

Looking Back at 50 Years of the Clean Air Act[†]

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We synthesize and review retrospective analyses of federal air quality regulations to examine the contributions of the Clean Air Act (CAA) to the vast air quality improvements seen since 1970. Geographic heterogeneity in stringency affects emissions, public health, compliance costs, and employment. Cap-and-trade has delivered greater emission reductions at lower cost than conventional mandates, yet has fallen short of textbook ideals. Market power also influenced the CAA's benefits and costs. New benefit categories have been identified ex post, but specific technology requirements have not yet been rigorously evaluated. Comparisons of aggregate benefits and costs of the CAA are beyond present capabilities. (JEL D61, K32, Q51, Q53, Q58)

1. Introduction

1.1. Motivation for Our Review

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 focus of most air quality regulation from the states to the federal government and stimulated a broad-based and costly effort to

limit harmful air pollutant emissions across the United States. Far more than aspirational, the act included specific targets and timetables for action, and it empowered citizens with the right to sue government officials as well as regulated entities that failed to perform their duties.

Despite the near-tripling of gross domestic product since 1980 (figure 1), air quality across the United States has improved substantially. The US Environmental Protection Agency (EPA) reports that concentrations of

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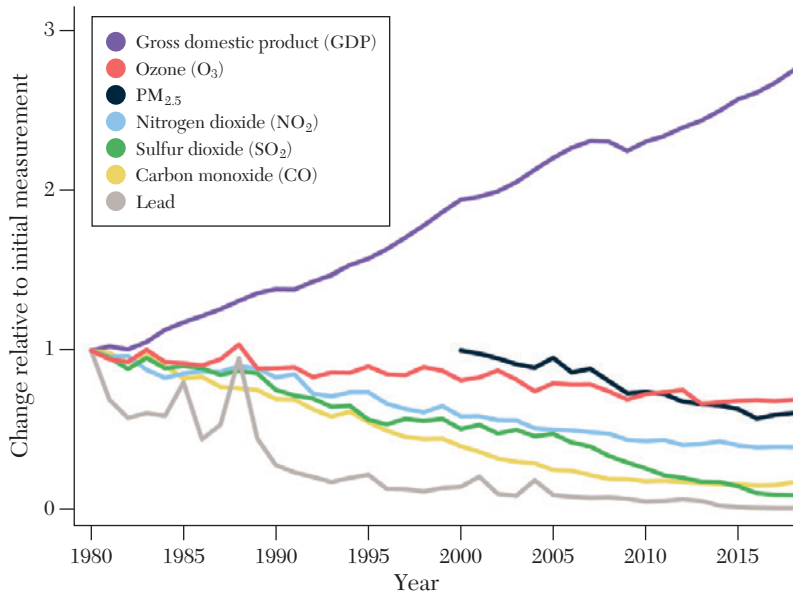


Figure 1. Changes in Gross Domestic Product and Six Common Air Pollutants, 1980–2019

Notes: The index begins at 1 in 1980, with the exception of fine particulate matter (PM_{2.5}), 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 (2020) and Environmental Protection Agency (2020).

the six most common air pollutants declined an average of 69 percent over 1980–2019. Fine particles declined 43 percent since 2000, ozone fell 34 percent since 1980, and lead decreased 98 percent since 1980 (EPA 2020). 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 results over the past 50 years beg the question of regulatory performance evaluation: what have been the causal economic, environmental, and public health impacts of the CAA?²

Pursuant to Executive Orders issued by Presidents Reagan and Clinton, the EPA has developed more than 100 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 Greenstone (2009)

¹Most of the epidemiological literature reports associations, rather than causal relationships, between air pollution and health. Currie and Walker (2019) summarize the recent economics literature that uses quasi-experimental methods to establish a causal relationship between air pollution and health.

²A major rule is one likely to result in “an annual effect on the economy of \$100 million or more” [Congressional Review Act: 5 U.S.C. §801(a)(1)(A)].

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.” As required by the 1990 CAA amendments, the 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 quality improvements are attributable to the CAA, and for the failure to disaggregate the analysis sufficiently by rule to determine whether 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 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 (both adverse and 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, and subpopulations). Further, a retrospective review might examine whether alternative rule designs could yield more effective

or efficient outcomes with fewer adverse consequences.⁴

The present review is best understood as a launching point for 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. The literature has focused on three questions:

- (i) What were the causal impacts of the CAA on emissions and ambient air quality?
- (ii) What were the health and other benefits attributable to CAA regulations?
- (iii) What were the costs of these regulations, including impacts on employment, market power, and the location of industry?

In practice, most retrospective analyses focus on a single aspect of a regulation, such as emissions reductions or job losses, and do not provide a comprehensive basis for assessing the costs, benefits, or distributional impacts of the CAA.

1.2. *Scope of Our Review*

Our paper differs from two recent reviews that assess particular aspects of the CAA. Schmalensee and Stavins (2019) examine the historical evolution of different policy instruments, and Currie and Walker (2019) conduct a broad-scale evaluation of evidence on the costs, benefits, and distributional impacts of the act. Our focus is principally on the methods used by economists

³For a detailed review of the EPA 1997 and 1999 studies, see Krupnick and Morgenstern (2002). More recently, the 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.

⁴See, for example, Schmalensee and Stavins (2013) for a review and synthesis of studies on the 1990 CAA amendments' Acid Rain Program and a discussion of the merits of a more ambitious sulfur dioxide emissions cap.

in quasi-experimental studies or structural analyses striving to provide causal answers to the three questions above. Although the EPA has developed some seasonally and regionally differentiated regulations, intentional experiments in regulatory design are generally not feasible. Neither is it possible to conduct randomized controlled trials looking backward in time. Thus, the preferred approach for examining regulatory performance is to rely on empirical strategies that exploit exogenous variation induced by the regulation, generally based on unique datasets.⁵ Economists have employed a variety of estimators—difference-in-differences, regression discontinuity, matching, and instrumental variables—to estimate the causal impacts of CAA regulations. Although these methods strive to mimic the degree of exogeneity achieved by randomized controlled trials, they mostly do not involve strictly random assignment to treatment or control groups, possibly resulting in (some) selection bias and its consequences.⁶ Our paper also differs from previous reviews by comparing the insights from retrospective analyses with insights provided by *ex ante* analyses.

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 the exception of studies examining the consequences of designating a county to be in nonattainment of the National Ambient Air Quality Standards (NAAQS), the focus is on published papers that examine responses to specific regulations, as opposed to broad programs. The broader

studies that have used nonattainment status as an exogenous source of variation in regulatory stringency yield insights on several important impacts of the CAA.

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 (NSPS), the New Source Review (NSR) program, and mobile source standards limiting tailpipe emissions—have not been examined retrospectively in a rigorous manner.⁷ Although these restrictions limit the ability of the present review to make broad statements about the contribution of the CAA to improving societal health and welfare, they do strengthen the basis for ascertaining the causal effects of a particular regulation. Arguably, too, this scope restriction helps identify what is not known about the performance of the CAA, which in turn suggests a roadmap for future research.

Major areas 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; others are more limited.

Following this brief introduction, section 2 describes the main features of the 1970 CAA and the 1977 and 1990 amendments, the nature of the pre-regulatory analyses

⁵Aldy (2014); Cropper, Fraas, and Morgenstern (2017); and Cropper, Morgenstern, and Rivers (2018) articulate the value of retrospective analysis of environmental regulation.

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

⁷Exceptions to this are papers by Gruenspecht (1982) and Nelson, Tietenberg, and Donihue (1993), which look at the impact of tailpipe emissions standards and NSPS on the turnover of the capital stock.

conducted by the 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 3 addresses the consequences of rules aimed at stationary sources, such as power plants and manufacturing facilities. Section 4 reviews studies of gasoline regulations and the Renewable Fuels Standard (RFS). Section 5 reviews regulatory outcome studies that rely on differences in regulatory stringency between areas classified as meeting the NAAQS and those that do not meet those standards—so-called nonattainment areas. In each section we discuss the impact of the regulations on emissions and ambient air quality, the health and other benefits, and the costs and economic impacts of the regulation. Section 6 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

2.1.1. 1970 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 the EPA to set NAAQS.⁸ Early on, the agency established NAAQS for six air pollutants in order to protect human health.⁹ The CAA authorized

the 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 the EPA has revised the NAAQS for several categories of pollutants over time in response to the latest public health research. (See appendix figure A1.) 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.

The CAA requires states to prepare State Implementation Plans (SIPs) for the NAAQS. For areas attaining the standard, a SIP would demonstrate how the state would ensure continued attainment of the standard, and for nonattainment areas, a SIP would show how the state would make progress toward meeting the standard. For the nonattainment areas, SIPs could include additional regulatory provisions, as necessary, to reduce emissions from stationary and mobile sources. States submit their SIPs to the EPA for review and approval.¹²

In addition to the NAAQS and SIP provisions, the 1970 CAA required the EPA to set uniform national emissions standards for new cars and light trucks. The law prescribed a 90 percent reduction in hydrocarbon, carbon monoxide (CO), and nitrogen oxide (NO_x) emissions by 1975 via these standards.¹³ The

ozone NAAQS, and adopted fine particle standards for particles smaller than 10 and 2.5 microns in size to replace the original TSP measure.

¹⁰42 U.S.C. 7409(b)(1).

¹¹*Whitman v. American Trucking Associations*, 121 S. Ct. 903 (2001), February 27, 2001.

¹²The EPA has some limited ability to enforce these requirements, including the authority to withhold federal highway funds. In addition, the CAA requires the EPA to develop a Federal Implementation Plan (FIP) for states that fail to develop an adequate SIP to attain and maintain the NAAQS.

¹³The 1975 deadline was extended (several times, including by the 1977 amendments), and ultimately the

⁸In general, the CAA requirements are prescriptive—limiting the EPA's discretion to consider benefits and costs or other factors in standard setting. As an important exception, the CAA does typically allow the consideration of factors like technical feasibility and cost (and cost-effectiveness) in setting technology-based standards.

⁹The EPA adopted NAAQS for SO₂, NO_x, total suspended particulates (TSP), CO, and photochemical oxidants. The EPA subsequently adopted an NAAQS for lead, replaced the photochemical oxidant NAAQS with the

law also mandated technology-based NSPS standards for new steel plants, oil refineries, and other major industrial facilities.

2.1.2. 1977 *Clean Air Act Amendments*

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

Further, the 1977 amendments imposed new technology-based NSPS that required a percentage reduction in emissions of sulfur dioxide (SO₂), NO_x, and PM from fossil fuel-fired power plants. The EPA implemented this provision by adopting a requirement—based on the performance of SO₂ scrubbers—that new and modified coal-fired power plants achieve a 90 percent reduction in SO₂ emissions.

2.1.3. 1990 *Clean Air Act Amendments*

In 1990, Congress amended the CAA a second time to address issues in bringing nonattainment areas into compliance with the NAAQS.¹⁴ Because major metropolitan

areas continued to encounter difficulty in meeting the NAAQS, the 1990 amendments included a classification system for ozone, carbon monoxide, and particulate matter nonattainment areas that reflected the severity of nonattainment 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 emissions standards for cars and light-duty trucks (“tier 1” standards) and gave the 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 nonroad sources (e.g., construction equipment and lawn and garden equipment) and provided additional authority to regulate fuel composition at the national level.

The 1990 amendments granted the EPA authority to use market-based instruments, such as cap-and-trade, to address air pollution. For example, the amendment’s acid rain provisions included a cap-and-trade program to reduce SO₂ emissions 50 percent below their 1980 levels. The amendments’ requirement for areas in “extreme” nonattainment for ozone to use market-based policies motivated Southern California to implement a cap-and-trade program targeting NO_x

EPA set a 1983 deadline for hydrocarbon and CO emissions and a 1985 deadline for NO_x emissions.

¹⁴The 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 the EPA to undertake a variety of studies and

reports, including the section 812 requirement that the EPA report to Congress on the economic impact (costs, benefits, and other effects) of the CAA.

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

emissions to demonstrate progress toward attaining the ozone NAAQS. The EPA has built on these experiences by implementing cap-and-trade and tradable credit programs for an array of air quality regulations.

The 1990 amendments also provided authority for the EPA to set technology-based Maximum Achievable 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 the 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 the EPA to revisit the MACT standards after eight 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 RFS and state “boutique fuels” programs. The Energy Independence and Security Act of 2007 revised the RFS. Over the years, in response to court decisions and new scientific, technological, and other developments, the EPA has established additional regulatory initiatives, including a shift from a photochemical

oxidant NAAQS to the ozone NAAQS and development of a standard for fine particles, the emergence of increasingly stringent NSR program requirements for sources in nonattainment, and prevention of significant deterioration areas. Other initiatives include the development of cross-state programs to limit SO₂ and NO_x emissions from power plants, which 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 versus Retrospective Analyses*

2.2.1. *Regulatory Impact Analyses of Air Pollution Regulations*

The EPA routinely conducts 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, required the EPA to undertake analyses of rules expected to have a major impact on the US economy. The Office of Management and Budget (OMB) provides guidance to regulatory agencies on the conduct of such analyses, and the EPA has issued peer-reviewed guidelines for benefit-cost analysis.

