of a particular regulation. Arguably too, this scope limitation helps identify what is not known about the performance of the CAA which, in turn, points to a roadmap for future research.

5 Aldy (2014) and Cropper et al. (2017, 2018) articulate the value of retrospective analysis of environmental regulation.

6 True randomized control studies are extremely rare in the environmental policy field due to legal and other restrictions on withholding environmental and health protections from some groups or areas.

7 Exceptions to this are papers by Gruenspecht (1982) and Nelson et al. (1993), which look at the impact of tailpipe emission standards and new source performance standards on the turnover of the capital stock.

Key areas that are addressed by the quasi-experimental economics literature include the performance of a broad set of cap-and-trade policies for multiple pollutants, the performance of a limited number of technology standards, the effects of differentiating standards on a spatial basis, and the responses to regulation in imperfectly competitive markets. Some of the findings apply to both stationary and mobile sources of pollution, while others are more limited.

Following this brief introduction, Section II describes the main features of the 1970 CAA and the 1977 and 1990 amendments, the nature of the pre-regulatory analyses conducted by EPA, and the selection criteria for studies included in this review. The subsequent three sections focus on retrospective studies, organized around different elements of the Act. Section III addresses the consequences of rules aimed at stationary sources, including power plants and manufacturing facilities. The section is subdivided into regulation-specific categories focusing on emissions trading programs established for SO_2 and NO_x, plus a set of technology-based standards for air toxics. Section IV reviews studies on the effectiveness and health benefits of key fuel standards, the market impacts of these standards, and the effects of the Renewable Fuels Standard. Section V reviews regulatory outcome studies that rely on the distinction between areas classified as meeting the National Ambient Air Quality Standards (NAAQS) from those that do not meet those standards, so-called non-attainment areas. The presentation is subdivided into impact categories—pollutant emissions/concentrations, costs, labor market impacts. Section VI concludes by highlighting some of the main findings of the literature and discussing what we don't know about the Clean Air Act.

2. Background

2.1. Overview of the Clean Air Act

The 1970 CAA represented a major shift in national environmental policy in response to public concern with the deterioration in air quality. The most fundamental provision of the CAA required EPA to set National Ambient Air Quality Standards (NAAQS).[8] Early on, the agency established NAAQS for six air pollutants to protect human health.[9] The CAA authorized EPA to set standards to "protect public health…allowing an adequate margin of safety."[10] The Courts have interpreted these provisions as prohibiting the consideration of cost in setting ambient air quality standards.[11] The CAA requires periodic review of the ambient standards and EPA has revised the NAAQS for several categories of pollutants over time in response to the latest public health research. Hence, an area's attainment status may change as a result of these adjustments to the NAAQS as well as changes in the area's air pollutant concentrations.

As a key element of NAAQS implementation, the CAA requires states to prepare State Implementation Plans (SIPs). For areas attaining the NAAQS, a SIP would demonstrate how the state would assure continued attainment of the standard and for non-attainment areas, a SIP would show how the state would make progress toward meeting the standard. For the non-attainment areas, SIPs could include additional regulatory provisions, as necessary, to reduce emissions from stationary sources, such as power plants and factories, and mobile sources. States submit their SIPs to EPA for review and approval.[12]

In addition to the NAAQS and SIP provisions, the 1970 Clean Air Act required EPA to set uniform national emission standards for new cars and light trucks. The law prescribed a 90 percent reduction in hydrocarbon, carbon monoxide, and nitrogen oxide emissions by 1975 via these standards. [13] The 1970 law also mandated technology-based standards for new steel plants, oil refineries and other major industrial facilities, so-called New Source Performance Standards (NSPS).

In 1977, the CAA was amended to address several issues that emerged with the initial efforts to implement the 1970 legislation. First, the 1977 amendments added new requirements for SIPs to address the problems major metropolitan areas were encountering in addressing non-attainment, especially for smog and ozone pollution. New sources located in non-attainment areas had to comply with more ambitious technology mandates and offset their emissions in their local area by retiring existing emission sources or working with them to reduce their emissions. In attainment areas, new emissions sources faced additional regulatory requirements to ensure that they would not cause the area to violate the NAAQS.

Further, the 1977 amendments imposed new technology-based NSPS which required a percentage reduction through continuous control of SO_2, NO_x and PM from fossil fuel-fired power plants. EPA implemented this provision by adopting a requirement—based on the performance of SO_2 scrubbers—that new and modified coal-fired power plants achieve a 90 percent reduction in SO_2 emissions.

In 1990, the CAA was amended a second time to address continuing issues in bringing non-attainment areas into compliance with the NAAQS.[14] To address the continuing problems major metropolitan areas were encountering in meeting the NAAQS, the 1990 amendments included a classification system for Ozone (O_3), Carbon Monoxide (CO), and Particulate Matter (PM) NA areas that reflected the severity of the NA problems.[15] These provisions also established offset requirements for new and modified stationary sources, control requirements for existing stationary sources (including smaller area sources, such as dry cleaners and gasoline stations), inspection and maintenance programs for cars and trucks, and adoption of local transportation control measures and local clean fuel programs for mobile sources.

The 1990 CAA amendments specified a new round of emission standards for cars and light duty trucks ("Tier 1" standards) and provided EPA the authority to establish more stringent "Tier 2" standards after showing a need for further reductions from these vehicles. Further, the 1990 CAA amendments expanded authority to regulate non-road sources (e.g., construction equipment, lawn and garden equipment), and provided additional authority to regulate fuel composition at the national level.

The 1990 amendments also included new provisions to address acid rain. These provisions included a cap-and-trade program to reduce SO emissions and revised authority to address NO_x emissions from electric power plants. A cap-and-trade system limits the aggregate emissions of regulated firms ("cap") by establishing a fixed number of tradable emission allowances—in sum equal to the cap—which are typically allocated to facilities as a function of their historic emissions or via an auction. Firms may buy and sell allowances, but they must surrender them to the government to cover their emissions at the end of a predetermined trading period in order to comply with the program. The cap creates scarcity in the right to emit pollution which, in theory and in the absence of significant complementary policies, translates into allowance prices reflecting the marginal value of pollution abatement among the regulated firms. A firm may identify pollution abatement opportunities that cost less than the price in the allowance market and decide to reduce its emissions in order to profit from the sale of the allowances no longer needed for compliance. Regardless of the initial allowance distribution, trading can result in emission allowances being put to

14 The 1990 CAA amendments also included major provisions establishing a centralized permit program for major sources and a regulatory program to protect stratospheric ozone (implementing the Montreal Protocol). Other provisions require EPA to undertake a variety of studies and reports including the Section 812 requirement that EPA provide a report to Congress on the economic impact of the CAA (including the costs, benefits, and other effects of key provisions of the Act).

15 For ozone, the amendments established five classes of non-attainment areas: marginal, moderate, serious, severe, and extreme. For CO and PM, the amendments established two classes of non-attainment: moderate and serious.

their highest valued use: covering those emissions that are most costly to abate and spurring firms to undertake the least costly reductions.

The 1990 amendments also provided authority for EPA to set technology-based Maximum Available Control Technology (MACT) standards to limit air toxics (e.g. Benzene, Chloroform and Formaldehyde) emissions from major industrial facilities. [16] MACT standards for existing sources were to be set at the level of control achieved by the best performing 12 percent of plants in the relevant industrial subcategory. [17] For new sources, the standards were to be set at the maximum feasible reduction in emissions taking into account cost and other non-air quality factors. In addition, the air toxics provisions required that EPA establish standards securing emissions reductions from smaller area sources accounting for 90 percent of the emissions of 30 hazardous air pollutants (HAPs) posing the greatest risk to public health. The air toxics provisions require EPA to revisit the MACT standards after 8 years to address significant residual risks for public health and the environment.

Congress has also amended specific provisions of the CAA through appropriations riders or as a collateral part of other legislative initiatives. For example, the Energy Policy Act of 2005 contains CAA provisions for fuels regulations, including the Renewable Fuels Standard, the oxygenate mandate, and state boutique fuels programs. The Energy Independence and Security Act of 2007 revised the Renewable Fuels Standard. Over the years, in response to court decisions and new scientific, technological and other developments, EPA has established additional regulatory initiatives, including a shift from a photochemical oxidant NAAQS to the Ozone NAAQS and development of a PM2.5 standard for fine particles, the emergence of increasingly stringent New Source Review program requirements for sources in non-attainment and prevention of significant deterioration areas. Other initiatives include the development of cross-state programs to limit SO_2 and NO_x emissions from power plants that render the 1990 acid rain provisions largely superfluous, and the development of regulations to address carbon dioxide and other greenhouse gas emissions.

2.2. Ex Ante Regulatory Impact Analyses

EPA routinely conducts Regulatory Impact Analyses (RIAs) to estimate the costs of air quality regulations and their benefits. The Reagan Administration Executive Order 12291, superseded by the Clinton Administration Executive Order 12866, have required EPA to undertake analyses of rules expected to have a major impact on the US economy. The Office of Management and Budget provides guidance to regulatory agencies on the conduct of such analyses and EPA has issued peer reviewed guidelines for benefit-cost analysis.

16 This provision listed 187 air toxics subject to these standards.

17 In cases where there are fewer than 30 plants in the industry, MACT is defined in terms of the best performing 5 facilities.

Air quality regulations typically drive firms to change their operations in order to reduce pollution. Such changes—investing in new pollution control equipment, modifying the mix of inputs, altering production—impose costs on the firm, some of which may be passed on to consumers in the form of higher prices, some passed on to workers through lower wages or layoffs, and some borne by the firm owners. These costs may spur innovative activity and reward other firms (and their workers) which produce lower-emitting technologies and processes. The reduced emissions then cause changes in atmospheric concentrations of air pollutants, which may vary due to complex, non-linear atmospheric chemistry as well as long-distant transport. The subsequent public health impacts—premature mortality and morbidity—may differ across socio-demographic groups. Health impacts may also vary based on weather, interactions with other pollutants, and self-mitigation (defensive investments) by potentially vulnerable populations.

When EPA produces an ex ante RIA, it draws from a now extensive literature on the atmospheric chemistry, epidemiology, and economics of air pollution in order to characterize the expected benefits and costs of the regulation. While these analyses are often complicated and elaborate, the description of the world without the regulation, e.g., the counterfactual level of emissions and ambient air quality, are often arbitrary out of necessity given the ex ante nature of the analysis.

The advantage of the retrospective studies we summarize is that they provide more defensible counterfactuals to the regulations studied. It is, however, the case that academic researchers often focus on one or a narrow set of dimensions of a given rule for their assessment. This reflects feasibility constraints in terms of researcher time and resources, data availability, and, in many cases, the nature of the identifying variation the researcher aims to exploit. In short, the academic literature will rarely deliver a retrospective analysis of a regulation that is sufficiently comprehensive to serve as an ex post analog to the ex ante RIAs published by the EPA. At the same time, findings from retrospective analyses can strengthen key parts of ex ante analyses such as describing the behavioral response of regulated entities and identifying important health damages.

2.3. Selection Criteria for Inclusion in this Review

This review includes published ex post economics studies of federal air quality rules that use quasi-experimental methods or structural econometric approaches to develop realistic baselines against which to compare observed outcomes. As noted earlier, the focus is on papers that examine responses to specific regulations as opposed to broad programs, with the exception of the relatively large and important body of research that has used NA designation as an exogenous source of variation in regulatory stringency.[18]

18 Appendix A3 classifies individual studies according to the endpoints considered and the methods and data used in the analyses.

3. The Impact of Environmental Regulations on Stationary Sources of Pollution

An important element of the economics-oriented CAA literature involves papers that estimate the impact of specific environmental regulations on stationary sources of pollution. This literature includes the regulation of electric utilities under Title IV of the 1990 CAAA, which established a trading program to limit emissions of sulfur dioxide (the SO_2 allowance program), and under the NO_x budget program, which limited emissions of ozone precursors from electric utilities in the Eastern US during the summer months. It also includes California's Regional Clean Air Incentives Market, commonly referred to as RECLAIM, developed under federal guidelines for so-called 'extreme' NA areas, which focused on emissions of ozone precursors, including NO_x. Further, the literature includes the regulation of certain air toxics issued under section 112 of the 1990 CAAA, specifically the Cluster Rule, EPA's first multi-media regulation.

3.1. Sulfur Dioxide Cap-and-Trade Program[19]

To address the acid rain problem, the 1990 CAAA created a nationwide SO_2 cap-and-trade program with the goal of cutting SO_2 emissions from fossil fuel power plants to one-half their 1980 levels. Phase I of the program (1995-1999) covered the 263 electricity generating units with the highest SO_2 emissions. Phase II, starting in 2000, covered all fossil fuel generating units with at least 25 megawatts of capacity—virtually all utility-scale power plants in the country. A Phase II unit could voluntarily opt into phase I, and more than 100 units did so. Each Phase I unit received free emission allowances based on its average heat input over 1985-1987 and an SO_2 emission rate of 2.5 pounds per MMBTU.[20] Covered units were required to install continuous emission monitors, which enabled high-frequency reporting to the EPA. Excess allowances could be banked for use in a future compliance period or sold to another regulated unit (or a third party).

While the SO_2 program intended to provide flexibility for regulated units to deploy least-cost compliance strategies, some power generators faced restrictions on such discretion, e.g. requirements for local emission reductions mandated under other sections of the CAA. NSPS mandated pollution abatement technology (scrubbers) on coal-fired units built after 1977.

A secondary market for emission allowances emerged, primarily brokered by a small set of firms (Ellerman et al. 2000). Phase I units built a large allowance bank, reflecting

19 This subsection draws heavily from Chan et al. (2018) and Schmalensee and Stavins (2013).

20 The phase II emissions rate was 1.2 pounds per MMBTU.

expectations about future allowance prices under the more stringent second phase of the program. Starting in 2003, the prospect of new air quality regulations as well as a series of federal court decisions delivered a period of high and volatile allowance prices. Later, as new, more stringent regulations affected power plant SO_2 emissions and provided less compliance flexibility than under the Acid Rain Program, the cap-and-trade program ceased to bind on power plants. By 2012, allowances cleared at auction prices less than $1 per ton, well below the $1,000 per ton allowance prices of the mid-2000s.

The SO_2 program has been subject to extensive research, with a number of papers focusing on the early years (such as Carlson et al. 2000 and Ellerman et al. 2000) and some recent synthesis and review papers which combine ex ante and ex post papers (such as Schmalensee and Stavins 2013). The ex ante analyses all suggest large cost savings based on a comparison of the least cost solution of achieving the cap to the command-and-control uniform performance standard case. Carlson et al. (2000) note that this cost reduction reflected dramatic declines in their estimated marginal abatement cost functions for sulfur dioxide emissions resulting from changes in technology and low-sulfur coal prices over 1985-1995.

The only true ex post study of the program's benefits and costs is by Chan et al. (2018), which finds much smaller cost savings than predicted ex ante. In part, this is the result of decisions of several power plants—in concert with their state public utility commissions—to install scrubbers rather than comply by purchasing allowances and/or using low sulfur coal, a decision that Chan et al. estimate increased annual compliance costs by nearly $100 million. Focusing on 2002 as a Phase II year before the transition to a period of regulatory uncertainty and using a mixed logit model of the firm's compliance decision, the authors find that the SO_2 program reduced compliance costs by about $200 million (1995$) and increased public health benefits by roughly $170 million. Chan et al. examine a performance standard that delivers the same aggregate emission outcome as the Acid Rain Program in 2002, which had much higher emissions than the cap due to use of banked allowances. Thus, the cost-savings of the two instruments may be smaller than they would have been under the statutory cap for 2002. Chan et al. also find that the prevailing pattern of allowance trading—from western generating units in sparsely populated areas to eastern generating units in more densely populated areas—increases public health damages by about $2 billion relative to a no-trade counterfactual.

The Chan et al. paper builds on the insights in Muller and Mendelsohn (2009), which illustrated through an integrated assessment model how the location of an emission source relative to a downwind population could dramatically affect the monetized damages of a ton of sulfur dioxide emitted at that source. In their counterfactual analyses, Muller and Mendelsohn estimated that trading ratios, based on the relative damages associated with a ton of emissions for a pair of locations, could improve social welfare by nearly $1 billion per year compared to the ton-for-ton trading in the SO_2 program as implemented. However, such differentiation in cap-and-trade implementation raises questions about administrative feasibility and accuracy in estimating ratios, especially in the presence of a complicated atmospheric chemistry that could induce negative ratios for NO_x (Fraas and Lutter 2012).

One of the key factors in driving the low-cost compliance with the SO_2 caps was the availability of low-sulfur coal from Wyoming. With the deregulation of rail shipping, the Powder River Basin's low-sulfur coal became an appealing compliance strategy for many Midwestern coal-fired power plants. The price of coal, especially low-sulfur coal, fell over the 1990s and contributed to significantly lower compliance costs than expected in ex ante assessments of the Acid Rain Program. As Busse and Keohane (2007) show, however, the freight rail duopoly that emerged over this time period was able to price discriminate on the basis of environmental regulation and geographic location and secure some of the economic rents created by the cap-and-trade program. To investigate this, the authors employed a difference-in-differences empirical strategy that exploited the variation in regulatory status in the 1990s: Phase 1 plants covered by the cap-and-trade program starting in 1995 and a set of control plants still subject to conventional command-and-control regulations during the entire 1990-1999 study period. They accounted for the potential for railroad market power to influence the price for low-sulfur coal with shipping distances from coal mines to power plants.

While overall coal prices fell during the latter half of the 1990s, Busse and Keohane found that delivered prices rose for plants covered by Phase I of the SO_2 cap-and-trade program relative to those still operating under command-and-control regulation, and prices rose more at plants near a low-sulfur coal source. Overall, they estimate that railroads enjoyed an increase in annual producer surplus of more than $40 million, which represented about 15 percent of the economic surplus created by the cap-and-trade program.

Looking beyond welfare impacts, Ferris et al. (2014) study the employment impacts of the SO_2 cap-and-trade program on power plants covered by Phase I (1995-1999) of the program. The authors employ a difference-in-differences empirical strategy that creates the study sample's control power plants through propensity score matching. Thus, the estimator exploits variation over time (before and after the start of Phase I in 1995) and in regulatory coverage (Phase I versus non-Phase I). Regardless of whether compliance occurs at the plant or utility level, the authors find no statistical evidence of changes in employment under the program. Likewise, they find no employment impacts when focusing on various, specific compliance strategies. These results are consistent with the labor demands of pollution control compliance offsetting the extent to which compliance reduces labor through productivity or output effects.

3.2. NO_x Budget Program[21]

The efforts to employ a cap-and-trade program to reduce nitrogen oxide (NO_x) pollution emerged over two phases in the eastern United States. The initial phase, established in 1999, covered twelve states and the District of Columbia over the May-to-September "ozone" season. The NO_x Budget Program expanded the geographic coverage to large point sources in 19 states over 2003-2008. The design of the program—applying to large emission sources in select states over certain months of the year—has served as the basis for several studies to identify the causal impacts of the regulation. For example, a researcher may exploit seasonal and spatial variation, as well as annual pre- and post-regulation variation, to estimate the impacts of the program on regulated entities' compliance strategies (Fowlie 2010; Linn 2008) or employment impacts (Curtis 2018). Deschênes et al. (2017) exploit these design characteristics in a triple-differencing empirical strategy to estimate a reduction in NO_x emissions of about 40 percent in the summer months for sources in the states covered by the program after it started. This translated into about a 6 percent reduction in mean ozone concentrations and a 35 percent reduction in the number of high-ozone days during the summer months.

The significant reductions in emissions and ozone concentrations contributed to substantial public health benefits. Deschênes et al. employed the same strategy to estimate a reduction in premature mortality of about 2,000 individuals annually, primarily among the 75 and older population. They monetized these mortality risk reduction benefits at about $1.3 billion. A novel element of the Deschênes et al. analysis focuses on how regulations improving air quality can reduce the demand for and expenditures on pharmaceuticals, medical care, and related defensive activities. With high-frequency, spatially disaggregated proprietary data on health insurance-related pharmaceutical spending, they estimate large reductions in such defensive expenditures, on the order of about $800 million per year.

To characterize the welfare impacts of the NO_x Budget Program, Deschênes et al compile their monetized estimates of the benefits and compare them to a back-of-the-envelope estimate of the costs of the program. For the latter, they assume that the allowance price clearing in the market (on average about $2,500 per ton of NO_x) can serve as the upper bound on the abatement costs. The product of the average allowance price and their estimated NO_x emission reductions to produce an upper bound cost estimate of about $1.1 billion annually. Based on medication expenditure cost-savings and reduced premature mortality, they estimate annual social benefits ranging from about $1.5 to $2.1 billion (2015$). Overall, they conclude that the net social benefits of the NO_x Budget Program are positive.

21 This sub-section is based on Curtis (2018), Deschênes et al. (2017), Fowlie (2010), and Linn (2008, 2010).

Fowlie (2010) and Linn (2008) investigate two different compliance strategies by facilities covered by the NO_x Budget Program. Recognizing that a power plant's regulatory status—whether it was subject to economic regulation and hence can recover prudently-incurred capital costs or was deregulated—influences the decision to invest in pollution-control equipment, Fowlie develops a model of mutually exclusive compliance strategies that accounts for the capital and operating costs of various pollution-control technologies in evaluating the decisions made by power plant managers in the 2000-2004 period leading up to the implementation of the cap-and-trade program. Given the limits on observing all the factors that may contribute to a manager's compliance decision, Fowlie estimates a random coefficient logit model to account for unobserved heterogeneity in how managers respond to the impending regulatory regime. This approach also enables her to account for correlation in decisions across generating units and plants owned and operated by the same firm.

Fowlie finds that plants operating in deregulated / restructured electricity markets were less likely to select capital-intensive compliance options. She uses the estimated model to simulate several policy counterfactuals that remove the asymmetric economic regulation that distorts the compliance equipment investment decision. While shifting to a common economic framework—all regulated or all deregulated—does not meaningfully influence aggregate compliance costs, it does affect the location of NO_x emissions. Given that economically deregulated power plants operate primarily in high-ozone concentration areas (northeast and mid-Atlantic regions), the current mixed approach to economic regulation results in higher NO_x emissions in potentially high-damage areas than a single economic regulatory environment counterfactual. [22]

Fowlie's work also shows how an econometric model that estimates technology adoption decisions—accounting for this heterogeneity in economic competition—can dominate an ex ante engineering cost model. Fowlie employs a detailed engineering model developed by the Electric Power Research Institute for the costs of various abatement technology options and uses these cost estimates in her mixed logit model of technology choice. As Fowlie demonstrates, however, the engineering estimates can also be used to directly identify cost-minimizing technology choices. The latter approach does a poor job of correctly predicting facilities' compliance strategies (also see Fowlie and Muller 2019). Specifically, they show that the ex ante engineering-based cost-minimization model correctly predicts 29 percent of regulated facilities' compliance choices. In contrast, the econometric model—building on the cost data and a richer representation of the economic environment—correctly predicts 79 percent of the compliance decisions. This illustrates the potential limitations to engineering cost models, which are commonly employed to estimate compliance costs of EPA regulations in the ex ante RIAs.