The goal of an RIA is to monetize the benefits and costs of a regulation, and of reasonable alternatives, to determine “whether the benefits justify the costs.” The RIA for a rule designed to reduce air pollution emissions must predict both future emissions from regulated firms or consumers in the absence of the regulation, and future emissions after the regulation is imposed. The impact of the change in emissions on ambient air quality is estimated using spatially detailed atmospheric chemistry models. Predicted changes in ambient levels of air pollution are then translated into health and welfare benefits using dose-response functions. In most air

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

¹⁷If there are fewer than 30 plants in an industry, MACT is defined in terms of the best-performing five facilities.

pollution RIAs, avoided premature mortality associated with particulate matter is the largest category of health benefits in monetary terms, and it often justifies the costs of the regulation. The costs of complying with a regulation are often estimated using engineering cost models associated with identified methods of pollution control.

When the EPA produces an ex ante RIA, it draws from an extensive literature on the atmospheric chemistry, epidemiology, and economics of air pollution in order to characterize the expected benefits and costs of the regulation. Although these analyses are often complicated and elaborate, the description of the world without the regulation—that is, the counterfactual level of emissions and ambient air quality—is often arbitrary, given the ex ante nature of the analysis. The associations between air pollution and health are based on epidemiological studies and do not represent causal relationships. And the costs associated with the regulation often focus on direct compliance costs developed from engineering cost models.

2.2.2. *Comparing Ex Ante and Ex Post Analyses*

The advantage of the retrospective studies we summarize is that they provide more defensible counterfactuals to the regulations studied. These studies provide causal estimates of changes in emissions and ambient air quality associated with a regulation. Some provide a causal link between regulations and health impacts, including premature mortality. Other studies focus on the adjustment costs or unintended impacts associated with a regulation. A regulation may cause firms to exit an industry or may discourage new firms from locating in a county. These impacts may affect employment and earnings. A regulation may amplify firms' market power. These effects are difficult to study in ex ante analyses, but are the subject of many of the articles we review.

What we should not expect from ex post analyses, however, is an estimate of the aggregate benefits and aggregate costs of a regulation. Although this is the objective of an ex ante RIA, academic researchers often focus on one component of the benefits or costs of a given rule for their assessment. This reflects feasibility constraints in terms of researchers' time and resources, data availability, and in many cases, the nature of the identifying variation the researchers aim to exploit. In short, the academic literature rarely delivers a retrospective analysis of a regulation that is sufficiently comprehensive to serve as an ex post analog to the ex ante RIA 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.

Throughout the paper we make three types of comparisons between ex ante and ex post studies. First, we identify examples in which ex post analyses estimate outcomes of interest that were previously estimated in the ex ante RIA. Second, we point out instances where an ex post study sheds light on benefits and costs not regularly examined in an RIA. Some of the studies reviewed here may provide insights for future RIAs, although, as discussed in OMB Circular A-4, analysts must decide on the priorities for quantifying and monetizing different benefits and costs. Finally, we compare the results of ex post studies with the ex ante economics literature. It is natural, for example, to compare ex post studies of the cost savings of a cap-and-trade program, relative to a uniform performance standard, with studies in the literature that predicted costs savings ex ante. Or to compare retrospective studies of compliance behavior of electric utilities with predictions in the industrial organization literature of how such regulated utilities are likely to behave.

2.3. Selection Criteria for Inclusion in this Review

This review includes 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. Most have been published in peer-reviewed journals. 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 nonattainment designation as an exogenous source of variation in regulatory stringency.

3. 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 CAA amendments, which established the SO₂ allowance program, a trading program to limit emissions of sulfur dioxide (the Acid Rain Program); and under the NO_x Budget Trading Program, which limited emissions of ozone precursors from electric utilities in the eastern United States 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 nonattainment areas, which focused on NO_x emissions as an ozone precursor. Further, the literature includes the regulation of certain air toxics issued under section 112 of the 1990 CAA amendments, specifically the Cluster Rule, the EPA's first multimedia regulation.

3.1. Sulfur Dioxide Cap-and-Trade Program¹⁸

A cap-and-trade system limits ("caps") the aggregate emissions of regulated firms 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 historical 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 their highest-valued use: covering those emissions that are most costly to abate and spurring firms to undertake the least costly reductions.

To address the acid rain problem, the 1990 CAA amendments created a nationwide SO₂ cap-and-trade program, with the goal of cutting SO₂ emissions from fossil fuel-fired power plants to one-half of their 1980 levels. Phase I of the Acid Rain Program (1995–99) covered the 263 electricity-generating units with the highest SO₂ emissions. Phase II, starting in 2000, covered all fossil fuel-fired 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

¹⁸This subsection draws heavily from Chan et al. (2018) and Schmalensee and Stavins (2013).

free emission allowances based on its average heat input over 1985–87 and an SO₂ emission rate of 2.5 pounds per one million British thermal units (MMBtu).¹⁹ Covered units were required to install continuous emissions 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).

Although the SO₂ program intended to provide flexibility for regulated units to deploy least-cost compliance strategies, some power generators faced restrictions on such discretion, such as requirements for local emissions reductions mandated under other sections of the CAA. In addition, NSR would mandate pollution abatement technology (scrubbers) for new coal-fired units.

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 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 required lower power plant SO₂ emissions and provided less compliance flexibility, the cap-and-trade program ceased to bind on power plants. By 2012, auctioned allowances cleared at prices less than \$1 per ton, well below the \$1,000 per ton allowance prices of the mid-2000s. The crash in the allowance prices reflected the overlapping of new regulations—initially the Clean Air Interstate Rule, followed by

the Cross-State Air Pollution Rule—that cover the same pollutant and emission sources as the SO₂ cap-and-trade program coupled with the absence of any discretion delegated to the EPA under the CAA to adjust the SO₂ emissions cap.

3.1.1. *Do Ex Post Estimates of the Costs Savings from Cap-and-Trade Match Ex Ante Estimates?*

The SO₂ program has been subject to extensive research, with several papers focusing on the early years (e.g., Carlson et al. 2000, Ellerman et al. 2000) and some recent synthesis and review papers that combine ex ante and ex post analyses (e.g., 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 reflects dramatic declines in their estimated marginal abatement cost functions for sulfur dioxide emissions resulting from changes in technology and low-sulfur coal prices over 1985–95.

The only true ex post study of the program's benefits and costs is by Chan et al. (2018), who find much smaller cost savings than predicted ex ante. In part, this is the result of a decision by 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 SO₂ program reduced compliance costs by about \$200 million (US\$(1995)) and increased public health benefits by roughly \$170 million relative to a counterfactual

¹⁹The phase II emissions rate was 1.2 pounds per MMBtu. The EPA also auctioned allowances representing a small percentage of the emissions under annual caps.

command-and-control performance standard. Chan et al. (2018) examine a performance standard that delivers the same aggregate emissions outcome as the Acid Rain Program in 2002, which had much higher emissions than the cap because of the use of banked allowances. Thus, the estimated cost savings of cap-and-trade relative to a performance standard may be smaller than would have been expected under the statutory cap for 2002. Nonetheless, the ex post estimated cost savings of the cap-and-trade approach fall short of the EPA (1992) ex ante estimated cost savings, projected to range between about \$700 million and \$1 billion annually (US\$(1990)).

Chan et al. (2018) 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—increased public health damages by about \$2 billion (US\$(1995)) relative to a no-trade counterfactual—that is, if each unit emitted SO₂ equal to its initial allocation of allowances. Although the EPA's ex ante assessment addressed regional variation in the costs and input market impacts of the SO₂ program (EPA 1992), it did not estimate regional variation in the public health benefits of reducing sulfur emissions.

Accounting for this geographic heterogeneity builds on the insights in Muller and Mendelsohn (2009). They illustrate, 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 estimate 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 (US\$(2000)) compared with the ton-for-ton trading in the SO₂ 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).

3.1.2. *Did the SO₂ Allowance Program Enhance Market Power?*

A major factor driving the low-cost compliance with the SO₂ 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 mid-western 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 employ a difference-in-differences empirical strategy that exploits the variation in regulatory status in the 1990s: phase I 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 1990–99 study period. They account for the potential for railroad market power to influence the price for low-sulfur coal with shipping distances from coal mines to power plants.

Although overall coal prices fell during the latter half of the 1990s, Busse and Keohane find that delivered prices rose for plants covered by phase I of the SO₂ 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 represents about 15 percent of the economic surplus created by the cap-and-trade program.

The trend toward economic deregulation that transpired in rail shipping also occurred in other industries, including to some degree the power sector. At the start of the Acid Rain Program, every coal-fired power plant in the country was subject to economic regulation by a state public utility commission. With state-level electricity restructuring occurring in a patchwork fashion across the country in the late 1990s, many power plants transitioned from cost-of-service rate regulation to competitive price-setting environments. This geographic and temporal variation in economic regulation provided opportunities to assess the Averch–Johnson (1962) effect in CAA contexts: does such rate regulation bias plants toward capital-intensive pollution control strategies?

To study the extent of the Averch–Johnson effect under the SO₂ allowance program, Cicala (2015) employs a matched difference-in-differences estimator that compares outcomes for pairs of power plants that were located in close proximity and consumed the same rank of coal but experienced different changes in their economic regulatory status after 1997. He finds that power plants divested from vertically integrated utilities as part of electricity-sector deregulation were less likely to install sulfur scrubbers than their regulated peers. Only three of about 200 divested generating units installed capital-intensive scrubbers in the first six years post divestiture, with a modest uptick in scrubber investment in later years among all power plants in response to more stringent requirements under the Clean Air Interstate Rule and Cross-State Air Pollution Rule.

3.1.3. *Employment Impacts of the SO₂ Allowance Program*

Looking beyond compliance costs, Ferris, Shadbegian, and Wolverton (2014) study the employment impacts of the SO₂ cap-and-trade program on power plants covered by phase I (1995–99) of the program. The authors employ a difference-in-differences empirical strategy using a sample of control power plants created 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 demand through productivity or output effects.

The first major cap-and-trade program under the CAA, the SO₂ allowance program delivered lower-cost emissions reductions than a conventional command-and-control program. These cost savings, however, fell short of savings identified in ex ante analyses. This reflects, to some extent, electricity sector regulations, which encouraged capital-intensive reductions in emissions, and also the lack of competition in markets for coal shipping, which allowed railroads to capture some of the potential cost savings.

3.2. *The NO_x Budget Trading Program*²⁰

The efforts to employ a cap-and-trade program to reduce nitrogen oxide pollution emerged over two phases in the eastern

²⁰This subsection is based on Curtis (2018); Deschênes, Greenstone, and Shapiro (2017); Fowlie (2010); and Linn (2008, 2010).

United States. The initial phase, established in 1999, covered 12 states and the District of Columbia during the May–September “ozone” season. The NO_x Budget Trading Program expanded the geographic coverage to large point sources in 19 states over 2003–08. The design of the program—applicable to large emission sources in select states over certain months of the year—has served as the basis for identifying 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 air quality, health, and regulated entities’ compliance strategies (Fowlie 2010, Linn 2008) or employment impacts (Curtis 2018).

3.2.1. *Impact of the NO_x Budget Trading Program on Air Quality and Health*

Deschênes, Greenstone, and Shapiro (2017) exploit those design characteristics 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, Greenstone, and Shapiro (2017) employ a triple-differencing empirical strategy—exploiting variation across regions, among seasons, and over years—to estimate a reduction in premature mortality of about 2,000 individuals annually, primarily among the 75-and-older population. This is more than three times the upper end of the estimated reduction in premature mortality from lower ozone and fine particulate matter in the ex ante EPA (1998b) analysis of this regulation.

A novel element of the Deschênes, Greenstone, and Shapiro (2017) 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 (US\$(2015)).

This revealed-preference measure of individuals’ actions to mitigate their risk of pollution-related morbidity differs in kind, and by method, from the morbidity impacts estimated in the ex ante analysis of this program. The EPA (1998b) relied on stated-preference studies, some of which were imperfectly aligned with specific health outcomes, to estimate morbidity benefits from reducing ozone and fine particulate matter pollution under the NO_x Budget Trading Program.²¹ The ex ante analysis did not address pharmaceutical expenditures and related defensive expenditures, although the EPA (1998b) estimated modest decreases, about 500 to 1,000 a year, in hospital admissions under the rule. Deschênes, Greenstone, and Shapiro (2017) examine hospital admissions in their ex post analysis, but do not identify statistically significant changes.

To characterize the welfare impacts of the NO_x Budget Trading Program, Deschênes, Greenstone, and Shapiro (2017) aggregate their monetized estimates of the benefits and compare them with a back-of-the-envelope estimate of the costs of the program. For the latter, they assume that the allowance price clearing the market (on average, about \$2,500 per ton of NO_x) can serve as the upper bound on abatement costs. The product of the average allowance price and their estimated NO_x emissions reductions produces

²¹ These were estimated to be \$200 million to \$400 million (US\$(2015)).