22 Fowlie does not explicitly estimate the public health benefits of the NO_x program, and the complex atmospheric chemistry associated with NO_x emissions, ozone, and fine particulates makes it difficult to translate changes in NO_x emissions into changes in pollutant concentrations, exposures, and health outcomes (Fraas and Lutter 2012).

In contrast to the capital investment compliance strategies studied in Fowlie (2010), Linn (2008) focuses on those facilities that opted against making major capital investments in abatement technologies, such as selective catalytic reduction, and instead pursued temporary boiler modifications as a way to reduce NO_x emissions. These modifications are considered relatively low-cost and can be reversed during the winter months when the NO_x cap-and-trade program does not operate. Linn limits his study sample to boilers that never invest in SCR or other major post-combustion pollution reduction equipment. The strategy exploits the staggered implementation of NO_x trading as well as its seasonal nature (summertime-only).[23] A key caveat to this analysis is that modifications are inferred, not observed. By excluding facilities with investment in new pollution control equipment, the paper assumes that reductions in NO_x reflect modifications, instead of new capital.

Linn finds that such modifications reduce NO_x emissions by 10 to 15 percent, at costs likely less than $2,000 per ton. He also notes how the cap-and-trade policy delivers incentives for emissions abatement through fairly modest process changes that would not likely occur under more prescriptive command-and-control regulations.

Curtis (2018) examines the labor market impacts of the NO_x Budget Trading Program. He also exploits variation across states and over time. In addition, he accounts for variation in the energy intensity of manufacturing industries, given the larger compliance costs associated with the more energy-intensive (and hence pollution-intensive) industries. He finds that the states covered by the NBP experienced a 1.3 percent decline in manufacturing employment (a loss of about 110,000 jobs in total) after the cap-and-trade program began, with larger percentage reductions in employment of nearly 5 percent in the most energy-intensive industries. In examining labor market flows, Curtis shows that the reduction in employment fell disproportionately on younger workers, with falling hiring rates contributing more to the employment impacts than increasing separation rates.

3.3. RECLAIM Cap-and-Trade Program[24]

The 1990 CAAA required those areas classified as "extreme" non-attainment for ambient ozone concentrations to implement "economic incentive programs" to reduce emissions of ozone precursors, such as NO_x. Given the extreme NA status for Los Angeles, the South Coast Air Quality Management District designed the RECLAIM, a cap-and-trade program covering NO_x emissions at 392 facilities in the greater Los Angeles area.[25] The program covered all private entities with at least four tons of annual emissions (public facilities, such as police and fire stations, were excluded).

23 The Ozone Transport Commission states along the East Coast started trading NO_x allowances in 1999 and were subsequently covered by the NO_x Budget Program starting in 2004.

24 This subsection is based on Fowlie et al. (2012), Fowlie and Perloff (2013), and Gangadharan (2004).

25 The RECLAIM market also covered sulfur dioxide emissions at 41 facilities. Most RECLAIM research has focused on the much larger NO_x cap-and-trade RECLAIM program.

These RECLAIM facilities represented about two-thirds of the area's NO_x emissions from stationary sources. The non-RECLAIM sources of NO_x emissions operated under command-and-control regulation. RECLAIM-covered facilities could buy and sell emission allowances, but they could not bank them for use in a future year. In addition, RECLAIM established two zones—coastal and inland—and prohibited the sale of allowances from the inland zone to the coastal zone.

The early years of the program witnessed allowance allocations that did not bind on the regulated firms—perhaps reflecting the political economy of easing regulated firms into a new program. As a result, the lax emission cap resulted in low allowance prices before 1999; with prices increasing to about $2,000 per ton in January 2000 before jumping to more than $120,000 per ton in March 2001. Fourteen power producers exited RECLAIM in 2001 and agreed to pay a non-compliance fee and to comply with conventional technology standards on existing generating units by 2004. These units rejoined a revamped RECLAIM in 2007.

Although allowance prices spiked during the 2000-2001 California electricity crisis as power generation within the RECLAIM region increased well above past levels, the RECLAIM program delivered significant NO_x reductions. Fowlie et al. (2012) evaluated the performance of the RECLAIM program by matching RECLAIM-covered sources with similar facilities in nearby non-attainment areas in the state and examining the change in emissions over time. While both RECLAIM and non-RECLAIM sources in their sample experienced falling emissions, they estimate that RECLAIM facilities emissions fell about 20 percent relative to their comparison group over the 1990-2005 period. The spike in allowance prices during the California electricity crisis suggests that in the absence of the cap, emissions would have increased, potentially by significant amounts.

The authors also explore whether hot spots arose in disproportionately low-income and/or minority communities, a key concern about the environmental justice implications of market-based instruments. Exploiting census-block level socio-demographic data and facility-level emissions data, Fowlie et al. find no evidence of so-called "hot spots" or lower relative emission reductions in areas near RECLAIM facilities. By exploring the spatial distribution of abatement activity under a cap-and-trade program, such an analysis can complement the findings of the efficacy of the instrument in reducing emissions by illustrating the distribution of the benefits as well.

One of the attractive characteristics of cap-and-trade programs is that they can promote cost-effective emission abatement. A necessary condition for delivering on this promise is that use of allowances by regulated firms to demonstrate compliance is independent of the initial allocation of emission allowances.[26] Fowlie and Perloff (2013) examine whether the independence condition holds in the context of the RECLAIM

26 Building on the work of Coase (1960), a number of applied theory papers have raised the possibility that transaction costs (Stavins 1995) or market power (Hahn 1984) could undermine this independence condition and reduce the cost-effectiveness of cap-and-trade programs.

program. Specifically, they exploit a distinctive design feature in RECLAIM—the program randomly assigned covered sources to one of two overlapping allowance allocation cycles. With the emissions cap decreasing over time (becoming more stringent to limit pollution), the RECLAIM program varies in the facilities-level allowance allocations both across facilities and over time. That is, two otherwise-equivalent facilities would receive different allowance allocations if they were covered by different allowance allocation cycles. While they find a positive correlation between allowance allocations and emissions in the cross-section, once they instrument for the allocations based on the variation induced in the allocation cycles, they find no statistically significant relationship between allocations and emissions, consistent with the independence condition.

3.4. Air Toxic Regulations Under the 1990 CAAA

EPA's approach to regulating air toxics changed significantly under the 1990 CAAA. Prior to adoption of the 1990 CAA Amendments, the Agency had authority to regulate individual air toxics based on their specific health risks. However, EPA had great difficulty negotiating the pollutant-specific, source-specific rulemaking process. From 1970 to 1990, EPA regulated only seven air toxics emitted by a small number of sources. The 1990 amendments adopted a technology-based approach to limit air toxics and focused the industry-specific regulations on the full range of the industry's air toxics emissions, rather than setting standards one chemical at a time.[27] The adoption of this technology-based approach substantially simplified the rulemaking process and paved the way for the agency to consider potential cross media pollution transfers in an integrated manner. The intent of MACT standards was to raise the laggards to the level of the best performers in the industry [defined as the level of control achieved by the best performing 12 percent of plants in the industry], rather than force the adoption of exotic and unproven technologies.[28] Between 1994 and 1998 the EPA issued 21 sets of MACT standards, including standards for 13 manufacturing industries. In its second report to Congress on the Benefits and Costs of the CAA, EPA (1999) reported that these standards would impose annual costs of $480 million in 2000.[29]

The MACT standard issued for the pulp and paper Cluster Rule is the most studied of EPA's air toxics regulations. It applied differentially to various sub-groups of pulp and

27 Technology-based standards were a core piece of the 1977 Clean Water Act (CWA), and their implementation over the 1980s was widely viewed as achieving substantial reductions in the industrial discharge of toxics in water. With the 1990 CAA Amendments, Congress hoped to replicate the CWA experience with a widespread initiative to reduce toxic air emissions.

28 At the same time, the EPA has the authority to adopt more stringent standards beyond the MACT requirements taking into account a variety of factors, including technological and economic feasibility, cost and effectiveness, and the expected additional risk reduction achieved. In practice, EPA has generally adopted emissions standards keyed to the basic MACT requirements (the so-called MACT floor).

29 EPA based this cost estimate on ex ante estimates developed as part of the rulemaking process.

paper plants and required reductions in benzene and other VOCs at mills that used chemical pulping techniques. The mills that used mechanical pulping techniques or purchased pulp faced less stringent standards on air emissions.

The Cluster Rule also set discharge limits for water toxics, including dioxin and furans, for pulp and paper mills using chemical (chlorine) bleaching. Under pressure from environmental groups to address dioxin discharges after the discovery in the early 1980s of dioxin contamination linked to water discharges from these mills, EPA had already launched an initial program in 1988 to address dioxin discharges by requiring states to develop water quality standards for dioxin (Hanmer 1988). By the early 1990s, states had proposed dioxin discharge limits for most pulp and paper mills, and a number of them had begun to move away from elemental chlorine bleaching by converting to chlorine dioxide and hydrogen peroxide as bleaching agents. By 1995, pulp and paper mills had already reduced their dioxin and furan discharges by 70 percent (61 FR 36481).

In addition to the early 1990s state-based water quality standards, EPA agreed to a revised consent decree requiring it to issue dioxin and furan Best Available Technology (BAT) water discharge limits for bleaching pulp mills by 1995.[30] Despite major efforts to meet the deadline, however, EPA struggled with technical issues in developing the rule. In response to industry requests, EPA decided to combine the final BAT rule with its MACT air toxics rule—creating the so-called Cluster rule—to provide the pulp and paper industry with a coordinated set of regulatory requirements. The final Cluster rule was issued in April 1998.

Fraas and Egorenkov (2018) examine the performance of the MACT standards in reducing emissions of air toxics in 5 industries: petroleum refining, pharmaceuticals, printing and publishing, pulp and paper and wood furniture. Using 1993-2003 data from the Toxic Release Inventory (TRI) they estimate difference-in-differences models to examine the impact of regulations issued between 1994 and 1998 on emissions of organic hazardous air pollutants (HAPs), air toxics that are classified as VOCs. Two sets of plants are used for controls: for printing and publishing and pulp and paper the authors use plants in similar industries as controls: plywood plants are used as controls for pulp and paper mills and unregulated paper and web surface coating plants serve as controls for regulated plants in the printing and publishing industry. A "potpourri" control group consisting of plants in 6 industries that were later subject to MACT standards (primarily industries that manufacture metal parts) is also used.

The authors find a significant reduction of 60-90 percent in aggregate HAP emissions at printing and publishing plants and a smaller percentage reduction of 20-33 percent in HAP emissions from pulp and paper mills. Results are sensitive to the control group used and to how the periods "before" and "after" regulation are defined. For example, MACT standards for pulp and paper mills were finalized in 1998, with a compliance

30 Environmental Defense Fund and National Wildlife Federation v. Thomas, D.D.C. No. 85-0973.

deadline of 2001. The authors define 1995-97 as the "before" regulation period; however, a proposed MACT rule was issued in 1993 which also included water pollution regulations to reduce emissions of chloroform and dioxin, which are released when pulp is bleached. It is possible that mills altered their emissions prior to the final MACT rule, either in anticipation of the regulation, or as a by-product of complying with water pollution regulations that were issued at the same time as MACT standards. The authors address this issue using an event study approach, i.e., by allowing regulatory coefficients to vary by year; however, data limitations (described below) make it difficult to estimate individual year coefficients precisely.

Fraas and Egorenkov (2018) illustrate some of the difficulties of estimating the impact of environmental regulations on industrial facilities. In contrast to thermal power plants, whose emissions are monitored under Title IV of the 1990 CAAA, data for manufacturing plants are self-reported. The TRI is the source most commonly used for studies of individual regulations because it provides annual data; however, all firms do not report in all years, and only firms producing emissions in excess of a reporting threshold are required to report. By restricting their sample to plants that reported data in all odd-numbered years between 1993 and 2003 Fraas and Egorenkov are able to include fewer than half of 155 pulp and paper plants subject to MACT standards in their analysis, and only about 6 percent of the printing and publishing facilities in their models. Data limitations precluded the authors from any analysis of 8 of the 13 MACT standards issued during the period.

Gray et al. (2014) study the impacts of the Cluster rule on employment and wages using a subset of the plants that relied on mechanical pulping as controls for the plants using chemical pulping techniques subject to MACT standards.[31] The authors assemble an unbalanced panel of plants subject only to MACT standards or to both MACT and BAT standards along with a set of control plants for the period 1993-2007. To examine the impact of each type of standards on employment and wages, difference-in-differences models are estimated which control for wages, unemployment rates and per capita income at the county level, state dummies and plant age and ownership variables. Models are also estimated including plant fixed effects. The "before regulation" period is treated, alternately, as 1993-1997 and 1993-2000.

In models with plant fixed effects, there are no significant differences between MACT-only and control plants in total employment, employment of production workers or production hours worked. Total employment is 6-7 percent lower at facilities subject to both MACT and BAT regulations, implying between 50 and 70 jobs are lost at a plant of 900 workers, with 40 of these jobs lost among production workers. Wages are 5 percent higher at MACT-only plants, compared to controls, with no significant change at plants subject to MACT plus BAT regulations. Overall, the Gray et al. results imply that the water-related rules are the more costly ones.

31 Ninety-six of the 155 chemical pulping plants were also subject to best available technology economically achievable (BAT) standards to reduce water discharges of chloroform, dioxin, and furans.

An important issue is how firms complied with the Cluster Rule. Limits on discharges of dioxin and chloroform under the BAT provisions of the Cluster Rule were designed to reduce the use of chlorine bleach in the production of paper products. Elrod and Malik (2017) investigate whether plants subject to BAT regulations complied by reducing their output of bleached paper in addition to (or in lieu of) altering the bleaching process. Using the MACT-only plants as controls for the MACT-plus-BAT plants, the authors estimate triple difference models comparing the output of bleached v. unbleached products, before (1992-97) and after (1998-2002) regulation for treatment and control plants. They find that MACT plus BAT plants are more likely to reduce bleached products in their product mix vis a vis MACT-only plants. They also report evidence that MACT-only plants adjust their product mix toward bleached products.[32]

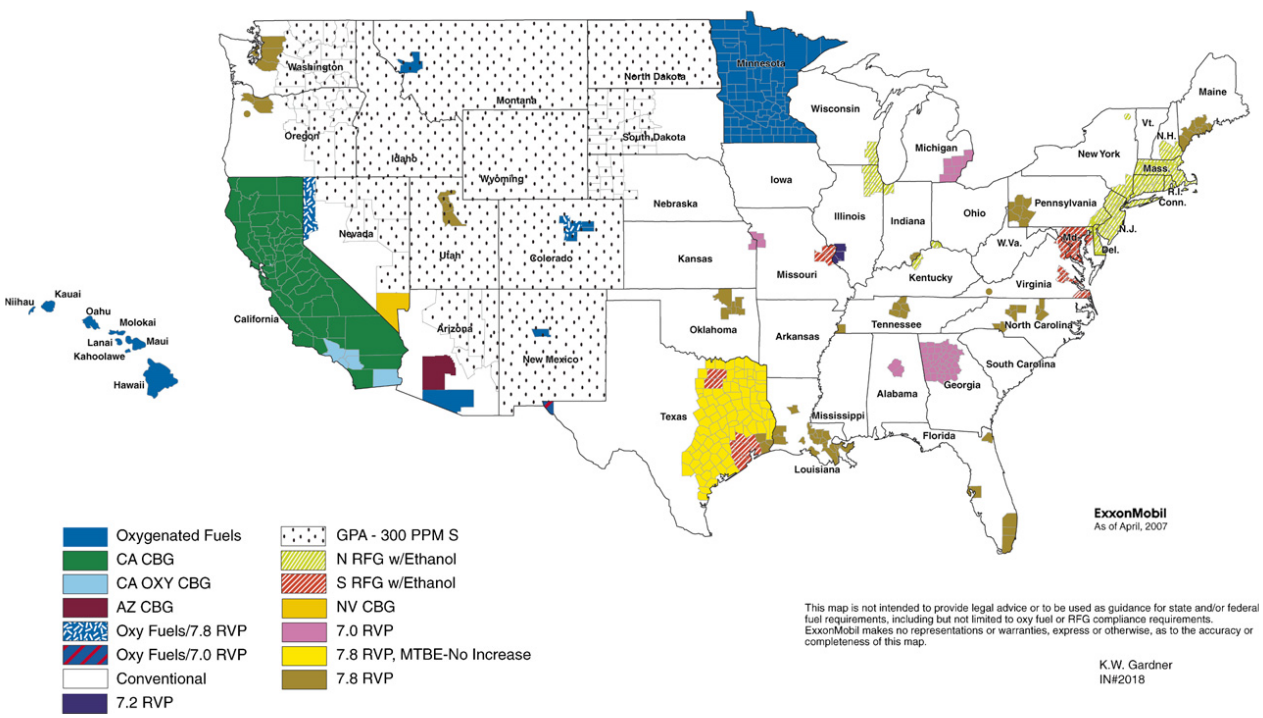
Much of the literature about the Cluster Rule has focused on the water pollution aspects of the rule and on forces that led to dramatic reductions in emissions of chloroform—and hence dioxin—by pulp and paper mills. As noted by Maynard and Shortle (2001), Popp et al. (2011) and Gray and Shadbegian (2015), the use of chlorine-free bleaching technologies predated the Cluster Rule and are likely to have been spurred by consumer awareness of the hazards of dioxin, a byproduct of the chlorine bleaching process. The literature does suggest that the air pollution standards issued as part of the rule were effective in reducing VOCs by about 30 percent (Fraas and Egorenkov 2018), although this represented a reduction substantially less than predicted by the RIA. Gray and Shadbegian (2015) report that reductions in air toxic releases were not as large as expected, with small and insignificant effects seen for the MACT-only plants, while MACT plus BAT plants saw marginally significant reductions. They found VOC reductions similar in magnitude to the ex ante predictions for OLS models but smaller—ranging from 15 to 36 percent—for fixed-effect models.

32 Results using propensity score matching indicate that plants subject to BAT regulations were 18.8–20 percent more likely to drop bleached products relative to unbleached products than the control group.

4. Literature on the Regulation of Mobile Source Fuel Content

Title II of the CAA requires the EPA to regulate fuels and fuel additives used in motor vehicles, motor vehicle engines, and nonroad engines and vehicles.[33] To reduce ground-level ozone and carbon monoxide the 1990 CAAA imposed requirements on gasoline sold in NA areas. Figure 2 (from Brown et al. 2008) shows differences in gasoline requirements across the United States in April 2007. Due to variations in state regulations, as well as difference in gasoline oxygenates, 17 different blends of gasoline were sold in the United States by 2004 (Brown et al. 2008). This fragmentation led to concerns that regulations had segmented the gasoline market, which could lead both to increased wholesale gasoline prices and increased market volatility. The fixed costs associated with producing different gasoline blends could also cause suppliers to exit some markets, reducing competition in these markets. The Renewable Fuel Standard (RFS) also affects the content of fuels sold in the United States. The literature evaluating mobile source fuel regulations has focused on three questions: (1) Are the regulations effective in reducing air pollution? (2) Have they led to health benefits? (3) What impact have they had on the market for vehicle fuels and the price of gasoline?

Figure 2. US Gasoline Requirements



Source: Fig. 2 of Brown et al. (2008).

33 The five general classes of gasoline regulations in 40 CFR Part 80 deal with Oxygenated Gasoline (Subpart C), Reformulated Gasoline (Subparts D&E), Detergent Gasoline (Subpart G), Gasoline Sulfur (Subparts H&O) and Gasoline Toxics (Subparts J&L).

The most studied fuel regulations are Reformulated Gasoline (RFG) regulations and regulations governing Reid Vapor Pressure (RVP). Both sets of rules target summertime ozone, which forms in the atmosphere when volatile organic chemicals (VOCs) combine with oxides of nitrogen (NO_x) in the presence of sunlight. To reduce ozone concentrations, one must limit the inputs to its production—either VOCs or NO_x. RVP regulations, which limit fuel volatility (and, hence, VOCs), are required in ozone non-attainment areas. RFG regulations are designed to reduce the VOCs and NO_x emitted when gasoline is burned. RFG regulations were initially required in severe ozone non-attainment areas and implemented in two phases, with an initial less-stringent standard over 1995-1999 followed by the more ambitious RFG rule taking effect in 2000. States were also given the option of opting-in to RFG regulations as part of their SIPs. Additionally, California implemented its own RFG standards, beginning in 1996. In the following subsections we discuss the effectiveness of the rules in reducing emissions, their health benefits, and fuel market impacts.

4.1. Effectiveness and Health Benefits of RVP and RFG Regulations

Auffhammer and Kellogg (2011) ask whether gasoline content regulations did in fact reduce ozone pollution. Specifically, they examine the impacts of RVP rules (Phase I and II), federal RFG standards, and California's gasoline content regulations on two measures of ozone pollution: (1) daily maximum concentration and (2) daily eight-hour maximum concentration. They note that regulations that don't specify which Volatile Organic Compounds (VOCs) refiners must remove may have little to no effect on ozone concentrations since the least cost way for refiners to meet these more flexible fuel content standards is by removing butane, which is less reactive in forming ozone than other VOCs. In contrast, California's gasoline content regulations may result in meaningful reductions in ozone because the regulations limit specific VOCs, like butane, that are highly reactive in forming ozone.

Auffhammer and Kellogg's results suggest that federal RFG and RVP regulations had little effect in reducing ozone formation, whereas California's gasoline content regulations did. They investigate this in two ways. The first is a difference-in-differences approach that compares monitor readings in the summer months in counties with increasingly stringent levels of federal regulation, or counties subject to California standards, to counties that had an RVP limit of 9.0 pounds per square inch. The second approach uses a temporal regression discontinuity (RD) design. Because the regulations affect all cars simultaneously and ozone decomposes overnight, changes in ozone can be detected immediately. The authors estimate monitor-specific treatment effects, controlling for monitor-specific weather shocks and monitor-specific time trends.

In the difference-in-differences analysis, the level of RVP regulation doesn't affect ozone. Federal RFG slightly reduces ozone (by about 3 percentage points), and

California Air Resources Board (CARB) standards result in the biggest reduction in ozone (around 9 percentage points). In the RD analysis RVP does not affect ozone. RFG has a negative effect in some places, but the authors show these negative effects are due to simultaneous reductions in NO_x emissions. CARB standards reduce ozone only in places that are VOC-limited (inland LA and San Diego).[34]

Marcus (2017) studies the health benefits of California's 1996 gasoline content regulations by examining the associated reductions in pollution and their impact on asthma-related hospital visits using data for the 1992-2000 period. She looks at NO_2, CO and SO_2 levels, averaged to month, zip code-level and then calculates the percent of days where pollution exceeds 75 percent of EPA's standard as an additional outcome. The paper compares pollution and asthma in zip codes near and far from a highway, before and after 1996.