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 billion to \$2.1 billion (US\$(2015)).²² Overall, they conclude that the net social benefits of the NO_x Budget Trading Program were positive.

3.2.2. *Costs of Complying with the NO_x Budget Trading Program*

Fowlie (2010) and Linn (2008) investigate two compliance strategies by facilities covered by the NO_x Budget Trading Program. Recognizing that a power plant's regulatory status—whether it was subject to economic regulation and hence could recover prudently incurred capital costs or was deregulated—influences the decision to invest in pollution control equipment, Fowlie develops a model of choice among mutually exclusive compliance strategies that accounts for the capital and operating costs of various pollution control technologies. Specifically, she estimates a random coefficient logit model to evaluate the decisions made by power plant managers in 2000–2004—the period leading up to the implementation of the cap-and-trade program. The model accounts for unobserved heterogeneity in how managers respond to the impending regulatory regime and also allows for correlation in decisions across generating units and plants owned and operated by the same firm.

As further evidence of the Averch–Johnson effect, Fowlie reports that firms in rate-regulated markets that could raise power rates to recover their investment costs were more likely to select capital-intensive control methods. Plants operating in deregulated or restructured electricity markets

were less likely to select capital-intensive compliance options. Indeed, the adoption rate of selective catalytic reduction, the most capital-intensive NO_x control, in regulated markets was double the rate in the deregulated markets.

Fowlie uses her model to simulate the impact of electricity sector regulations on compliance costs. Examining the effects when all generating units behave as though they were regulated—or all units behave as though deregulated—she finds no significant impact on aggregate compliance costs. Shifting to a common regulatory framework does, however, affect the location of NO_x emissions. Given that economically deregulated power plants operate primarily in areas with high ozone concentrations (the Northeast and mid-Atlantic), the current mixed approach to economic regulation results in higher NO_x emissions in potentially high-damage areas than would a single economic regulatory environment counterfactual.²³

3.2.3. *Are Engineering Cost Estimates of Compliance Costs Necessarily Correct?*

Fowlie's work also shows how an economic 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

²² Deschênes, Greenstone, and Shapiro (2017) use a value of statistical life of \$1.78 million for persons aged 1–64 years, \$0.7 million for persons 65–74, and \$0.3 million for persons 75 and older (all in US\$(2015)).

²³ Fowlie does not explicitly estimate the public health benefits of the NO_x Budget Trading Program, but Fowlie and Muller (2019) estimate the public health benefits of socially optimal NO_x cap-and-trade and emission tax systems inspired by it. 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).

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 predicting facilities' compliance strategies. Specifically, Fowlie and Muller (2019) show that the ex ante engineering-based cost-minimization model correctly predicts only 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.

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 could be reversed during the winter months, when the NO_x cap-and-trade program did not operate. Linn limits his study sample to boilers that never invested in selective catalytic reduction or other major post-combustion equipment to reduce pollution. The strategy exploits the staggered implementation of NO_x trading as well as its seasonal nature (summertime only).²⁴ A big caveat to this analysis is that modifications are inferred, not observed. By excluding facilities that invested in new pollution control equipment, the paper assumes that

reductions in NO_x reflected modifications instead of new capital.

Linn finds that such modifications reduced 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 delivered incentives for emissions abatement through fairly modest process changes that would not likely have occurred under more prescriptive command-and-control regulations.

3.2.4. *Employment Impacts of the NO_x Budget Trading Program*

Curtis (2018) also exploits variation across states and over time to examine the labor market impacts of the NO_x Budget Trading Program. 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 program 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 higher separation rates.

This ex post analysis stands in contrast to the EPA (1998a) ex ante analysis. The prospective analysis estimated labor impacts based on the labor requirements of pollution control equipment and the net effect on coal and natural gas demand. It did not consider manufacturing employment impacts in response to changes in power prices, and it estimated that the rule would result in a modest increase in labor demand. Understanding the economic incidence of the rule—and in

²⁴The Ozone Transport Commission states along the East Coast started trading NO_x allowances in 1999 and were subsequently covered by the NO_x Budget Trading Program, starting in 2004.

this case the broader labor market impacts of regulating air pollution—requires an analysis of impacts beyond the firms directly covered by the regulation.

The NO_x Budget Trading Program's design—varying regulatory stringency across states and seasons, as well as over time—enabled a number of quasi-experimental investigations of its impacts. The program reduced emissions and delivered public health improvements not forecast *ex ante*. Regulated firms responded to two kinds of incentives in their compliance decisions: the discretion to seek out lowest-compliance strategies and, for those under economic regulation, the opportunity to gain higher utility rates and thus higher returns through capital-intensive investments. The economic impact of higher power prices from the program contributed to lower employment among energy-intensive manufacturing firms in the states covered by the program.

3.3. *The RECLAIM Cap-and-Trade Program*²⁵

The 1990 CAA amendments required those areas classified as extreme nonattainment for ambient ozone concentrations to implement “economic incentive programs” to reduce emissions of ozone precursors such as NO_x. Given the extreme nonattainment status for Los Angeles, the South Coast Air Quality Management District of California designed the RECLAIM cap-and-trade program covering NO_x emissions at 392 facilities in the greater Los Angeles area.²⁶ The program covered all private entities emitting at least four tons of NO_x per year (public facilities, such as police and fire stations,

were excluded). 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 emissions 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, before 1999 the lax emissions cap resulted in allowance prices lower than *ex ante* analyses projected (Johnson and Pikelney 1996); prices then increased 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 noncompliance fee and to comply with conventional technology standards on existing generating units by 2004. These units joined a revamped RECLAIM in 2007.

3.3.1. *Air Quality and Health Impacts of the RECLAIM Program*

Although allowance prices spiked during the 2000–2001 California electricity crisis as power generation in the RECLAIM region increased well above past levels, the RECLAIM program delivered significant NO_x reductions. Fowlie, Holland, and Mansur (2012) evaluated the performance of the RECLAIM program by matching RECLAIM-covered sources with similar facilities in nearby nonattainment areas in the state and examining the change in emissions over time. Although both RECLAIM and non-RECLAIM sources in their sample experienced falling emissions, they estimate that RECLAIM facilities' emissions fell

²⁵This subsection is based on Fowlie, Holland, and Mansur (2012), Fowlie and Perloff (2013), and Gangadharan (2004).

²⁶The 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.

about 20 percent relative to their comparison group over 1990–2005, exceeding the ex ante projection of a comparable emissions impact among command-and-control and RECLAIM sources (Johnson and Pikelney 1996). 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.

Fowlie, Holland, and Mansur (2012) also explore whether “hot spots” arose in disproportionately low-income and/or minority communities, reflecting concern about the environmental justice implications of market-based instruments. Exploiting Census Block-level sociodemographic data and facility-level emissions data, the authors find no evidence of hot spots or lower relative emissions reductions in areas near RECLAIM facilities. In characterizing these neighborhood effects, the authors have mapped emission impacts to the sociodemographic characteristics of zip codes within concentric circles of a specified radius around each of the RECLAIM program sources.

In more recent work, Grainger and Ruangmas (2018) employ the Fowlie, Holland, and Mansur (2012) matching strategy and combine it with a richer atmospheric chemistry model that accounts for the dispersion and transport of emissions. Although all populations experience a reduction in emissions exposure, Grainger and Ruangmas find evidence of larger emissions reductions in higher-income neighborhoods. Conditional on income, they find that Black populations appear to experience larger reductions, but Latino populations appear to experience smaller reductions, compared with white populations. 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.

3.3.2. *Did the RECLAIM Program Follow Ex Ante Predictions for Cap-and-Trade?*

One of the attractive characteristics of cap-and-trade programs is that they can promote cost-effective emissions 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.²⁷ Fowlie and Perloff (2013) examine whether the independence condition holds in the context of the RECLAIM 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. Although 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.

The RECLAIM cap-and-trade program reduced emissions faster than a command-and-control alternative. By the

²⁷ Building on the work of Coase (1960), some 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.

nature of a trading program, the geographic location of resulting emissions is not determined by the regulator, as evident by the satisfaction of the independence condition in the RECLAIM case. The spatial variation of emissions has important distributional and political economy implications, since higher-income households appeared to enjoy greater air quality improvements than lower-income households and the reduction in emissions varied across ethnic groups.

3.4. *Air Toxics Regulations under the 1990 CAA Amendments*

The EPA's approach to regulating air toxics changed significantly under the 1990 CAA amendments. Prior to adoption of the 1990 amendments, the agency had authority to regulate individual air toxics based on their specific health risks. However, the EPA had great difficulty negotiating the pollutant-specific, source-specific rulemaking process. From 1970 to 1990, the EPA regulated only seven air toxics emitted by a small number of sources. The 1990 amendments adopted a technology-based approach—centered on MACT standards²⁸—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.²⁹ 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, rather than force the adoption of exotic and unproven technologies. 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 (1999), the EPA stated that these standards would impose annual costs of \$480 million in 2000.³⁰

The MACT standard issued for the pulp and paper cluster rule is the most studied of the EPA's air toxics regulations. It applied differentially to various subgroups of pulp and paper plants and required reductions in benzene and other volatile organic compounds (VOCs) at mills that used chemical pulping techniques.³¹ In addition to the 1990 CAA amendments' air toxics requirements, the EPA agreed in 1988 to a revised consent decree with environmental groups requiring it to issue dioxin and furan best available technology (BAT) water discharge limits for bleaching pulp mills.³² In response to industry requests, the EPA decided to combine the water rule with its MACT air toxics rule—creating the so-called “cluster rule”—

²⁸The basic MACT standard is defined as the average emissions level achieved by the best-performing 12 percent of plants in the industry. The EPA has the authority to adopt more stringent standards beyond the MACT floor requirements, taking into account technological and economic feasibility, cost and effectiveness, the expected additional risk reduction achieved, and other factors. In practice, the EPA has generally adopted emissions standards keyed to the basic MACT requirements (the so-called MACT floor).

²⁹Technology-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.

³⁰The EPA based this cost estimate on ex ante estimates developed as part of the rulemaking process.

³¹Mills using nonchemical techniques (e.g., mechanical pulping) or purchased pulp faced less stringent standards on air emissions.

³²*Environmental Defense Fund v. Thomas*, 657 F. Supp. 302 (D.D.C. 1987) and *Environmental Defense Fund and National Wildlife Federation v. Thomas*, D.D.C. No. 85-0973. Under pressure from environmental groups to address dioxin discharges, the EPA launched an initial program requiring states to develop water quality standards for dioxin in 1988 (Hammer 1988). By 1995, pulp and paper mills had already reduced their dioxin and furan discharges by 70 percent (61 FR 36481).

to give the pulp and paper industry a coordinated set of regulatory requirements. The final cluster rule was issued in April 1998.

3.4.1. *Impact of MACT Standards on Emissions and Air Quality*

Fraas and Egorenkov (2018) examine the performance of the MACT standards in reducing emissions of air toxics in five 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 HAPs, air toxics that are classified as VOCs. Two sets of plants are used for controls. Plants in six industries that were later subject to MACT standards (primarily industries that manufacture metal parts) constitute a “potpourri” control group for evaluating all five MACT rules. In addition, to evaluate two of the MACT rules, the authors use as controls unregulated plants in similar industries: plywood plants are the controls for regulated pulp and paper mills, and paper and web surface coating plants serve as controls for regulated plants in the printing and publishing industry.

3.4.2. *Did Emissions Reductions Match Ex Ante Predictions?*²

Fraas and Egorenkov (2018) find a significant reduction, of 60 to 90 percent, in aggregate HAP emissions at printing and publishing plants. The reduction in HAP emissions from pulp and paper mills is smaller—20–33 percent. This falls short of the 60 percent reduction predicted by the RIA.³³ 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 deadline of 2001. The authors define 1995–97 as the “before” regulation period. However, it is possible that mills altered their emissions in this 1995–1997 baseline period in anticipation of a final rule after the EPA issued a cluster rule proposal in 1993. The authors address this issue using an event study approach—that is, they allow 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 CAA amendments, 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 can include fewer than half of the 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 for manufacturing industries issued during the period.

³³Gray and Shadbegian (2015)—using a difference-in-differences approach—report that reductions in air toxics releases were not as large as expected by the EPA,

with small and insignificant effects seen for the MACT-only plants, while MACT plus BAT plants saw marginally significant reductions.

3.4.3. *Employment Impacts of the Cluster Rule*

Gray et al. (2014) study the impacts of the cluster rule on employment and wages by assembling an unbalanced panel of plants subject to MACT standards only or to both MACT and BAT standards, along with a set of control plants, for 1993–2007.³⁴ To examine the impact of each type of standards on employment and wages, difference-in-differences models are estimated that 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 1993–97 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 to 7 percent lower at facilities subject to both MACT and BAT regulations, implying that 50 to 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 with controls, with no significant change at plants subject to MACT plus BAT regulations. Overall, the Gray et al. (2014) results imply that in terms of employment, the water-related requirements are more costly than air regulations.