Marcus uses two treatment variables. The first is the percentage of the population in a zip code that lives within 1 km of highway, which relies on within-zip code population density estimates from the 2000 Census. The second is an indicator for whether this percentage is greater than the median percentage. She tests for differential effects according to whether the zip code's centroid is most often downwind, upwind, or crosswind from nearest highway segment. The intuition is that treatment effects should be largest in downwind zip codes. She also tests for differential effects according to whether the zip code's centroid is near or far from a highway by whether the zip code has high or low traffic. The intuition is that for high traffic zip codes, the policy should have effects regardless of how close the zip code centroid is to a highway. But for low traffic zip codes, the policy should only have an effect in zip codes close to a highway.

Marcus finds that asthma hospitalizations decrease by 4.5 per 10,000 children, an 8 percent reduction relative to the group's pre-policy level. Treatment effects are not different for crosswind vs. downwind zip codes, but both these groups do have larger negative effects than the upwind zip codes. Impacts are also greater for high traffic zip codes. In sum, she finds that the policy reduced asthma hospitalizations by 1,449 per year, resulting in $13.2 million in avoided health expenditures. This suggests that more stringent regulations on gasoline had a significant impact on child health, as well as reducing asthma treatment costs.

34 Ozone is formed through a chemical reaction (similar to a Leontief production function) requiring NO_x, VOCs, sunlight and heat. Some areas have excess VOCs and are hence NO_x limited, while others have excess NO_x and are VOC limited. NO_x limited area ozone concentrations hence increase in NO_x, and VOC limited area ozone concentrations are increasing in VOCs.

4.2. Market Impacts of RVP and RFG Regulations and Oxygenated Fuel Regulations

The effectiveness of gasoline content regulations must be balanced against their costs. In addition to raising production costs, RFG regulations may segment the market for gasoline, thus giving producers the power to raise prices in isolated markets. Brown et al. (2008) estimate the effect of both RFG, during its initial phase, and RVP regulations on gasoline prices. They examine average weekly gasoline price from 1994 through 1998 and the volatility (quarterly standard deviation) of average weekly gasoline price in treated cities—cities subject to RVP or RFG regulations. They also examine prices in matched control cities, which were not subject to these regulations.

Brown et al. (2008) find that RFG increases gas price by about 3 cents per gallon on average, while RVP increases gas price by about 1 cent per gallon. The impact of RFG on the spot price of gasoline, however, varies across regulated cities by approximately 8 cents per gallon. The change in the number of suppliers in treatment and control cities helps to explain some of the variation in impacts across cities, although some is also due to the degree of isolation of the local market. There is little evidence that regulation increases price volatility. On balance, the authors provide evidence that some of the gas price increases occurred because regulations were spatially heterogeneous, allowing refiners who produced specialty fuels to exercise market power. The bottom line is that heterogeneous regulation of RFG and RVP is costly because of imperfect competition, but the cost is partially offset by spillovers to unregulated regions.

Chakravorty et al. (2008) explore the impact of heterogeneous gasoline content regulations on the price of gasoline and on the market power associated with a more fragmented gasoline market. Using annual, state-level data, they examine both the RFG program and Oxygenated Gasoline program (OXY).[35] Specifically, they estimate a three equation system to explain the wholesale price of gasoline, a refinery concentration index, and (for each program) a measure of regulation in the state relative to regulation in neighboring states. The latter is measured by the fraction of the state's population subject to the program minus the fraction of neighboring states' populations subject to the program.

The main findings are that if a state-imposed RFG or OXY requirements across its entire jurisdiction, gasoline prices are estimated to increase by 16 percent. Their results also indicate that segmentation of markets with RFG or OXY requirements increases the market power of refineries. This is relevant for policy as homogenizing the nation's gasoline content regulations would have two countervailing effects. If the national regulation was more stringent than the status quo, gas prices would increase because

35 Oxygenated Fuel Regulations require the addition of oxygenates (e.g., MTBE, ethanol) to gasoline to enhance the combustion process and lower emissions. In areas where wintertime carbon monoxide levels exceed federal standards, the 1990 CAAA requires the addition of oxygenates.

refiners would have to produce more expensive gasoline. But ending the segmentation of gas markets would decrease prices by reducing refineries' market power.[36]

Neither Brown et al. (2008) nor Chakravorty et al. (2008) employ standard quasi-experimental methods to estimate the impact of fuel content regulations on gasoline prices. Brown et al. (2008) match regulated cities to controls, although they rely on a restricted sample of regulated and unregulated city pairs that use different gasoline blends. Chakravorty et al. (2008) attempt to estimate the relationship between gasoline prices, refinery concentration and a spatial measure of regulatory impact using instruments to capture the endogeneity of regulation. Their unit of analysis is the state-year which may not be of sufficient spatial or temporal resolution for the research question. The studies do, however, suggest that heterogeneous regulation may have resulted in increases in gasoline prices.

The responses by refiners to these regulations raise questions about the appropriateness of the application of a difference-in-differences empirical framework and highlight the potential role for structural econometric analyses. For example, Sweeney's (2015) evaluation of reformulated gasoline regulations accounts for the imperfect competition characterizing regional refined petroleum markets. In estimating models of refineries' decisions to produce and market RFG he identified an important spillover to non-RFG markets: some refiners opted against producing RFG and the net result was an increase in supply and lower prices of conventional gasoline during the summer months in the non-RFG markets. A conventional difference-in-differences model that compares RFG market to non-RFG market prices before and after the implementation of the rule would erroneously over-estimate the price increase of RFG by failing to account for this spillover from the "treated" markets with the RFG regulation to the "control" markets without RFG requirements.

Using data from 1994 to 2003, Sweeney estimates refinery-level costs to produce gasoline subject to applicable fuel content regulations. He finds that gasoline prices in RFG regions are about 7 cents per gallon higher than they otherwise would be. This price change translates to a $25 billion reduction in consumer surplus from 1995 to 2003 ($2.85 billion per year). Since some refiners opt against producing RFG and reallocate supply toward unregulated regions, the gasoline price in unregulated regions decreases by about 2 cents per gallon, resulting in an $11 billion increase in consumer surplus in these regions. This also illustrates how structural models permit an explicit examination of the interplay of market structure and regulatory implementation, which can be important in a variety of air quality contexts in which the regulated sources operate in imperfectly competitive markets.

36 Muehlegger (2006) estimates a structural model of refinery production to estimate the effect of regulatory heterogeneity on gasoline prices in California, Chicago, and Milwaukee. He finds that, if these regions had used the federal RFG standard, 72-92 percent of the increase in gasoline prices from local refinery outages would have been reduced.

4.3. Renewable Fuels Standard (RFS)

The RFS requires the blending of renewable fuels with gasoline and diesel, with the dual objectives of reducing the carbon intensity of transportation fuels and enhancing US energy security. The revision to the RFS in the 2007 Energy Independence and Security Act set ambitious annual targets for biofuels, ramping up from 9 billion gallons in 2008 to 36 billion gallons in 2022. Within the aggregate annual targets, the law creates targets for sub-categories as a function of technology and carbon intensity—cellulosic ethanol (60 percent reduction in carbon emissions than a benchmark petroleum-based fuel), biodiesel (50 percent), advanced (50 percent), and conventional (20 percent). Any biorefinery in operation before December 2007 could satisfy the conventional biofuels requirements regardless of its carbon intensity.

EPA converts the national annual targets into a renewable volume obligation for petroleum refiners and importers of gasoline and diesel based on their proportional shares of the US transportation fuel market. Blending biofuels with gasoline and diesel generates tradable credits, called Renewable Identification Numbers (RINs). Petroleum refiners and importers must acquire these RINs and surrender them to EPA to demonstrate compliance with their renewable volume obligation.

Lade et al. (2018a) conclude that EPA's biofuel mandates have been overly ambitious, as they far exceed the economically feasible levels, especially for liquid cellulosic fuels. As a result, the EPA has been forced to reduce its cellulosic mandate since 2011. More importantly, it became clear in 2013 that the mandates would breach the blend wall—the maximum amount of biofuel that can be mixed with gasoline and used in regular vehicles (10 percent).[37] As a consequence, EPA has been forced to reduce its overall mandates. These adjustments, and the fact that the mandates are set each year instead of for multi-year periods, have created significant uncertainty for fuel producers. This uncertainty can be seen in the market for RINs. Annual announcements of renewable fuel mandates (and their anticipation) have led to extreme volatility in RIN prices as reflected in comparing the time series of RIN prices plotted against annual EPA mandate announcements and announcements of mandate adjustments.

Lade et al. (2018b) also examine whether EPA-announced reductions in ethanol mandates reduced biofuel tradeable credit prices (RINs) and the stock prices of advanced biofuel and biodiesel firms. They exploit the fact that 20 percent of a firm's RIN obligation can be met with RINs generated in previous years (banking). Firms are allowed to borrow RINs against a future compliance year only once. Specifically, the authors conduct an event study in which they regress the logarithm of first-differenced RIN prices on the logarithm of first-differenced fuel futures prices (crude oil, soybean

37 National ethanol consumption can increase beyond the blend wall only if consumption of 85 percent ethanol fuel (E85) increases or if biodiesel consumption increases. E85 can be used only in flex-fuel vehicles and requires dedicated fuel pumps at gas stations. Biodiesel is expensive to produce.

oil, and ethanol), flexible time variables, and event indicators using data for the period January 2012 to May 2014.[38] The event indicators are intended to capture the unanticipated impact of the events on future compliance costs, net of adjustments in fuel markets. The authors also regress the logarithm of first-differenced commodity futures prices on the logarithm of first-differenced US stock market indices, time controls, and event indicators. Lade, et al. (2018b) estimate a similar specification with the logarithm of first-differenced stock market prices of biofuel firms as the dependent variable.

They show that RIN prices increased in 2013 as mandates forced ethanol consumption closer to the blend wall. In August 2013, the EPA's 2013 final rule hinted that the 2014 total mandate would be reduced because of the market's limited capacity to consume gasoline containing more than 10 percent ethanol. This announcement reduced RIN prices by about 30 percent over the next three days, which translates to a $7 billion reduction in the value of the 2013 RIN market. Two subsequent events—a leak of the 2014 proposed rule and the official release of the 2014 proposed rule—are associated with smaller decreases in RIN prices. There are small changes (1-2 percent) in commodity futures prices coincident with some of the three events.

Stock prices of firms producing corn ethanol were not significantly affected by any of the three events. However, firms producing more expensive biofuels that would have been increasingly produced in the future had the mandate continued to increase saw their stock prices decrease by about 5 percent following the 2014 proposed rule official announcement.

The message from Lade et al. (2018b) is that regulatory uncertainty is costly for firms on the technological frontier and creates volatility in tradeable permits markets. The authors recommend more communication between regulators and regulated firms to reduce RIN price volatility. They also recommend a price ceiling and floor for RINs.[39]

A recent set of papers studies the pass through of the Renewable Fuels Standard into fuels prices. As a tradable performance standard, the RFS effectively taxes petroleum-based fuels (by requiring the manufacturer of these fuels to purchase RINs) to subsidize biofuels (that generate the RINs). Given that the retail product—e.g., gasoline blended with ethanol—is a mix of both the implicitly taxed petroleum product and the implicitly subsidized biofuel, the net effect on prices faced by consumers depends on the composition of the fuel and the competitiveness of the retail fuel markets. Lade and Bushnell (2019) study pass-through for E85, which is a transportation fuel containing 51 to 83 percent ethanol, based on transactions from about 500 gas stations in the United States from January 2013 to June 2016. Given the very large fraction of subsidized biofuels comprising E85, the net effect of the RFS should be to subsidize E85

38 The three events of interest are EPA's 2013 Final Rule, a leak of the 2014 Proposed Rule and the official release of the 2014 Proposed Rule.