By issuing MACT standards for toxic air pollutants under the 1990 CAA amendments—standards that required all firms in an industry to achieve the level of control of the cleanest firms—the EPA significantly

expanded the scope of industries and substances that it could regulate. In the case of pulp and paper mills, the EPA simultaneously issued standards to control water as well as air emissions via the cluster rule, its first multimedia regulation. Lack of data on air toxics emissions and lack of a suitable control group for firms in a particular industry have hampered causal analyses of the effectiveness of these regulations; however, there is evidence that emissions of HAPs declined by one-third in pulp and paper mills.

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.³⁵ One of the more important but least well-studied successes of the CAA is the nationwide reduction in lead from gasoline motor vehicles, which caused a 99 percent reduction in lead in gasoline between 1975 and 1990. To reduce ground-level ozone and carbon monoxide, the 1990 CAA amendments imposed specific requirements on the content of gasoline sold in nonattainment areas. These include reformulated gasoline (RFG) regulations and regulations governing Reid vapor pressure (RVP). Both sets of rules target summertime ozone, which forms in the atmosphere when VOCs combine with NO_x in the presence of sunlight. RVP regulations, which limit fuel volatility (and hence VOCs), are required in ozone nonattainment areas. RFG regulations are designed to reduce the VOCs and NO_x emitted when gasoline is burned. In addition, the renewable fuels standard (RFS) implements

³⁴Ninety-six of the 155 chemical pulping plants were also subject to best available technology (BAT) economically achievable standards to reduce water discharges of chloroform, dioxin, and furans. Mills in the control group include plants using nonchemical pulping techniques, like mechanical pulping.

³⁵The five general classes of gasoline regulations in Code of Federal Regulations, title 40, 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).

national biofuel goals intended to reduce carbon dioxide (CO₂) emissions associated with transportation. The RFS mandates the blending of biofuels—such as ethanol, biodiesel, cellulosic ethanol, and other low-carbon advanced biofuels—into gasoline and diesel fuels sold in the United States.

The implementation of RFG (and RVP) regulations led to fragmentation of the gasoline market. RFG regulations were initially required in severe ozone nonattainment areas and implemented in two phases, with an initial, less stringent standard over 1995–99, 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. Figure 2 (from Brown et al. 2008) shows differences in gasoline requirements across the United States in April 2007. Because of variations in state regulations, as well as differences in gasoline oxygenates, 17 different blends of gasoline were sold in the United States by 2004 (Brown et al. 2008). The number of varieties of gasoline sold led to concerns that regulations had segmented the gasoline market and could lead to both higher 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 literature evaluating mobile source fuel regulations has focused on three questions: (i) Are the regulations effective in reducing air pollution? (ii) Have they led to health benefits? (iii) What impact have they had on the market for vehicle fuels and the price of gasoline?

4.1. *Effectiveness and Benefits of the Lead Phaseout from Motor Gasoline*

Airborne concentrations of lead have fallen by 99 percent since 1980, primarily

because of the phasing out and eventual ban on leaded gasoline in commerce. A 1973 EPA regulation required gasoline stations to market unleaded gasoline because lead in gasoline damaged catalytic converters, a tail-pipe emissions control technology mandated by other CAA regulations targeting carbon monoxide pollution. In 1976, the EPA established a NAAQS for lead. Removing lead from gasoline aimed to lower concentrations of carbon monoxide and lead in the 1970s and 1980s (Nichols 1997).

The lead phasedown established a lead fuel content standard—measured in grams per gallon (gpg)—for petroleum refineries. The initial rules set declining standards over time, with less stringent requirements for smaller refineries. In response to a growing scientific understanding of the adverse health consequences of lead exposure—primarily lower IQs in children as well as hypertension in the general population—the EPA implemented an accelerated phasedown schedule through a tradable credit program during the 1980s (Nichols 1997, Newell and Rogers 2003). By 1986, the lead fuel content had fallen to 0.1 gpg, representing more than a 90 percent decline in lead content, and in 1996 the EPA banned lead in gasoline. At the time the agency promulgated the lead phasedown with credit trading, the EPA (Schwartz et al. 1985) estimated about \$500 million (US\$(1983)) in annual children's health benefits, reflecting both medical care for health risks associated with high blood lead levels and the compensatory education spending associated with cognitive impacts from lead exposure. The EPA (Schwartz et al. 1985) also estimated approximately \$5 billion in health benefits from reduced adult blood pressure, primarily resulting from reduced premature mortality and fewer nonfatal heart attacks.³⁶

³⁶ The EPA used a \$1 million value of statistical life (US\$(1983)) to monetize premature mortality benefits (Schwartz et al. 1985, Nichols 1997).

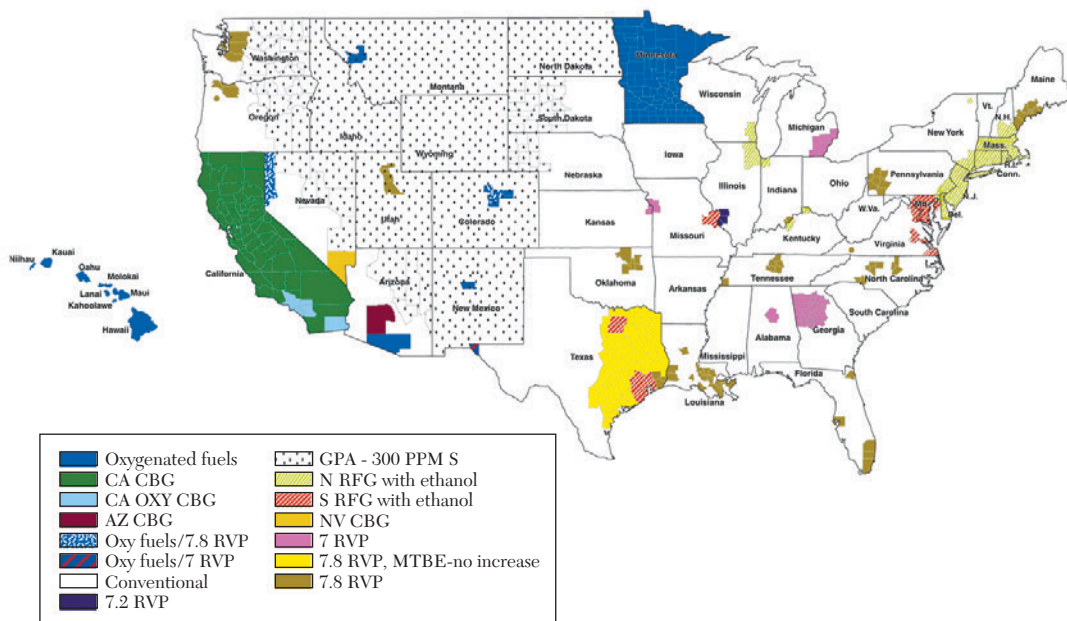


Figure 2. US Gasoline Requirements

Source: Brown et al. (2008, figure 2). Reprinted from the *Journal of Environmental Economics and Management*, vol. 55, by Jennifer Brown, Justine Hastings, Erin T. Mansur, and Sofia B. Villas-Boas, “Reformulating Competition? Gasoline Content Regulation and Wholesale Gasoline Prices,” 1–19, copyright 2008, with permission from Elsevier.

Because the near-elimination of lead in gasoline occurred well before the application of quasi-experimental methods in environmental economics and the collection and compilation of high-quality datasets, there are only a few ex post studies of the lead phaseout.³⁷ Reyes (2007) uses state-specific reductions in leaded gasoline to study the effect of childhood lead exposure on crime rates. Lead increases impulsivity and aggressivity and lowers IQ—outcomes that are strongly correlated with criminal behavior. She finds robust evidence that reduced

exposure to lead in the late 1970s and early 1980s explains 56 percent of the drop in crime rates in the 1990s. She uses actual monitor readings at the state-quarter level to estimate the direct effect of lead via childhood exposure on crime rates decades later, and this is identified based on an empirical strategy that employs lead content of local gasoline, which is partly driven by the CAA regulation, as an instrument. This is an example of an unexpected regulatory outcome: the benefit from reducing lead exposure was not anticipated or evaluated in the EPA’s ex ante analysis.

Hollingsworth and Rudik (2021) employ a regulatory exemption that permitted use of leaded gasoline in racecars, such as those participating in the NASCAR racing series,

³⁷There are quasi-experimental studies of the impact of lead exposure on children’s cognitive skills (e.g., Aizer et al. 2018) but none of which we are aware that evaluate the CAA per se.

to evaluate the health impacts of eliminating lead in gasoline. They use a spatial discontinuity design—recognizing that populations in closer proximity to a racetrack with a major race and associated practice runs will bear greater exposure to lead pollution—coupled with the 2007 transition from leaded gasoline to unleaded gasoline at these tracks to identify the impacts of lead on public health. They find elevated ambient lead concentrations, higher blood lead levels in children, and higher adult mortality rates in populations near racetracks before the 2007 transition to unleaded gasoline. The monetized benefits of reducing premature mortality for racetrack-adjacent populations in one year—more than \$2 billion—exceed the value of all NASCAR racing teams.³⁸ The NASCAR races using leaded gasoline caused about 4,500 premature mortalities per year in the counties hosting NASCAR racetracks and their bordering counties. Considering the much greater scope of leaded gasoline prior to the EPA phasedown—in every county throughout the country over the course of the entire year—in contrast to NASCAR race-day use, the EPA (Schwartz et al. 1985) estimate of 5,000 avoided fatalities from the ban on leaded fuel falls far short of the likely adverse impacts of lead exposure on premature mortality.

The phasedown and ban of lead represent a unique case in terms of ex post evaluation of the Clean Air Act. In most contexts, a variety of policy and market factors may influence or confound our understanding of the impacts of any given CAA regulation, which necessitates careful quasi-experimental empirical strategies. With the vast majority of airborne lead emissions resulting from a single economic activity—burning leaded gasoline—produced by refiners who had little economic

incentive to alter five decades of practice of using lead to boost octane in gasoline for better performance, it is uncontroversial to connect the dramatic decline in lead concentrations with CAA regulations. The recent papers cited above show the value added of applying causal inference methods to understand the impacts of lead reductions on crime and public health.

4.2. *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 (phases I and II), federal RFG standards, and California's gasoline content regulations on two measures of ozone pollution: (i) daily maximum concentration, and (ii) daily eight-hour maximum concentration. They note that regulations that don't specify which 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 olefins, 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, with counties that had an RVP limit of 9.0 pounds per square inch. The second approach uses a temporal regression discontinuity design. Because the regulations affect

³⁸Hollingsworth and Rudik (2021) monetize premature mortality based on expected life-years lost and value each life-year at \$140,000 (US\$(2019)), resulting in about \$0.55 million per elderly mortality.

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 degree of RVP regulation doesn't affect ozone. Federal RFG slightly reduces ozone (by about 3 percentage points), and California Air Resources Board standards result in the biggest reduction in ozone (around 9 percentage points). In the regression discontinuity analysis, RVP does not affect ozone. RFG reduces ozone in some places, but the authors show these effects are due to simultaneous reductions in NO_x emissions. The California standards reduce ozone only in places that are VOC-limited (inland Los Angeles and San Diego).³⁹ The absence of a meaningful effect of RFG on ambient ozone concentrations outside California highlights a major omission in the EPA ex ante analysis of the RFG regulation: the agency did not quantify changes in ambient ozone concentrations and thus did not monetize ozone-related benefits (EPA 1993, Anderson and Rykowski 1997).

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 1992–2000. She looks at NO₂, CO, and SO₂ levels, averaged to month at the zip code level, and then calculates the percentage of days when pollution exceeds 75 percent of the 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 (2017) uses two treatment variables. The first is the percentage of the population in a zip code that lives within 1 km of a 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 the 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 have an effect only in zip codes close to a highway.

Marcus (2017) 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 versus 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, Marcus finds that the policy reduced asthma hospitalizations by 1,449 per year, resulting in \$13.2 million (US\$(2006)) 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. This ex post analysis helps fill the void in the unusual ex ante analysis that the EPA performed in 1993 that failed to quantify any ozone-related health impacts of a regulation focused on ozone pollution.

³⁹Ozone 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; 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.

Taken together, the studies by Auffhammer and Kellogg (2011) and Marcus (2017) paint a fairly clear picture of the effectiveness of gasoline content regulations. Specifically, Auffhammer and Kellogg demonstrate that rules that fail to specify which VOCs refiners must remove have little to no effect on ozone concentrations, since refiners choose to remove the cheapest (and least reactive) component, namely butane. At the same time, more restrictive regulations, such as those issued in California, have clear impacts on ozone levels. Marcus demonstrates how the California rules resulted in measurable health impacts, specifically reduced hospitalizations for children's asthma.

4.3. *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 prices from 1994 through 1998 and the volatility (quarterly standard deviation) of average weekly gasoline prices in treated cities—those subject to RVP or RFG regulations. They also examine prices in matched control cities—those not subject to these regulations.

Brown et al. (2008) find that RFG increases gas prices by about 3 cents per gallon on average, while RVP increases gas prices by about 1 cent per gallon. This average RFG price impact is modestly below the EPA (1993) ex ante estimate for phase I of RFG, 3.9 cents 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 variation 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 increases in the supply of gasoline to unregulated regions, which lowered gas prices in those regions.

Chakravorty, Nauges, and Thomas (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 (OXY) program.⁴⁰ 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 last 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 imposes RFG or OXY requirements across its entire jurisdiction, gasoline prices are estimated to increase by 16 percent. The results also indicate that segmentation of markets with

⁴⁰Oxygenated 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 CAA amendments require the addition of oxygenates.

RFG or OXY requirements increases the market power of refineries. This is relevant for policy, since homogenizing the nation's gasoline content regulations would have two countervailing effects. If the national regulation were more stringent than the status quo, gas prices would increase because refiners would have to produce more expensive gasoline. But ending the segmentation of gas markets would decrease prices by reducing refineries' market power.⁴¹

Neither Brown et al. (2008) nor Chakravorty, Nauges, and Thomas (2008) employ standard quasi-experimental methods to estimate the impact of fuel content regulations on gasoline prices. Brown et al. match regulated cities to controls, although they rely on a restricted sample of regulated and unregulated city pairs that use different gasoline blends. Chakravorty, Nauges, and Thomas attempt to estimate the relationships among 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.

Generally, the literature on the market impacts of RVP and RFG regulations and oxygenated fuel regulations reveals that heterogeneous regulation is costly because of the reduction in competition among producers in some markets. At the same time, the added costs are partially offset by spillovers to unregulated regions: some refiners increase the supply of conventional gasoline during summer months in the non-RFG markets, which

results in lower prices in those markets. The potential interaction of fuel content regulations and local market power on market outcomes—and the prospect of heterogeneous fuel price impacts across the country—did not receive any attention in the EPA (1993) ex ante analysis of the RFG regulation.

4.4. *Market Impacts of the Renewable Fuels Standard*

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 the required quantity from 9 billion gallons in 2008 to 36 billion gallons in 2022. Within the aggregate annual targets, the law creates targets for subcategories as a function of technology and carbon intensity: cellulosic ethanol, a 60 percent reduction in carbon emissions compared with a benchmark petroleum-based fuel; biodiesel, 50 percent; advanced biofuel, 50 percent; and conventional biofuel, 20 percent. Any biorefinery in operation before December 2007 could satisfy the conventional biofuels requirements regardless of its carbon intensity.

The 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 the EPA to demonstrate compliance with their renewable volume obligation.

The first strand of research in this literature deals with the consequences of the

⁴¹ Muehlegger (2004) uses 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.

struggle to ramp up production to meet the different required targets, especially in the early years of the policy. A second thread in the literature examines the effectiveness of the tradable performance standard in passing through the biofuel subsidy associated with the RFS biofuel mandates to consumers of higher-ethanol blends.

4.4.1. *The RFS and the Market for RIN Credits*

Lade, Lawell, and Smith (2018a) examine the problems emerging in the early years of RFS implementation with the ramp-up of biofuels from 9 billion gallons in 2009 to 36 billion gallons in 2022. They cite two major challenges to implementation: the failure of cellulosic ethanol to produce commercial-scale volumes, and the decline and slow growth in the demand for gasoline, which caused the RFS-mandated biofuel volumes to exceed 10 percent (the so-called blend wall). In practice, cellulosic ethanol production over 2010–18 was less than 4 percent of the cumulative volumes of the goals mandated in the 2007 law. It also became clear in 2013 that the overall biofuel mandates would breach the 10 percent blend wall—the maximum amount of biofuel that can be mixed with gasoline and used in regular vehicles.⁴² As a result, the EPA has been forced to waive the statutory goals for cellulosic ethanol and issue new goals through new regulations since 2011.

Adjustments in biofuels requirements, and the fact that the mandates are set each year instead of for multiyear 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 seen when the time series of RIN prices is plotted against annual EPA mandate announcements and announcements of mandate adjustments. RIN prices over 2013–17 fluctuated in the range of \$0.50 to \$1.00 per gallon, with prices in 2013 briefly rising to \$1.50 per gallon (Lade, Lawell, and Smith 2018a). In a related working paper, Lade, Lawell, and Smith (2015) estimated that the blend wall issues from 2012 to 2014 raised gasoline prices by as much as 5 cents per gallon. The EPA's RIA estimated costs of one-half cent per gallon in the early years of the program. However, the EPA's RIA for the RFS rule primarily focused on the benefits and costs in 2022 and did not give attention to the potential issues with the blend wall and the potential failure of cellulosic ethanol production to meet the RFS-mandated production levels.

Lade, Lawell, and Smith (2018b) also examine the effect of EPA-announced reductions in ethanol mandates on biofuel tradable credit prices 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 (i.e., by 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 oil, and ethanol), flexible time variables, and event indicators using data for January 2012 to May 2014.⁴³ The event indicators are intended to capture the unanticipated impact of the events on future compliance costs, net of adjustments

⁴²National 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.

⁴³The three events of interest are the EPA's 2013 final rule, a leak of the 2014 proposed rule, and the official release of the 2014 proposed rule.

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. They estimate a similar specification with the logarithm of first-differenced stock market prices of biofuel firms as the dependent variable.

Lade, Lawell, and Smith (2018b) 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. Small changes (1 to 2 percent) in commodity futures prices are 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, which 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 RIA did not examine the impacts of updating the rules on stock prices or include an examination of RIN price scenarios.

4.4.2. *Impact of the Renewable Fuels Standard on Fuels Prices*

A recent set of papers studies the pass-through of the RFS into fuels prices. 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—for example, 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. The EPA's RIA did not address this issue. Although the RIA did discuss impacts of the RFS on petroleum prices, the analysis mostly focused on the displacement of imports and its consequences in terms of energy security.

Lade and Bushnell (2019) study pass-through for E85, 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 relative to conventional gasoline. They find that 50 to 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.

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 Minnesota over 2007–15. They show that pass-through 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's (2019), on the order of 0.53 averaged across the state. The heterogeneity in their results is interesting: they show almost complete pass-through in the Twin Cities (with a more competitive market) compared with less pass-through in other parts of the state.

Knittel, Meiselman, and Stock (2017) use variation in RIN prices for 2013–15 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, the authors find little to no pass-through 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. Whereas Knittel, Meiselman, and Stock (2017) look at national data over a relatively short period, the other researchers use much more disaggregated gas station-level data from the Upper Midwest over longer (and more recent) periods.

Overall, the literature on the market impacts of the renewable fuels standard (RFS) suggests that the Energy Independence and Security Act's biofuel mandates have been overly ambitious and have exceeded the industry's production capacities—especially for cellulosic ethanol. The overambition, in turn, has created substantial uncertainty in fuel markets and forced the agency to set new annual mandates out to 2022 to replace the infeasible statutory goals. Arguably, announcing feasible, multiyear targets in advance, as was done under the SO₂ trading program and NO_x Budget Trading Program, would have aided in the functioning of the market.

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 nonattainment status on air quality, the benefits of improved air quality, and economic activity. Beginning with the 1970 CAA, the EPA established National

Ambient Air Quality Standards for criteria air pollutants to protect human health and welfare. To implement the NAAQS, states and tribes are required to identify nonattainment areas and prepare SIPs to ensure attainment and maintenance of the standards in their jurisdictions. For nonattainment areas, SIPs must include provisions to reduce emissions from both stationary and mobile sources.⁴⁴ Nonattainment status also triggers more stringent federal regulation. Under the 1977 CAA amendments, plants locating in nonattainment areas must buy pollution offsets from existing firms and are subject to more stringent emissions standards than plants locating in attainment areas.

Since nonattainment status is, effectively, imposed on states by the EPA and requires them to adopt measures to achieve compliance with the NAAQS, it has been viewed as an exogenous source of variation in regulatory stringency to the individual persons/firms affected. This has led to a substantial literature examining the impact of the CAA on various outcomes—including ambient air quality, health benefits, the location of manufacturing plants, and the earnings and employment of manufacturing workers—all using nonattainment status as a measure of regulatory stringency.

The retrospective analysis literature based on nonattainment status evaluates outcomes that may not have been subject to any rigorous ex ante analysis. As noted in section 2.2.1, executive orders on federal regulation, dating back to President Reagan's 1981 executive order, have required federal agencies to conduct RIAs of their proposed and final regulations. Several of the NAAQS

⁴⁴Demonstration of attainment must be supported by approved air quality monitoring data in urban and rural areas, supplemented, if needed, with modeling of local air quality. When the EPA sets a new NAAQS or revises an existing one, the process is repeated and a new designation declared. Attainment was defined by Air Quality Control Region prior to 1978 and by county thereafter.

and associated nonattainment designations subject to retrospective analyses predate this requirement. For example, the 1971 NAAQS for total suspended particulates has served as the basis for evaluations of premature mortality (Chay and Greenstone 2003), housing values (Chay and Greenstone 2005), and labor force participation and earnings (Isen, Rossin-Slater, and Walker 2017), and the 1971 and 1979 NAAQS for ozone have served as the basis for evaluations of air pollutant concentrations and manufacturing plant location (Henderson 1996). In these cases, retrospective analyses illuminate what were previously information voids, as opposed to updating our understanding of an outcome examined in *ex ante* EPA analyses.⁴⁵

5.1. *The Impact of Attainment Status on Emissions and Air Quality*

If nonattainment status under the NAAQS spurred states to issue more stringent regulations to control emissions in nonattainment than in attainment counties, we would expect air quality to improve more at monitors in nonattainment counties than in attainment counties. This hypothesis has been tested for three of the criteria air pollutants—ozone, PM, and SO₂—using nonattainment status under the 1977 and 1990 CAA amendments. Over time, changes in the criteria for nonattainment (see appendix figure A1) have caused counties to be declared out of attainment with the NAAQS and have provided a basis for examining the impact of nonattainment on ambient air quality. In all cases there

is some evidence that air pollution declined more rapidly at monitors in nonattainment (versus 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 nonattainment status under the 1977 CAA amendments on ozone levels at 643 monitors in 332 urban counties over 1977–87. 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 nonattainment status on ozone readings was identified based on changes in attainment status over the period. He found that a change from nonattainment 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 to 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, possibly due to nationwide regulations.

An important question is whether Henderson's (1996) results hold for other criteria pollutants. Auffhammer, Bento, and Lowe (2009) examine the effects of nonattainment 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 nonattainment status at the county level on PM₁₀ at the monitor level. They find that nonattainment designation at the county level had no effect on PM₁₀ concentrations at monitors in nonattainment counties; that is, the average treatment effect of nonattainment status was not significantly different from zero.⁴⁶

⁴⁵It should also be noted that the counterfactual in the studies reviewed in this section differs from the counterfactual in the EPA's RIAs. An RIA compares a world in which firms or consumers are subject to environmental regulation with a world in which they are not. The studies reviewed in this section compare regulated firms or consumers in nonattainment counties with similar firms or consumers in attainment counties. The impact of a regulation in nonattainment counties is measured relative to attainment counties.

⁴⁶One referee raised the valid point that some of this effect may be due to mean reversion.

When Auffhammer, Bento, and Lowe (2009) allow for heterogeneous treatment by type of monitor and county, they find that nonattainment status at the monitor level had a significant effect on PM_{10} levels. Specifically, PM_{10} concentrations at monitors with concentrations above the national annual standard in the previous year dropped by 7 to 9 $\mu\text{g}/\text{m}^3$, 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. The authors report similar treatment effects for monitors that were out of attainment in counties that were in attainment.⁴⁷ These results suggest that regulators focused their attention on reducing pollution near the monitors that were in violation of the standard, whether or not the monitors were in attainment or nonattainment counties. These monitor-specific results are larger than the county-level impacts estimated by the EPA (1997) in its *ex ante* analysis of the 1997 PM NAAQS. The EPA estimated that in PM_{10} nonattainment counties in 2010, PM_{10} concentrations would be about 2.5 $\mu\text{g}/\text{m}^3$ lower than the baseline (counterfactual) emissions for these counties.

The results for sulfur dioxide are somewhat mixed. Greenstone (2004) examines the impact of SO_2 nonattainment on ambient SO_2 under the 1977 CAA amendments using data for three six-year periods: 1975–80, 1981–86, and 1987–92. The question is whether nonattainment 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 nonattain-

ment on reductions in SO_2 occurred in the third period studied: nonattainment status in 1990 significantly reduced SO_2 concentrations, by 7–11 percent, in 1992.⁴⁸

If more stringent regulation in nonattainment 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 TRI, he constructs annual cross section emissions data for PM, lead, and VOCs from iron and steel plants for each of the years 1987–97. He examines the impact of nonattainment 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 nonattainment 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.