39 Currently, there are limited provisions for a price ceiling and floor but they are difficult to use.

relative to conventional gasoline. They find that 50-70 percent of the subsidy is passed on to consumers, albeit with a lag of one to two months. They also offer evidence that market structure affects the speed and magnitude of the pass through.

Further, Li and Stock (2019) study pass through for E85 as well as E10, which is gasoline with as much as 10 percent biofuel content and has a much larger market share. Their analysis focused on the state of Minnesota over the period 2007-2015. They show that passthrough for the more popular E10 is 100 percent after a lag of one month. For the smaller market for E85, they find pass through rates consistent with Lade and Bushnell (2019) on the order of 0.53 averaged across the state. The heterogeneity in their results is interesting, as they show almost complete passthrough in the Twin Cities (with a more competitive market) than outside the Twin Cities. Knittel et al. (2017) use variation in RIN prices during the period 2013-2015 to study pass through to US wholesale and retail prices. Pooling over six fuels, they find almost complete pass through of RIN prices two days after an unexpected shock in RIN markets. In contrast to the previous findings, Knittel et al. (2017) find little to no passthrough of variation in RIN prices to retail E85 prices. What this suggests is that petroleum refiners recover the cost of RINs in other ways. We note that this is inconsistent with the findings by Lade and Bushnell (2019) and Li and Stock (2019). The difference is in identification of the effects. While Knittel et al. (2017) look at national data over a relatively short period, the other two papers use much more disaggregated gas station level data from the upper Midwest over longer (and more recent) periods.

5. Literature on Attainment Status Under the CAA

In addition to studying the costs, benefits and unintended consequences of specific rules, the literature on the CAA has studied the effect of non-attainment status on air quality and economic activity. Beginning with the 1970 CAA, EPA established National Ambient Air Quality Standards (NAAQS) for criteria air pollutants to protect human health and welfare. To implement the NAAQS, states and tribes are required to identify NA areas and to prepare State Implementation Plans (SIPs) to assure attainment and maintenance of the standards in their jurisdictions. For NA areas, SIPs are to include provisions to reduce emissions from both stationary and mobile sources. Demonstration of attainment must be supported by approved air quality monitoring data in urban and rural areas supplemented where needed with modeling or other information characterizing local air quality. Both stationary and mobile sources are covered by the demonstrations. When EPA sets a new NAAQS or revises an existing one, the process is repeated and a new designation is required.

Since NA status is, effectively, imposed on counties by the EPA and requires them to adopt measures to achieve compliance with the NAAQS, it represents an exogenous source of variation in regulatory stringency. This has led to a substantial literature examining the impact of the CAA on various outcomes—including ambient air quality, health benefits, production costs, labor markets effects, and the location of manufacturing plants—all using NA status as an exogenous measure of regulatory stringency. It has also been used to examine the impact of the CAA on manufacturing employment, plant investment and production costs.

5.1. Impact of Attainment Status on Emissions and Air Quality

If NA status under the NAAQS spurred counties to issue more stringent regulations to control emissions than attainment counties, we would expect air quality to improve more at monitors in NA counties than in attainment counties. This hypothesis has been tested for three of the criteria air pollutants—ozone, particulate matter and sulfur dioxide—using NA status under the 1977 and 1990 CAAAs. In all cases there is some evidence that air pollution declined more rapidly at monitors in NA (v. attainment) counties, and at monitors that were out of attainment, regardless of location, than at monitors that were in attainment.

In a pioneering article, Henderson (1996) examined the impact of NA status under the 1977 CAAA on ozone levels at 643 monitors in 332 urban counties over the period 1977-1987. Because he controlled for monitor-specific fixed effects, as well as temperature, employment and other time-varying factors that could influence ozone levels, the impact of county NA status on ozone readings was identified based on changes in attainment status over the period. He found that a change from NA to attainment status was associated with an 8 percent drop in the median of maximum daily July ozone levels and a 4 percent drop in mean July ozone readings. He also found an 11-13 percent drop in ozone readings across all counties between 1977 and 1982, suggesting that there was an across-the-board improvement in air quality, plausibly due to federal regulations.

An important question is whether Henderson's (1996) results hold for other criteria pollutants. Auffhammer et al. (2009) examine the effects of NA status for PM10 under the 1990 CAA Amendments on ambient concentrations of PM10 between 1988 and 2005. They first estimate Henderson's (1996) model, which examines the effect of NA status at the county level on PM10 at the monitor level. They then examine the effect of NA status at the monitor level on ambient concentrations measured at the monitor level. They find that NA designation at the county level had no effect on PM10 concentrations at monitors in NA counties; i.e., the average treatment effect of NA status was not significantly different from zero.

When Auffhammer et al. (2009) allow for heterogeneous treatment by type of monitor and county, they find that NA status at the monitor level had a significant effect on PM10 levels. Specifically, PM10 concentrations at monitors with concentrations above the national annual standard in the previous year dropped by 7 to 9 $\mu g/m^3$, equivalent to an 11-14 percent drop. Monitors in violation of the daily standard experienced two fewer days in violation of the daily standard the following year. They report similar treatment effects for monitors that were out of attainment in counties that were in attainment.[40] These results suggest that regulators focused their attention on monitors that were in violation of the standard, whether or not the monitors were in attainment or NA counties.

The results for the impact of sulfur dioxide NA status on ambient SO_2 are somewhat mixed. Greenstone (2004) examines the impact of SO_2 NA under the 1977 and 1990 CAAs using data for three six-year periods: 1975-80, 1981-86, and 1987-92. The question is whether NA status at the county level in year four of each period had a significant impact on the change in mean ambient SO_2 at the county level between years four, five and six of the period and year three, controlling for SO_2 concentrations at the beginning of the six-year period and covariates such as county employment, population and per capita income. The strongest impact of NA on reductions in SO_2 occurred in the third period studied: NA status in 1990 significantly reduced SO_2 concentrations by 7-11 percent in 1992.

If more stringent regulation in NA counties resulted in greater reductions of ambient pollution than in attainment counties, one would expect lower levels of emissions from highly polluting firms. Greenstone (2003) documents that this is the case for the iron and steel industry. Using the Toxic Release Inventory (TRI), he constructs annual cross section emissions data for PM, lead and volatile organic chemicals (VOCs) from iron and steel plants for each of the years 1987-97. He examines the impact of NA status for each of the three categories of pollutants in year t-1 on the percentage changes in emissions between t and t-1, controlling for time fixed effects. The percentage reductions in air emissions are 7.7 percent for lead, 2.4 percent for PM and 3.4 percent for VOCs. The percentage reductions in emissions to all media, as a function of NA status, are 7 percent for lead, 3.5 percent for PM and 5.6 percent for VOCs, suggesting that firms did not reduce air emissions by increasing emissions to other media.

Both Henderson (1996) and Auffhammer, Bento and Lowe (2009) identify the impact of regulatory stringency under the CAA based on changes in NA status. This assumes symmetry in impacts—a change from attainment to NA has the same effect (but opposite in sign) as a change from NA to attainment status. It also relies on a large enough number of counties changing status to identify the effect. [41]

All of the studies referenced here depend on sufficient monitoring data to investigate the impact of NA status on ambient air quality. Greenstone (2004) has data on SO_2 readings for only 62 counties (18 of which were designated NA) for the 1975-80 period, which may account for the lack of a significant impact of NA status on ambient SO_2 for this period. In contrast, data for the 1987-92 period cover 203 counties.

40 This is possible because non-attainment status is based on a three-year, geometric mean average of annual PM10.

41 Henderson (1996) notes that this is true for 18 percent of his counties; Auffhammer et al. (2009) report that it is true for 22 percent of their counties.

Data issues notwithstanding, the literature suggests that, over some periods, and for some pollutants, air quality improved faster in NA counties than in attainment counties. Auffhammer et al.'s (2009) result suggests that regulators were most concerned about lowering pollution levels at monitors that violated the NAAQS than at all monitors within an NA county. This raises issues about the placement of monitors—a topic which has received considerable attention in the recent literature (Grainger and Schreiber 2019; Grainger et al. 2019).

An important issue that this literature has not addressed is the effectiveness of CAA technology standards and other national level policies in reducing ambient air pollution. During the period covered by these studies, federal controls on automobile emissions, NSPS on industry and MACT controls on hazardous air pollutants were instituted throughout the country—in attainment as well as in NA areas. There is indirect evidence that these policies improved air quality. Henderson (1996) notes the significant downward trend in ambient ozone at all monitors in urban counties in the United States over the 1978-87 period. Auffhammer et al. (2011) note that the large reduction in NO_x emissions from motor vehicles in California was likely responsible for part of the observed decrease in PM10 at monitors within the state over the 1990-99 period. This reduction in NO_x emissions cannot be attributed to county-level policies. There is, however, no quasi-experimental evidence of the effect of these national-level policies on ambient air quality of which we are aware.

5.2. Impact of Attainment Status on Manufacturing Activity

The fact that regulations facing new plants were more stringent in NA than in attainment counties may have discouraged new plants from locating in NA counties. It could be argued that this was a necessary step to improving air quality in NA areas; however, it may also have raised costs for firms in certain industries, given the locational advantages of NA counties (e.g., proximity to markets and natural resources), affected manufacturing output in NA counties, and had unintended impacts on county employment levels. A first step in studying the impact of non-attainment status on manufacturing activity is to establish whether new plants in certain industries were less likely to locate in non-attainment counties.

The literature on the impact of non-attainment status on plant location focuses primarily on the impact of ozone NA under the 1977 CAA on industries that are major emitters of ozone precursors (VOCs and NO_x), including industrial organic chemicals, plastics, steel and petroleum refining. Using annual data from 1977 through 1987, Henderson (1996) examines the impact of being in ozone attainment for the past three years on the logarithm of the number of plants in a given industry in a county. Because many counties have no firms in a particular industry, he estimates Tobit models, including county fixed effects, an index of attainment for other criteria pollutants and the log of metropolitan area employment. Being in attainment with the ozone standard for three years increased the number of plants producing plastics (SIC 282 and 307) and engaged in petroleum refining (SIC 291) by about 6 percent and organic chemical plants (SIC 286) by about 9 percent.

Henderson's (1996) analysis illustrates the importance of controlling for county fixed effects in analyzing the impact of NA status on plant location. As noted, NA counties have many locational advantages, including proximity to natural resources and other input markets which, if not adequately controlled, would make more stringent environmental regulation appear to attract polluting industries. An earlier literature on the impact of environmental regulation on plant location (Bartik 1988, 1989; Levinson 1996; McConnell and Schwab 1990) found either small or no impacts of the stringency of environmental regulation on plant location. The literature estimated logit models of new plant location, albeit with limited controls for the desirable features of locations with more stringent regulations.[42]

Henderson (1997) and Becker and Henderson (2000) significantly advanced the literature on the impact of the 1977 CAA on plant births. Henderson (1997) estimates a fixed effects (Chamberlain) logit model using annual data for the period 1977-87 for selected, high-VOC emitting industries. Identification of the impact of NA status in the fixed effects logit model depends, however, on switches from NA to attainment status, and assumes that the impacts of such switches are symmetric. A superior approach is to model the impact of NA status on the birth of new plants using longer time periods, as is done by Becker and Henderson (2000).

Becker and Henderson (2000) examine the impact of ozone non-attainment status on the birth of manufacturing plants in high-VOC emitting industries. The authors use data from the Census of Manufactures to examine plant births over two pre-regulation periods (1963-67 and 1967-72) and four post-regulation periods (1972-77, 1977-82, 1982-87, 1987-92). They estimate conditional Poisson models to explain the number of plant births, by county and period, for each of four high-emitting industries and eight low-emitting industries. The models control for manufacturing employment and the real wage in the county, as well as time and county fixed effects. Ozone NA status at the beginning of the period is measured by a dummy variable, although the authors distinguish in some specifications between NA counties that were monitored and those that were not.