Gibson (2019) also finds reductions in air emissions at plants located near monitors that are out of attainment, using TRI data for 1990–2014. Specifically, he finds that manufacturing plants within 1 km of a monitor that is out of attainment for PM reduce their air emissions by 38 percent compared with nontreated plants. In contrast to Greenstone (2003), however, he finds that increases in water emissions offset 9 percent of the air emissions decrease, indicating some substitution from air to water as a disposal medium.

⁴⁷This is possible because nonattainment status is based on a three-year, geometric mean average of annual PM_{10} .

⁴⁸Because nonattainment status changes only when the county can show that it does not have monitored violations and it has controls in place to maintain attainment for 10 years, it is important to study the impact of nonattainment status on emissions and air quality with a lag. See Gibson (2019) for a thorough discussion.

There is also evidence of leakage effects: air emissions increase by 11 percent at plants operated by the same firms in attainment counties.

All of the studies referenced here depend on sufficient monitoring data to investigate the impact of nonattainment status on ambient air quality. Greenstone (2004) has data on SO₂ readings for only 62 counties (18 of which were designated nonattainment) for 1975–80, which may account for the lack of a significant impact of nonattainment status on ambient SO₂ for this period. In contrast, data for the 1987–92 period cover 203 counties.⁴⁹

Data issues notwithstanding, the literature suggests that over some periods and for some pollutants, air quality improved more in nonattainment counties than in attainment counties. Auffhammer, Bento, and Lowe's (2009) result and Gibson's (2019) paper suggest that regulators were most concerned about lowering pollution levels at monitors that violated the NAAQS than at all monitors within a nonattainment county. This raises issues about the placement of monitors—a topic that has received considerable attention in the recent literature (Grainger and Schreiber 2019; Grainger, Schreiber, and Chang 2019).⁵⁰ Nevertheless, the literature suggests that the CAA caused maximum July ozone concentrations to decrease 8 percent more in nonattainment counties than in attainment counties in the 1980s, and SO₂ concentrations to decrease 7–11 percent more in nonattainment than in attainment counties in the early 1990s. Between 1990 and 2000, PM₁₀ concentrations decreased 11 to 13 percent more

at monitors that were out of attainment than at monitors that were in attainment.⁵¹

5.2. *Use of Attainment Status to Measure the Health Benefits of the CAA*

The health benefits associated with reductions in ambient air pollution are a major impetus for regulation under the CAA and constitute the majority of quantified benefits in ex ante RIAs. Exogenous variation in ambient air pollution due to nonattainment status presents a method for estimating the impacts of air pollution on human health while attributing these impacts to the CAA.⁵² In the epidemiological literature, PM_{2.5} has been linked to premature mortality and morbidity (Pope et al. 2002, Global Burden of Disease 2017 Risk Factor Collaborators 2018) more often than the other criteria pollutants. PM nonattainment status has been used as an instrument for changes in ambient particulate matter, which in turn have been associated with premature mortality, losses in adult earnings, and an increased incidence of dementia. By linking nonattainment status under the CAA to human capital formation and dementia, ex post studies have broadened the set of health benefits attributable to air pollution regulation compared with ex ante RIAs.

⁴⁹Another source of information about the impact of the CAA on ambient air quality is provided by studies that have used nonattainment status to instrument for observed changes in air quality. These studies, summarized in sections 5.2 and 5.3, provide further evidence that air quality improved faster in nonattainment than in attainment counties.

⁴⁹The number of counties out of attainment for SO₂ ranges from 46 to 49 between 1987 and 1992.

⁵⁰Grainger and Schreiber (2019) and Grainger, Schreiber, and Chang (2019) suggest that newly sited monitors are placed in relatively clean areas in attainment counties; in contrast, Muller and Ruud (2018) find that regulators are more likely to add a monitor and less likely to drop an ozone monitor where prior maximum readings are high.

⁵²A growing literature estimates the health impacts of air pollution using quasi-experimental methods but does not link changes in air pollution to the CAA. Deryugina et al. (2019) use wind direction and wind speed to estimate the causal impact of short-term variation in PM on mortality. Schlenker and Walker (2015) leverage flight delays in the air traffic network to instrument for airplane idling times at airports, which explain variation in NO_x and CO emissions.

In the first ex post study of the health benefits of the CAA, Chay, Dobkin, and Greenstone (2003) use nonattainment status for total suspended particulates 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 nonattainment counties, and also by comparing the 85 attainment counties with TSP between 60 and 75 $\mu\text{g}/\text{m}^3$ and the 91 counties with TSP between 75 and 90 $\mu\text{g}/\text{m}^3$ in 1970.

Chay, Dobkin, and Greenstone (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. Nonattainment status in 1972, measured by whether a county's average TSP reading in 1970 exceeded 75 $\mu\text{g}/\text{m}^3$, is significantly negatively related to the change in mean TSP concentrations. The impact of nonattainment status on the change in mortality is not as strong; however, in the preferred specification the coefficients are -8.97 (s.e. 5.02) for the full sample and -8.18 (s.e. 7.40) for the second set of counties. Based on the second set of counties, a 1 $\mu\text{g}/\text{m}^3$ increase in TSP increases 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, Dobkin, and Greenstone (2003), nonattainment status under the 1970 CAA accounts for virtually all of the reduction in average TSP between 1971 and 1972 (a 9–12 $\mu\text{g}/\text{m}^3$ 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 nonattainment 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 $\mu\text{g}/\text{m}^3$ to be out of attainment, was not officially announced until April 1971. Because states had to complete their implementation plans to achieve the NAAQS by January 1972, it is 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 nonattainment status under the 1970 CAA to instrument for TSP later in the decade, as in Chay and Greenstone (2005) and Isen, Rossin-Slater, and Walker (2017).⁵³

Isen, Rossin-Slater, and Walker (2017) use nonattainment status under the 1970 CAA to examine the impact of early-life exposure to particulate pollution on earnings and labor force participation between ages 29 and 31. Exposure to particulate pollution in utero or during the first year of life may have lifelong consequences—through either physiological effects (on birthweight, lung function, and development of the cardiovascular system) or neurological effects (development of the brain). To measure the impact of early-life exposure, the authors compare the outcomes of cohorts born in TSP nonattainment 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

⁵³Chay and Greenstone (2005) examine the effect of TSP on housing prices between 1970 and 1980 using a two-stage instrumental variables (IV) strategy in which nonattainment status in 1975 is employed as an instrument for TSP.

1971 are considered births before the CAA took effect; births between 1972 and 1974 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 nonattainment counties after 1971.

To examine the adult consequences of early-childhood exposure to particulate matter, Isen, Rossin-Slater, and Walker (2017) use Longitudinal Employer Household Dynamics (LEHD) data on workers in 24 states accounting for two-thirds of the non-farm workforce. These data provide the birth date and birth year of each worker and provide information on his or her earnings and labor market outcomes, as long as the worker remains in one of the sample states. The authors estimate that a 10 percent reduction in exposure to TSP (equivalent to $10 \mu\text{g}/\text{m}^3$) during the first year of life 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 (US\$(2008)), 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, Rossin-Slater, and Walker (2017) have contributed to a literature exploring the mechanisms by which such effects may occur (e.g., Voorheis 2017) and the literature on the long-term effects of early-life exposure to pollution.

A recent study by Bishop, Ketcham, and Kuminoff (2019) exploits variation in exposure to $\text{PM}_{2.5}$ over 2004–13 to measure the effects of long-term exposure to $\text{PM}_{2.5}$ on the probability of being diagnosed with dementia. The authors assemble data on a panel of 2.4 million Medicare recipients aged 65 or older in 2004 who lived in a county with $\text{PM}_{2.5}$ monitors. The authors have detailed data on baseline health, health history from 2004 through 2013, and residential location by year at the Census Block Group level. This enables the authors to construct exposure histories for each person over the 10-year period. The impact of average exposure is identified using variation in $\text{PM}_{2.5}$ between attainment and nonattainment counties and variation in exposure within counties based on distance from the residence to a monitor that is out of attainment.

Using data for the 1.3 million people who survived to the end of the 10-year period, Bishop, Ketcham, and Kuminoff (2019) estimate that a $1 \mu\text{g}/\text{m}^3$ change in average $\text{PM}_{2.5}$ exposure between 2004 and 2013 increased the probability of a dementia diagnosis over the period by 1.68 percentage points. This implies that the CAA reduced the number of dementia diagnoses over this period by 180,000 persons, which translates to \$214 billion in benefits, assuming that the value of avoiding a statistical case of dementia is \$1.2 million (2018\$). These significant public health benefits from reduced dementia illustrate how ex post analysis can identify and estimate outcomes that were not even envisioned by the EPA when it promulgated the $\text{PM}_{2.5}$ standards. The 1997 ex ante analysis of the $\text{PM}_{2.5}$ NAAQS does not list dementia or any cognitive or neurological impacts from reducing fine particulate matter concentrations among its quantified and unquantified categories of benefits.

The studies reviewed here that estimate the health benefits associated with the CAA are a useful adjunct to the epidemiological literature underlying the calculation of health

benefits in ex ante RIAs. They provide evidence of a causal association between changes in PM attributed to the CAA and health, and they expand the scope of health endpoints associated with air pollution to include impacts on human capital and dementia. The first stage of the analysis in these studies also suggests the impact of nonattainment status on improvements in air quality: Isen, Rossin-Slater, and Walker (2017) provide evidence that nonattainment status for particulate matter caused significant reductions in TSP in nonattainment counties in the 1970s, and Bishop, Ketcham, and Kuminoff (2019) provide similar evidence that nonattainment status reduced PM_{2.5} under the 1990 CAA amendments.

5.3. *Use of Attainment Status to Measure the Capitalization of Air Quality Benefits of the CAA into Property Values*

Economists have, for decades, measured the benefits of improvements in air quality by estimating their impact on property values. Because these estimates may capture people's perceptions of the health benefits of air quality, in addition to the aesthetic and visibility benefits of cleaner air, they are not used in ex ante RIAs of air quality regulations to avoid the double counting of health benefits. Nevertheless, the impact of air pollution on property values provides important evidence that households value air quality. Exogenous variation in air quality associated with nonattainment status provides a means of estimating households' valuation of some of the benefits associated with cleaner air. It also improves on an earlier literature relating air quality to housing values—studies that ignored the endogeneity of air quality.

Chay and Greenstone (2005) examine the impact of the large reductions in TSP between 1970 and 1980 on housing values, using county-level data for 988 counties accounting for 80 percent of the country's

population. Their two-stage IV model instruments for the change in TSP using TSP nonattainment status in 1975–76 and controls for changes in the median value of owner-occupied homes using changes in housing characteristics (age of the housing stock), country demographic variables (population density, race, education, age, and per capita income), and amenities (crime rates, doctors per capita, and measures of government revenues and expenditures). The first stage of their analysis indicates that the CAA caused TSP to decline by 9–10 $\mu\text{g}/\text{m}^3$ more in nonattainment than in attainment counties over the decade. Housing values increased by 2 to 3.5 percentage points more in nonattainment than in attainment counties. These estimates together imply that a 10 $\mu\text{g}/\text{m}^3$ reduction in TSP led to a 2 to 4 percent increase in housing prices.

The analysis by Chay and Greenstone (2005) focuses on the impact of the CAA on the prices of owner-occupied housing. From a distributional perspective, it is of interest to know whether increases in housing values due to air quality improvements are passed on to renters in the form of higher rents. If the value of air quality improvements is fully reflected in rents, then renters enjoy no net gain from air quality improvements.

To shed light on this question, Grainger (2012) studies the impact of PM₁₀ reductions between 1990 and 2000 on the change in the value of owner-occupied units and rental units in 300 US counties containing PM₁₀ monitors. When the TSP standard for PM was replaced in 1987 by a standard for PM₁₀, 69 counties were judged out of attainment. Grainger uses county nonattainment status in 1991–93 to instrument for the change in PM₁₀ between 1990 and 2000. Using an approach similar to Chay and Greenstone's (2005), he aggregates census data to the county level to determine the impact of air quality improvements on the change in the value of owner-occupied and rental

properties. His first-stage results suggest that PM_{10} declined by approximately 4.1–4.6 $\mu g/m^3$ more in nonattainment than in attainment counties. His second-stage results suggest that a 5 $\mu g/m^3$ decrease in PM_{10} (equivalent to a 10 $\mu g/m^3$ decrease in TSP) raised the value of owner-occupied housing by 6 to 10 percent between 1990 and 2000—an effect about twice as large as found by Chay and Greenstone (2005). However, the impact of air quality improvements on rental values is only half as large as that on owner-occupied housing, suggesting that renters do not fully pay for the improvement in air quality.

Bento, Freedman, and Lang (2015) extend Grainger's analysis of the distributional effects of housing price changes under the CAA by examining the capitalization of air quality improvements at a finer spatial scale. Using data on 375 PM_{10} monitors in 230 counties, they examine the capitalization of air quality improvements around monitors that were out of attainment with the PM_{10} NAAQS during the 1990s, using housing data at the census tract level. Monitors in attainment in counties that were in attainment and monitors in attainment in nonattainment counties serve as controls. When monitor nonattainment status is used to instrument for the change in PM_{10} between 1990 and 2000, the authors find that the elasticity of housing prices with respect to air quality improvements is greater within 5 miles of a monitor than at distances farther away. For homeowners, the elasticity of housing prices with respect to PM_{10} is -0.6 within a five-mile radius of a monitor that is not in attainment. The elasticity of rental values with respect to PM_{10} is statistically significant only within 3 miles of a monitor and is -0.2 . By examining the income of owners living at various distances from monitors that were out of attainment, the authors are able to express the capitalization of housing prices as a percentage of owners' incomes. Their results suggest that the impact of the

1990 CAA amendments on housing values was progressive for homeowners.

The literature using nonattainment status to measure the impact of the CAA on housing values extends the literature on the capitalization of air quality into property values and enables researchers to compute households' willingness to pay for cleaner air. Chay and Greenstone (2005) estimate that the benefits of reductions in TSP in nonattainment counties between 1970 and 1980 were \$45 billion (US\$(1982)). The results in Bento, Freedman, and Lang (2015) suggest that the benefits of reductions in PM_{10} between 1990 and 2000 in nonattainment counties were approximately \$44 billion (US\$(2000)). It is important to note that all of the studies cited, by instrumenting for air pollution, find much higher elasticities of housing prices with respect to air pollution (in absolute value) than the previous literature relating air quality to housing values (Smith and Huang 1995).

5.4. *The Impact of Attainment Status on Manufacturing Activity*

The more stringent regulations of nonattainment versus attainment counties may have discouraged new plants from locating in nonattainment counties. Under the 1977 CAA amendments, new plants located in nonattainment counties were required to achieve lowest achievable emissions rate standards, whereas new plants in attainment counties were subject to less stringent best achievable control technology standards. New plants in nonattainment counties were also required to purchase pollution offsets from existing plants. It could be argued that these were necessary steps to improving air quality in nonattainment areas; however, it may also have raised costs for firms in certain industries, given the locational advantages of nonattainment counties (e.g., proximity to markets and natural resources), affected manufacturing output in nonattainment counties, and had unintended impacts on county employment levels.

RIAs of air pollution rules estimate compliance costs for regulated firms, but generally do not look at the entry and exit impacts on an industry or consider the employment impacts, except in qualitative terms.⁵⁴ More recent analyses of specific industry regulations do discuss such impacts;⁵⁵ however, the RIAs for the NAAQS that underlie the literature discussed in this section do not present *ex ante* analyses with which the *ex post* literature can be compared.

A first step in studying the impact of nonattainment status on manufacturing activity is to establish whether new plants in certain industries were less likely to locate in nonattainment counties. The literature on the impact of nonattainment status on plant location focuses primarily on the impact of ozone nonattainment under the 1977 CAA amendments on industries that are major emitters of ozone precursors (VOCs and NO_x), such as petroleum refining and production of industrial organic chemicals, plastics, and steel. Using annual data from 1977–87, Henderson (1996) examines the impact of being in ozone attainment for the past three years on the count 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 metropolitan area employment. Being in attainment with the ozone standard for three years increased the number of plants

producing plastics and refining petroleum by about 6 percent each, and organic chemical plants by about 9 percent.

Henderson's (1996) analysis illustrates the importance of controlling for county fixed effects in analyzing the impact of nonattainment status on plant location. As noted, nonattainment 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 that the stringency of environmental regulation had either small or no impacts 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.⁵⁶

Henderson (1997) and Becker and Henderson (2000) significantly advanced the literature on the impact of the 1977 CAA amendments on plant births. Henderson (1997) estimates a fixed-effects logit model using annual data for 1977–87 for selected high VOC-emitting industries. Identification of the impact of nonattainment status in the fixed-effects logit model depends, however, on switches from nonattainment to attainment status and assumes that the impacts of such switches are symmetric. A superior approach is to model the impact of nonattainment 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 nonattainment status

⁵⁴Smith, Gans, and Yuan (2013) state that until 2011, the EPA only intermittently provided employment impacts in its RIAs. See OMB (2017) for a discussion of the impact of federal regulations on wages and employment and how these topics have been addressed in RIAs. As OMB notes, many regulations may be too small to have a direct impact on employment or plant closures. Closure impacts on electric utilities have been considered in regulations issued since 1990.

⁵⁵The 2011 Mercury and Air Toxics Standards RIA analyzes the labor market impacts of the rule on the power sector and on input markets. The 2015 Clean Power Plan RIA also contains a chapter on labor market effects.

⁵⁶It 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 nonattainment status under the CAA. McConnell and Schwab (1990) use ozone nonattainment status but do not include county fixed effects.

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 preregulation periods (1963–67 and 1967–72) and four post regulation periods (1972–77, 1977–82, 1982–87, and 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 nonattainment status at the beginning of the period is measured by a dummy variable, although the authors distinguish in some specifications between nonattainment counties that were monitored and those that were not.

A county's nonattainment status in 1978, 1982, and 1987 reduced plant births by 45 percent in industrial organic chemicals and by 26 to 29 percent in metal containers, plastics, and wood furniture.⁵⁷ These percentages apply to the entire post-regulation period.⁵⁸ Additional models suggest that the impact was greater in nonattainment counties that were monitored versus those that were not.

Using data on the births of high VOC-emitting plants in New York State over 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 (nonattainment) county-year observations in the dataset.⁵⁹ Overall, the conditional Poisson model suggests that ozone nonattainment 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 nonattainment status affected the growth of plants in high-emitting industries. Becker and Henderson (2000) investigate the impact of ozone nonattainment status on the value of sales by plants in multiple industries over 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. Nonattainment status is interacted with plant age. They find that new plants are significantly larger in nonattainment than in attainment counties, especially for the years 1987 and 1992. They interpret this as indicating plants' larger upfront investment in nonattainment counties due to environmental regulation: these plants are scrutinized more by regulators than plants in attainment

⁵⁷No significant effects were found in the eight low-emitting control industries.

⁵⁸To illustrate, there were 134 births in organic chemicals in nonattainment counties between 1967 and 1972 and 57 in attainment counties. In 1987–92, the model predicts that there would be 74 births in nonattainment and 57 in attainment counties. So the predicted share of births in nonattainment counties fell from 70 to 56 percent over the period.

⁵⁹Using three 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).

counties, so it pays to concentrate the initial negotiations (and investment) rather than extending them over time.

The quasi-experimental retrospective literature, which focuses on nonattainment status for ozone, suggests that plants that were large emitters of ozone precursors were less likely to locate in nonattainment than in attainment counties after the 1977 CAA amendments. Becker and Henderson (2000) find that a county being in nonattainment in 1978, 1982, and 1987 reduced plant births by 45 percent in industrial organic chemicals and by 26–29 percent in metal containers, plastics, and wood furniture. Henderson (1997) provides similar evidence for steel plants. List et al. (2003) find a similar percentage reduction (~40 percent) in the birth of plants in high-emitting industries in New York ozone nonattainment counties during 1980–90. There is also evidence that regulation altered plant size in these industries, leading to smaller plants in attainment counties in some industries (Becker and Henderson 2000).

5.5. *The Impact of Attainment Status on Employment and Earnings*

A concern of policy makers and the general public is that environmental regulation may reduce firm competitiveness and the demand for labor, especially in manufacturing industries. Whether job losses constitute a cost associated with environmental regulation depends on the adjustment costs incurred. If workers experience long periods of unemployment, economic costs may be substantial. Earnings losses among workers also raise distributional concerns. The literature that examines the impact of nonattainment status on employment and earnings in manufacturing has found significant negative effects, especially in high-emitting industries.⁶⁰

⁶⁰As noted in section 5.3, more recent RIAs discuss the employment impacts of regulations; however, they do not estimate wage impacts.

Greenstone (2002) provides a particularly thorough investigation of the impact of nonattainment status on manufacturing activity and employment, using data on all manufacturing plants for 1967, 1972, 1977, 1982, and 1987. Specifically, he estimates the impact of nonattainment status for CO, ozone, SO₂, and 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 nonattainment status is identified based on three sources of variation: cross-sectional variation in nonattainment status, changes in attainment status for a plant over time, and a comparison of polluting with nonpolluting plants. Polluting plants are those in any one of 12 manufacturing industries that are high emitters of any of the criteria air pollutants or their precursors.

Greenstone (2002) thus asks whether the 1970 CAA and the 1977 amendments affected manufacturing activity and employment for both new and existing plants. Under the 1970 and 1977 legislation, SIPs were to control existing sources in nonattainment areas; hence the analysis captures the impact of controls on existing plants and on both plant births and deaths.⁶¹ Each model controls for the impact of nonattainment status for a particular criteria pollutant, holding constant nonattainment status for other pollutants.

The results are most pronounced for CO and ozone nonattainment status. For plants in high-emitting industries in nonattainment counties, nonattainment 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; the effects on employment are largest in iron and steel (–18 percent) and petroleum refining (–13 percent). Ozone nonattainment status

⁶¹Of the 1,737,753 plant observations across four periods, 29 percent represent births, 27 percent deaths, and 44 percent stayers.

is associated with a statistically significant 4.9 percent decline in employment for plants in high-emitting industries; the effects are largest in the pulp and paper, iron and steel, printing, and plastics industries, and slightly smaller in the stone, clay, and glass industries, ranging from -7 to -11 percent over a five-year period.

The implications of those estimates for the number of jobs lost are that environmental regulations resulted in a loss of 591,000 jobs over 1972–89 at high-emitting plants in nonattainment counties (39,000 jobs per year).⁶² To put this in perspective, total annual manufacturing employment was 17.4 million during 1967–72. As Greenstone (2002) acknowledges, it is not possible to say whether some of the jobs lost in nonattainment counties went to attainment counties. The corresponding figures for the declines in the capital stock and value of shipments at high-emitting plants in nonattainment counties are \$37 billion and \$75 billion (US\$(1987)), respectively. Both figures represent declines over 1972–87, relative to plants in attainment counties, but are not significantly different from zero.⁶³

Kahn and Mansur (2013) examine the effects of nonattainment status for ozone on manufacturing employment over 1998–2009 by examining variation in attainment status, energy prices, and labor regulations between adjacent counties. The advantage of the border-pair methodology is that other factors that affect the location of manufacturing industry—such as manufacturing wages and proximity to input suppliers and purchasers of the products—are likely to be constant within border pairs. Employment is measured at the county, border-pair, year, and industry level. The impact of ozone

nonattainment status on employment varies according to a pollution index, which measures the total amount of ozone precursors emitted by each industry. Kahn and Mansur find significant negative effects of ozone nonattainment on employment for industries with high pollution indexes, although results are sensitive to the specification of the equation. As in Greenstone (2002), impacts represent employment losses relative to attainment counties.

To determine whether employment losses in nonattainment counties were made up by gains in manufacturing employment in attainment counties, the subsequent labor market experience of workers displaced by the CAA must be followed. Walker (2013) combines information on the pollution status of plants under the 1990 CAA amendments with data from LEHD files and the Longitudinal Business Database (LBD) to study the impacts of the 1990 CAA amendments 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 to 2005, is used to examine pre-1990 trends in employment and earnings and for some of the baseline analysis. Manufacturing plants in counties that are in nonattainment for ozone or PM_{10} were classified as polluting plants if they required a permit from the EPA to operate. All manufacturing plants fall into one of four polluting sectors: emitting PM_{10} only, emitting ozone precursors only, emitting both, or nonpolluting. Data from the LEHD are aggregated to the cohort–sector–industry level. Data from the LBD are aggregated to the county–sector–year level.

Walker (2013) uses a triple-difference estimator to capture the impact of

⁶²Ninety-five percent CI = $-118,400$ to $-1,065,200$.

⁶³Ninety-five percent CI = \$16.4 billion to $-\$89.6$ billion for the capital stock and \$27.4 billion to $-\$178$ billion for the value of shipments.

nonattainment 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 nonattainment for pollutant p and the plant is emitting pollutant p , and if t is after the 1990 CAA amendments 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 on employment and earnings.

In Walker's (2013) 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 borne 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 preregulation annual earnings. Within this group, workers who change industries suffer larger losses than those who remain in the same industry. These results indicate the magnitude of adjustment costs associated with environmental regulation and also inform the larger literature on the adjustment costs of worker displacement (Gibbons and Katz 1991; Jacobson, LaLonde, and Sullivan 1993; von Wachter, Handwerker, and Hildreth 2009).

The literature on the employment effects of the CAA indicates that regulation under the CAA had impacts on manufacturing firms—shifting high-emitting firms to attainment counties—and caused employment losses in high-emitting industries. Indeed, Greenstone (2002) estimates that this resulted in the loss of 39,000 jobs per year

between 1972 and 1989 in nonattainment relative to attainment counties. Walker's (2013) study suggests that there were significant, unanticipated effects on employment and earnings due to regulations issued under the 1990 CAA amendments: 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 questions about how these impacts could have been ameliorated and how they should be dealt with in the future.