A county being NA in 1978, 1982 and 1987 reduced plant births by 45 percent in industrial organic chemicals, by 26-29 percent in metal containers, plastics and wood furniture.[43] These percentages apply to the entire post-regulation period. To illustrate, there were 134 births in organic chemicals in NA counties between 1967 and 1972 and 57 in attainment counties. In 1987-92 the model predicts that there would be 74 births

42 It should also be noted that most of these studies examine regulatory stringency at the state level, using indices of how "green" a state is, rather than non-attainment status under the CAA. McConnell and Schwab (1990) do use ozone non-attainment status but do not include county fixed effects.

43 No significant effects were found in the eight low-emitting control industries.

in NA and 57 in attainment counties. So the predicted share of births in NA counties fell from 70 percent to 56 percent over the period. Additional models suggest that the impact was greater and faster for corporate firms than for non-affiliated firms and greater in NA counties that were monitored v. others.

Using data on the births of high-VOC emitting plants in New York State 1980-90, List et al. (2003) confirm the Becker and Henderson (2000) results List et al. estimate a conditional Poisson model similar to Becker and Henderson's to explain the number of births in each of 62 counties during the 11-year period. They also use propensity score matching to find matches for the 172 treated (NA) county-year observations in the dataset.[44] Overall, the conditional Poisson model suggests that ozone NA status reduces the probability of a high-emitting plant locating in a county by 50 percent—within the ranges estimated by Becker and Henderson (2000) as well as List and McHone (2000). This translates into a loss of 0.2 high-emitting plants per year. The treatment effect on the treated and difference-in-differences estimates using propensity score matching vary greatly in magnitude and significance across the six matching specifications. Results using propensity score matching suggest a reduction of about 0.7 high-emitting plants per year (difference-in-differences estimator based on within-year, within region matching). The difference-in-differences estimator based on within-county matching implies a reduction of 1.3 high-emitting plants.

Also of interest is how NA status affected the growth of plants in high-emitting industries. Becker and Henderson (2000) investigate the impact of ozone NA status on the value of sales by plants in multiple industries over the period 1972-92 by regressing the real value of plant sales over time on county characteristics, plant age and corporate status, and year and county dummies. NA status is interacted with plant age. They find that new plants are significantly larger in NA than in attainment counties, especially for the years 1987 and 1992. They interpret this as indicating larger upfront investment by plants in NA counties due to environmental regulation: these plants are scrutinized more by regulators than plants in attainment counties, so it pays to concentrate negotiations (and investment) initially, rather than extending them over time.

5.3. Impact of Attainment Status on Employment and Earnings

A key concern of policymakers and the general public is that environmental regulation may reduce firm competitiveness and the demand for labor. Greenstone (2002) provides a particularly thorough investigation of the impact of NA status on

44 Using three different matching criteria and two calipers, they compute estimates of the difference in new dirty plants between treatments and controls (the treatment effect on the treated), as well as the difference-in-differences estimator (the difference between dirty plants and clean plants, for treatments minus the difference between dirty plants and clean plants for controls).

manufacturing activity and employment using data on all manufacturing plants, for the years 1967, 1972, 1977, 1982 and 1987. Specifically, he estimates the impact of NA status for carbon monoxide (CO), ozone, SO_2 and particulate matter (TSP) on the value of shipments at plants in high-emitting industries, as well as on the value of capital stocks and employment. The impact of NA status is identified based on three sources of variation: cross-sectional variation in NA status; changes in attainment status for a plant over time; and, a comparison of polluting v. non-polluting plants. Polluting plants are those in any one of 12 four-digit industries that are high emitters of any of the criteria air pollutants, or their precursors.

Greenstone thus asks whether the 1970 and 1977 CAAs affected manufacturing activity and employment both for new and existing plants. Under the 1970 and 1977 CAAs, SIPs were to control existing sources in NA areas; hence the analysis captures the impact of controls on existing plants, and on both plant births and deaths.[45] Each model controls for the impact of NA status for a particular criteria pollutant, holding constant NA status for other pollutants.

The results are most pronounced for CO and ozone non-attainment status. For plants in high-emitting industries in NA counties, NA for CO is associated with statistically significant declines in employment (16 percent) and the value of shipments (15 percent), both measured over a five-year period. Ozone NA status is associated with a statistically significant decline in employment of 4.9 percent for plants in high-emitting industries. Employment effects for ozone NA are largest in the pulp and paper, iron and steel, printing and plastics industries, as well as stone, clay and glass, ranging from decreases of 7 percent to 11 percent over a five-year period. CO regulation effects on employment are largest in iron and steel (–18 percent) and petroleum refining (–13 percent).

The implications of these estimates for the number of jobs lost are that environmental regulations resulted in a loss of 591,000 jobs over the period 1972-89 at high-emitting plants in NA counties (39,000 jobs per year).[46] To put this in perspective, total annual manufacturing employment was 17.4 million during the 1967-72 period. As Greenstone acknowledges, it is not possible to say whether some of the jobs lost in NA counties went to attainment counties. The corresponding figures for the declines in at high-emitting plants in NA counties are $37 billion and $75 billion (1987$), for the capital stock and the value of shipments, respectively. Both figures represent declines, over the 1972-87 period, relative to plants in attainment counties, but are not significantly different from zero.[47]

45 Of the 1,737,753 plant observations across four periods, 29 percent represent births, 27 percent deaths and 44 percent stayers.

46 95% CI = –118,400 to –1,065,200.

47 95% CI = $16.4 to –$89.6 billion for the capital stock and $27.4 to –$178 billion for the value of shipments.

Greenstone (2002) finds significant earnings losses in counties that were out of attainment for CO and ozone under the 1977 CAAA; however, these are losses in NA counties relative to counties that were in attainment. As with other analyses of the impact of NA, they recognize losses in NA counties but do not allow the researcher to draw policy conclusions about the impact of the CAA on employment throughout the United States: Were employment losses in NA counties made up by gains in manufacturing employment in attainment counties, or were there net losses in manufacturing employment as a result of the CAA? Addressing this question requires following workers displaced by the CAA to determine their subsequent labor market experience.

Walker (2013) combines information on the pollution status of plants under the 1990 CAAA with data from the Longitudinal Employer Household Dynamics (LEHD) files and the Longitudinal Business Database (LBD) to study the impacts of the 1990 CAAA on employment and earnings. He uses LEHD files for the four states that have data beginning in 1990: Illinois, Maryland, Washington and Wisconsin. The 3 million workers in manufacturing and the power generation industry in these states in 1990 are followed for the next 10 years. The LBD, which provides employment and payroll data at the plant level from 1975-2005, is used to examine pre-1990 trends in employment and earnings and for some of the baseline analysis.

The impact of ozone and PM NA are examined by classifying manufacturing plants in counties that are in NA for ozone or PM10 as polluting plants if they required a permit from EPA to operate. All manufacturing plants fall into one of four polluting sectors: emitting PM10 only; emitting ozone precursors only; emitting both; non-polluting. Data from the LEHD are aggregated to the cohort-sector-industry level (based on two-digit SIC). Data from the LBD are aggregated to the county-sector-year level.

Walker (2013) uses a triple-difference estimator to capture the impact of NA status on employment and earnings. The outcome (either earnings or employment) in polluting sector s of industry j in county c in year t is regressed on an indicator = 1 if the plant is in a county newly designated as NA for pollutant p and the plant is emitting pollutant p and t is after the 1990 CAAA went into effect. Variation in county attainment status, pollution status of the plant, and years before and after regulation are used to estimate the impact of the 1990 CAAA on employment and earnings.

In Walker's preferred specification, the average worker in a newly regulated plant experiences a present discounted earnings loss equal to 20 percent of annual pre-regulatory earnings (over a nine-year period, using a 4 percent discount rate). In the aggregate this loss is $5.4 billion, although there is great heterogeneity in the pattern of losses. Workers who remain with their pre-regulation firms suffer essentially no losses. Losses are born by workers who change firms—especially older, higher-paid workers. On average, workers who change firms suffer an earnings loss equal in present value to 120 percent of their pre-regulation annual earnings. Within this group, workers who change industries suffer larger losses than those who remain in the same industry.

Walker's study suggests that there were significant, unanticipated effects on employment and earnings due to regulations issued under the 1990 CAAA: employment in newly regulated plants was approximately 15 percent lower in 2000 than in 1990 and the earnings losses suffered by workers in these plants were significant. This raises the question of how these impacts could have been ameliorated and how they should be dealt with in the future.

5.4. Use of Attainment Status to Measure the Health Benefits of the CAAA

Exogenous variation in air pollution regulations and, hence, in ambient air pollution, presents a method for estimating the impacts of air pollution on human health—a major impetus for regulation under the CAA. In the epidemiological literature PM has most often been linked to premature mortality and morbidity (Pope et al. 2002), rather than the other criteria pollutants. TSP non-attainment status has been used as an instrument for changes in ambient particulate matter which, in turn, has been associated with premature mortality and losses in adult earnings.

Chay et al. (2003) use TSP NA status in 1972 to instrument for the change in TSP between 1971 and 1972, and then link the change in TSP to the change in adult mortality over the same period. The analysis is performed at the county level, using 231 attainment and 270 NA counties, and also by comparing the 85 attainment counties with TSP between 60 and 75 $\mu g/m^3$ and the 91 counties with TSP between 75 and 90 g/m^3 in 1970.

Chay et al. (2003) find a significant impact of attainment status on the change in TSP, but a weaker impact of attainment status on the change in mortality. NA status in 1972, measured by whether a county's average TSP reading in 1970 exceeded 75 $\mu g/m^3$, is significantly negatively related to the change in mean TSP concentrations. The impact of NA status on the change in mortality is not as strong; however, in the preferred specification the coefficients are –8.97 (5.02) for the full sample and –8.18 (7.40) for the second set of counties. Based on the second set of counties, the impact of a 1 $\mu g/m^3$ increase in TSP is to increase deaths over age 50 by 1.38 in 10,000 but the effect is not statistically significant.

Chay and Greenstone (2003) use a similar identification strategy to measure the impact of TSP on infant mortality. Here the results are more significant: as in Chay et al. (2003), NA status under the 1970 CAA accounts for virtually all of the reduction in average TSP between 1971 and 1972 (a 9-12 $\mu g/m^3$ reduction); however, in Chay and Greenstone (2003), the instrumented change in TSP is statistically significant and accounts for almost all of the observed decrease in infant mortality between 1971 and 1972. The validity of both sets of results depends on whether the decline in annual average TSP in NA counties between 1971 and 1972 can be viewed as the result of regulations issued under the 1970 CAA.

The use of attainment status under the 1970 CAA to instrument for the change in TSP between 1971 and 1972 raises important issues of timing: The TSP NAAQS, which declared counties with annual average TSP in excess of 75 $\mu g/m^3$ to be out of attainment, was not officially announced until April of 1971. States, which were responsible for formulating implementation plans (SIPs) to achieve the NAAQS, had to have these plans ready by January of 1972. It is therefore doubtful that regulations issued under the 1970 CAA could have caused the reduction in TSP between 1971 and 1972. It is easier to justify an identification strategy that uses NA status under the 1970 CAA to instrument for TSP later in the decade as in Chay and Greenstone (2005) and Isen et al. (2017). [48]

Isen et al. (2017) use NA status under the 1970 CAA to examine the impact of early life exposure to particulate pollution on earnings and labor force participation between the ages of 29 and 31. Exposure to particulate pollution in utero or during the first year of life may have lifelong consequences—either through physiological effects (on birthweight, lung function and the development of the cardiovascular system) or neurological effects (the development of the brain). To measure the impact of early life exposure, Isen et al. (2017) compare the outcomes of cohorts born in TSP NA counties just before and just after the 1970 CAA took effect, using cohorts born in attainment counties over the same periods as controls. Births occurring between 1969 and 1971 are considered births before the CAA took effect, while births between 1972-74 are designated as occurring after the CAA. The authors regress the outcomes of interest for cohorts born in year t in county c on annual average TSP in county c in year t, a vector of socioeconomic, demographic and climatic controls, county fixed effects, and birth-state by birth-year fixed effects. TSP is instrumented using a dummy variable equal to 1 for non-attainment counties after 1971.

To examine the adult impacts of early childhood exposure to particulate matter the authors use LEHD Data on workers in 24 states containing two-thirds of the non-farm workforce. These data provide the birth date and birth year of each worker and provide information on earnings and labor market outcomes for the worker, as long as the worker remains in one of the sample states. Isen et al. (2017) estimate that a 10 percent reduction in exposure to TSP during the first year of life (equivalent to 10 $\mu g/m^3$) increases annual quarters worked between ages 29 and 31 by 0.7 percent and mean annual earnings at these ages by about 1 percent. If the impact on earnings were to continue over the life cycle, it would result in a present discounted value of $4,300 (2008 dollars), using an annual discount rate of 5 percent.

Although the human capital impacts of early childhood exposure to particulates are small, they affect a large population. In the aggregate, the human capital benefits of reduced PM exposure represent a significant and potentially large category of benefits not previously considered in RIAs of air pollution control regulation. Isen et al. (2017)

48 Chay and Greenstone (2005) examine the effect of TSP on housing prices between 1970 and 1980 using a two-stage IV strategy in which non-attainment status in 1975 is employed as an instrument for TSP.

has contributed to a literature exploring the mechanisms by which such effects may occur (e.g., Voorheis 2017) and contributes to the literature on the long-term effects of early life exposure to pollution.

Several factors limit the use of NA status to measure the health benefits of air quality improvements under the CAA. The large drop in particulate pollution that occurred during the 1970s represents a significant reduction in lifetime exposure for infants, but not for adults, implying that it may not be a good way to measure the effects of chronic exposure to air pollution for adults. It is, therefore, not surprising that Chay and Greenstone (2003b) and Isen et al. (2017) focus on the impacts of early childhood exposure. It is also the case that NA status under the CAA is not a good instrument for short-term variation in air pollution; i.e., for measures of acute exposure, which have been linked in the epidemiological literature to premature mortality, hospital admissions and emergency room visits (would cite NMMAPS studies.) Economists have also used windspeed (Derugina et al. 2018) and airport flight schedules (Schlenker and Walker 2015) to instrument for air pollution in examining various health outcomes.

6. Conclusions

What have we learned about air quality regulation from ex post studies of the Clean Air Act? The literature we have summarized provides insights in several areas. The largest number of papers we reviewed speak to the impact of spatially differentiated regulations. A key feature of the CAA was to impose more stringent regulations in areas with poorer air quality. This is true of emissions standards for stationary sources, but also of requirements for cleaner gasoline. A key question is what were the costs of spatially differentiated standards and what were the benefits. The CAA is also notable for promoting market-based policies—specifically, cap-and-trade—to reduce emissions. A significant portion of the literature is devoted to analyzing the performance of pollution permit markets in the real world. Other papers examine the unanticipated consequences of regulations to reduce emissions; for example, situations where a regulation had no impact on ambient air quality. Finally, the literature has provided information about categories of benefits (e.g., medical expenditures and human capital benefits) not previously associated with improvements in air quality.

An important feature of the CAA was that it required states to impose more stringent regulations on counties declared out of attainment with the National Ambient Air Quality Standards and, in the 1977 CAAA, directly imposed more stringent emissions standards on plants located in non-attainment areas. This led the share of new plants in high-emitting industries to decline and also reduced employment in these industries in non-attainment, relative to attainment, counties. The value of shipments also declined in some industries. And, there is evidence that workers in regulated industries, especially those who changed firms, suffered significant earnings losses. At the same time, there is evidence that the ambient concentrations of ozone, particulate matter, and sulfur dioxide declined faster in non-attainment than in attainment counties. This raises several questions: Were the adjustment costs imposed on non-attainment counties by the CAA justified by the additional air quality improvements in these counties? What would have been the impact of imposing equally stringent standards on stationary sources in attainment counties? And, could some of the adverse impacts on workers have been mitigated through a program similar to Trade Adjustment Assistance?

The literature on reformulated gasoline also raises the issue of whether the costs of spatially differentiated standards are justified by the benefits. By 2004 there were over a dozen different varieties of reformulated gasoline sold throughout the United States to reduce ambient ozone pollution. The question is whether multiple varieties of gasoline, by segmenting the market, increased market power, thus raising the price and price volatility of gasoline. The literature suggests that this was the case; however, the unanswered question is whether the benefits of spatially varying standards exceeded the costs of those standards.

The CAA was responsible for launching national cap-and-trade programs to reduce sulfur dioxide (the SO_2 Allowance Program) and nitrogen oxides (the NO_x Budget

Program) as well as a NO_x trading program (RECLAIM) in Southern California. A market for renewable fuel (RIN) credits was also made part of the implementation of the Renewable Fuel Standard. The SO_2 Allowance Program has been widely heralded as the triumph of market-based instruments over command-and-control and was predicted, ex ante, to lead to large cost savings compared to imposing a uniform performance standard on electric utilities. The ex post literature suggests that the program led to cost savings compared to a uniform performance standard, although not as large as was predicted ex ante—due, in part, to the decision of some utilities to install scrubbers rather than switch to low-sulfur coal. There is also evidence that some of the potential cost savings were appropriated by railroads, who raised the cost of transporting low-sulfur coal to power plants.

An important issue in the design of permit markets is the impact of a market on the distribution of damages. While studies have estimated the benefits of trading SO_2 allowances at prices that reflect the marginal damages of different emitters, important issues remain about the administrative feasibility of this approach. A related question is whether markets in which permits trade one-for-one have led to "hot spots" (areas of high damages caused when purchasers of permits are located in areas where marginal damages are much higher than in areas where sellers of permits are located). Studies of the RECLAIM market in Southern California suggest that this was not a problem there.

The literature has also documented situations in which permit market design could be improved. In the case of the market for renewable fuel credits, which refiners were required to produce to meet the Renewable Fuel Standard, annual (rather than multi-year) announcements by EPA of the required credits led to volatility in the price of credits. Announcing renewable fuel mandates several years in advance, as was done under the SO_2 Allowance and NO_x Budget programs, would have aided in the functioning of the market. Arguably, price ceilings might also have improved market functioning in some cases, e.g., in the Renewable Fuels Standard and also in the RECLAIM program.

In addition to permit trading, another method of reducing compliance costs is to allow firms flexibility in meeting regulatory standards, rather than prescribing a technology standard. In the case of reformulated gasoline, there is evidence that flexible federal regulations which gave refiners latitude to choose which VOCs to remove from gasoline were not effective in reducing ozone levels. Refiners chose the cheapest option—removing butane—which is less reactive than other VOCs. In contrast, the more prescriptive rules issued by the California Air Resources Board did yield measurable benefits.

In terms of the benefits of the CAA, the retrospective literature has provided evidence about two categories of benefits—reduced medical expenditures and improved human capital—not previously associated with improvements in air quality. Retrospective analysis of the NO_x budget program provides evidence that the program delivered greater reductions in ozone-related mortality than originally estimated by EPA. The study also provides evidence that the program reduced medical expenditures, which had not previously been quantified as a category of benefits in an air pollution RIA.

In the case of human capital, there is a literature that documents the impact of early childhood exposure to fine particles (PM2.5) on brain development and on IQ. Isen et al. (2017) find that reduced exposure to particulate pollution during the first year of life results in higher earnings and probability of employment among young adults. This is an additional category of benefits from air pollution regulation that has been established by exploiting variation in exposure associated with attainment status under the CAA. Although the magnitude of these effects is small, they can potentially affect a large exposed population, resulting in large aggregate benefits from reducing ambient particulate matter.

Although we have learned much from retrospective studies of the CAA, there is much that we do not know about the CAA. Air quality has improved dramatically in the United States since 1970, but we do not know how much of these improvements are attributable to the CAA. Studies that demonstrate that air quality improved faster in non-attainment than in attainment counties do not estimate absolute reductions in air pollution. These studies often show a decline in air pollution in both attainment and non-attainment counties, but we do not know to what extent these declines are attributable to federal regulations such as tailpipe emission standards or New Source Performance Standards.

The other area in which we are ignorant is in terms of the costs of the CAA. There are few quasi-experimental studies that estimate the direct costs of complying with air quality regulations. Structural econometric models have been used to investigate the impacts of a regulation in cases where it is difficult to identify a control group necessary for conducting a quasi-experimental study. Such models explicitly account for an understanding of the production function of the firms covered by the regulation, the consumer demand for the products whose characteristics may change under a regulation, and the nature of competition in the market affected by the regulation. They can also provide a framework for exploring the dynamics of how firms respond to environmental regulations, including technological innovation as well as firm exit and entry. In modeling the impacts of a regulation on both consumers and firms, structural econometric models can provide welfare estimates of a regulation and counterfactual regulatory options. Of course, structural econometric models also face potential limitations.[49]

49 First, some scholars have reservations about the extent to which the assumptions in the structural model, as opposed to the data, drive the empirical results. Second, an analyst must exploit identifying variation in estimating a credible structural econometric model. The characteristics of the market, the regulation, and the availability of data may influence the extent to which this feasible in various regulatory contexts. Third, a structural econometric model of a fast-changing industry may not provide useful analysis of future regulations. Nonetheless, such an approach could compliment the quasi-experimental literature and address some of the limitations of quasi-experimental approaches.

Finally, the often narrowly focused approach taken in quasi-experimental, retrospective analyses of air quality regulations does not necessarily facilitate a broader understanding of the cumulative impacts of the Clean Air Act. Given growing interest among some stakeholders in reducing the cumulative burden of agency regulatory actions, aggregating the results of analyses—across various dimensions of a given rule and across the full suite of Clean Air Act—would illustrate the full costs and returns on those investments in the nation's air quality program. Such an effort may also examine the potential interactions—both positive and negative—among regulations affecting common regulated entities. It may further enable a comparison of cost-effectiveness across regulatory approaches that could inform future refinements.

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Appendix

Table A1. Number of Non-attainment Counties under National Ambient Air Quality Standards

Table A1. continued. Number of Non-attainment Counties under National Ambient Air Quality Standards

1970 Clean Air Act · 1977 CAA amendments pass · 1990 CAA amendments pass

Pollutant	Standard	Year	Number of non-attainment counties
PARTICULATE MATTER	1971 - Total Suspended Particulates standard set (24-hrs 260 $\mu g/m^3$)	1972	296[a]
		1977	235
		1978	307[d]
		1982	176
	1987 - PM-10 (24-hrs 150 $\mu g/m^3$; annual 50 $\mu g/m^3$)	1992	74
		1997	81
		2002	75
	1997 - PM-2.5 (24-hrs 65 $\mu g/m^3$; annual 15 $\mu g/m^3$)	2005	208
		2019	14
	2006 - PM-2.5 (24-hrs 35 $\mu g/m^3$; annual 15 $\mu g/m^3$)	2009	121
		2014	122
		2019	40
	2012 - PM-2.5 (24-hrs 35 $\mu g/m^3$; annual primary 12 $\mu g/m^3$)	2015	20
		2019	18

Table A1. continued. Number of Non-attainment Counties under National Ambient Air Quality Standards