6. Summary and Conclusions

6.1. Findings from Retrospective Studies

The quasi-experimental economics literature addresses an array of important questions about the performance of CAA regulations. What have we learned from ex post studies of the CAA? Was the CAA effective in reducing emissions and improving air quality? What do we know about the health and welfare benefits of the CAA that we did not know before? And what were the costs and economic effects of the CAA on consumers, firms, and workers? In synthesizing the literature relevant to these questions, we have also identified some gaps in knowledge that can motivate future research.

6.1.1. What We Know about the Impact on Emissions and Air Quality

Ex post studies provide causal evidence that the CAA improved air quality: concentrations of the criteria pollutants fell faster in nonattainment counties—which were required to implement stringent regulations to comply with the NAAQS—than in attainment counties. Particulate matter, measured by TSP, fell by 9–10 $\mu\text{g}/\text{m}^3$ (11–12 percent) more in nonattainment counties than in attainment counties between 1970 and 1980. Between 1990 and 2000, PM_{10} fell 7–9 $\mu\text{g}/\text{m}^3$

more (11 to 13 percent) at monitors that were out of attainment than at monitors that were in attainment. And as a result of the 2006 standard for fine particles, $PM_{2.5}$ fell by $1.24 \mu\text{g}/\text{m}^3$ (69 percent) more in nonattainment than in attainment counties between 2004 and 2013.

Studies have also documented improvements in ground-level ozone and sulfur dioxide due to the CAA. Between 1977 and 1987, maximum July ozone levels in nonattainment counties fell by 8 percent more in nonattainment than in attainment counties. The NO_x budget program, designed to reduce emissions of ozone precursors in the eastern United States, reduced high-ozone days by 35 percent during the years that the program operated (2003–07). The RECLAIM cap-and-trade program reduced NO_x emissions at covered facilities 20 percent more than comparable sources regulated by command-and-control regulation in Southern California. And by 1992, SO_2 had fallen 7 to 11 percent faster in counties that were out of attainment for SO_2 in 1990 than for counties that were in attainment.

There are, however, cases where CAA regulations failed to improve air quality. In states where refiners were given flexibility in selecting which VOCs to remove from gasoline, ozone levels did not improve: refiners chose the cheapest option—removing butane, which is less reactive than other VOCs. In contrast, the more prescriptive fuel content rules issued by the California Air Resources Board did yield measurable benefits in terms of lower ozone concentrations and adverse health outcomes, yet mostly in California's urban areas.

6.1.2. *What We Do Not Know about the Impact on Emissions and Air Quality*

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 the studies we have reviewed, federal controls on automobile emissions and NSPS on industry were instituted throughout the country, in both attainment and nonattainment areas. There is indirect evidence that these policies improved air quality. Studies of the impact of the NAAQS on ambient ozone in nonattainment counties over 1978–87 show a significant downward trend in ambient ozone at all monitors in urban counties in the United States, which could be due to federal policies. The large reduction in NO_x emissions from motor vehicles in California—a reduction unrelated to county-level policies—was likely responsible for part of the observed decrease in PM_{10} at state monitors over 1990–99. This reduction in NO_x emissions cannot, however, be attributed to county-level policies, and we are not aware of any quasi-experimental evidence of the effect of these national-level policies on ambient air quality.⁶⁴

6.1.3. *What We Know about the Impact on Health and Welfare*

A major justification of the CAA is to protect human health. Ex ante RIAs estimate the health benefits associated with reductions in air pollution using observational studies from the epidemiological literature. As Currie and Walker (2019) point out, economists have produced a large quasi-experimental literature documenting the impact of the criteria pollutants on adult and infant mortality, emergency hospital admissions, and other health endpoints.⁶⁵ This literature provides

⁶⁴The dramatic reduction in the emissions of chlorofluorocarbons and other substances that deplete the stratospheric ozone layer may also reflect EPA regulations, as well as independent changes in firms' production processes and consumer behavior.

⁶⁵Currie and Walker (2019) provide an excellent summary of this literature. We note that although this literature establishes a causal relationship between the criteria pollutants and various health outcomes, most studies do not

evidence of a causal relationship between air pollution and health. Our review focuses on the part of this literature that uses CAA regulations to establish a causal link between the legislation and health.

Ex post studies provide evidence that reductions in air pollution attributable to the CAA have improved health. The NO_x Budget Trading Program reduced deaths associated with ozone by about 2,000 per year in the 19 states where the program operated, and it also reduced defensive medical expenditures—a category of benefits not currently counted in RIAs—by approximately \$800 million (2015\$) annually. Eliminating the use of leaded gasoline at NASCAR races delivered more than \$2 billion (2019\$) in benefits in terms of premature mortality. California's 1996 gasoline content regulations reduced children's asthma hospitalizations by 8 percent, saving \$13.2 million (2006\$) in health care costs annually.

Other studies of health benefits that we have reviewed link reductions in air pollution under the CAA to human capital losses and dementia—health impacts not previously considered in RIAs. Reduced exposure to particulate pollution during the first year of life, based on data from the early 1970s, has been shown to result in higher earnings and higher probability of employment among young adults. Specifically, a 10 $\mu\text{g}/\text{m}^3$ reduction in TSP exposure during the first year of life increases earnings at age 30 by about 1 percent. A recent study estimates that a 1 $\mu\text{g}/\text{m}^3$ change in average PM_{2.5} exposure between 2004 and 2013 increased the probability of a dementia diagnosis over this period by 1.68 percentage points. This implies that the CAA reduced the number of dementia diagnoses between 2004 and 2013 by 180,000 persons, which translates to \$214 billion in benefits.

Improvements in air quality also provide aesthetic benefits, including improved

visibility in residential areas. Economists have long used the capitalization of air quality in property values to estimate what households perceive to be the benefits of clean air.⁶⁶ Ex post studies of the CAA have demonstrated that air quality regulations in nonattainment counties increased property values in these counties. The benefits of reductions in TSP in nonattainment counties between 1970 and 1980, as reflected in housing values, were \$45 billion (US\$(1982)). The corresponding benefits of reductions in PM₁₀ between 1990 and 2000, as reflected in property values in nonattainment counties, were approximately \$44 billion (US\$(2000)).

From a distributional perspective, it is of interest to know whether increases in housing values due to air quality improvements are passed on to renters in the form of higher rents. If the value of air quality improvements is fully reflected in rents, then renters enjoy no net gain from air quality improvements. The literature, however, suggests that renters do not fully pay for improvements in air quality: rental values do not increase as much as the value of owner-occupied homes.

6.1.4. *What We Do Not Know about the Health and Welfare Benefits*

No quasi-experimental studies provide estimates of the aggregate benefits of a regulation:⁶⁷ they do not attempt to estimate the impact of the regulation on each of the criteria pollutants and then translate this impact into health and welfare benefits.

⁶⁶The benefits of clean air, as perceived by households, may include health benefits. To avoid the double-counting of health benefits, the impact of reductions in air pollution on residential property values are not included in RIAs.

⁶⁷The closest exception is Deschênes, Greenstone, and Shapiro's (2017) study of the NO_x Budget Trading Program, which provides estimates of premature mortality and defensive expenditures (morbidity-related) benefits. This paper, however, does not address other categories of benefits monetized in the ex ante analysis by the EPA (1998b), such as agricultural productivity, worker productivity, lost school days, and nitrogen deposition in estuaries.

establish that reductions in air pollution are the result of the CAA.

Whereas RIAs are tasked with estimating the aggregate benefits of a regulation, this is not the objective of the ex post literature. It is also the case that, even conditional on the reductions in ambient pollution assumed in RIAs, ex post studies do not provide estimates of aggregate benefits that can be compared with those generated in the original RIA. As noted by Currie and Walker (2019), the economics literature has not yet produced a concentration–response function linking particulate matter to premature mortality that can be compared with the relationships used in RIAs. It is therefore not possible to compare, for example, the EPA’s estimate of the benefits of the 1990 CAA amendments (EPA 1999, 2011) with a comparable estimate from retrospective studies.

6.1.5. *What We Know about the Costs*

The CAA was responsible for launching a national cap-and-trade program to reduce sulfur dioxide (the SO₂ allowance program) and multiple regional trading programs—the NO_x Budget Trading Program, covering NO_x emissions in 21 states, as well as RECLAIM in Southern California, which capped NO_x and SO₂ emissions. The EPA implemented nationwide tradable credit programs to reduce the lead content of gasoline and to increase biofuel shares of gasoline and diesel through the RFS.⁶⁸ Ex post studies have provided estimates of the cost savings from cap-and-trade and have also answered questions about the functioning of cap-and-trade markets in the real world.

The SO₂ 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 with imposing a uniform performance standard on electric utilities. The ex post literature suggests that the program led to cost savings equal to about 20 percent of the costs of complying with a uniform performance standard that would deliver comparable emissions outcomes. These savings are not as large as were predicted ex ante—in part because of some utilities’ decision 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, which raised the relative cost of transporting low-sulfur coal to power plants.

The design of allowance markets can have important implications for the distribution of damages. Although studies have estimated the benefits of trading SO₂ allowances at prices that reflect the marginal damages of different emitters, questions remain about the administrative feasibility of this approach. Another question is whether markets in which allowances traded one-for-one have led to hot spots—areas of high damages caused when allowance purchasers are located in areas where marginal damages are much higher than in areas where the sellers are located. Studies of the RECLAIM market in Southern California suggest that emissions fell across all areas, but higher-income neighborhoods experienced relatively larger emissions reductions.

The literature has also documented situations in which pollution market design could be improved. In the case of the market for renewable fuel credits, the technologically ambitious targets for cellulosic ethanol volume have turned out to be commercially infeasible. This has required the EPA to revise the regulatory obligations for refiners, which are required to submit credits to comply with the Renewable Fuel Standard. The EPA’s approach—announcing annual rather than multiyear credit targets—undermined policy

⁶⁸ Beyond these CAA pollution markets that have been subject to ex post analysis in the academic literature, the EPA has employed tradable allowance and credit programs for a variety of CAA rules, including the Cross-State Air Pollution Rule and the sulfur and benzene fuel content regulations.

predictability and led to volatility in the price of credits. Announcing feasible renewable fuel mandates several years in advance, as was done under the SO₂ 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, as in the RECLAIM program, which experienced a 100-fold increase in allowance prices over about one year.

The design of underlying power markets has also influenced the compliance strategies pursued by power plants. Under both the SO₂ allowance and the NO_x budget programs, power plants operating under cost-of-service rate regulation invested in capital-intensive pollution control equipment at significantly greater rates than power plants selling electricity into competitive wholesale power markets. This evidence of the Averch–Johnson effect illustrates how the costs of compliance with CAA regulation may depend on the incentives that arise at the intersection of environmental and economic regulatory regimes.

Ex post studies have also explored the economic impacts and adjustment costs associated with spatially differentiated environmental standards. The CAA required states to impose more stringent regulations on counties declared out of attainment with the NAAQS and, in the 1977 CAA amendments, directly imposed more stringent emissions standards on plants located in nonattainment areas. This caused the share of new plants in high-emitting industries to decline and also reduced employment in these industries in nonattainment versus attainment counties. The literature suggests that plants that were large emitters of ozone precursors were between 30 and 45 percent less likely to locate in nonattainment than in attainment counties after the 1977 CAA amendments. It has been estimated that CAA regulations resulted in a loss of 591,000 jobs over 1972–89 at high-emitting plants

in nonattainment counties (39,000 jobs per year) relative to attainment counties.

There is evidence that workers in regulated industries, especially workers who changed firms, suffered significant earnings losses. Between 1990 and 2000, the average worker in a newly regulated plant experienced an earnings loss equal in present value to 20 percent of annual pre-regulatory earnings. In the aggregate, this loss was \$5.4 billion (US\$(1990)), although the pattern of losses shows great heterogeneity. Workers who remained with their pre-regulation firms suffered essentially no losses, but workers who changed firms—especially older, higher-paid workers—bore most of these losses.

The literature has also documented instances where regulations issued under the CAA segmented the input or output markets and gave firms the opportunity to exercise market power. By 2004, more than a dozen varieties of RFG, designed to reduce ambient ozone pollution, were being sold throughout the United States. Evidence suggests that by segmenting the market, multiple varieties of gasoline increased market power in some regional markets, thus raising the price and price volatility of gasoline. Moreover, environmental regulations under the 1990 CAA amendments may have led to greater concentration of market power in the cement industry by raising the fixed costs of market entry (Ryan 2012).

6.1.6. *What We Do Not Know about the Costs*

Most ex post studies of the costs of the CAA have focused on its impacts on industry structure, plant location, and employment and earnings. Few have attempted to measure the direct costs that firms incur in complying with regulations—costs that are often measured in RIAs using engineering cost models. Obtaining causal information on compliance costs has been difficult because of the lack of a control group. Structural models

can sometimes be used to fill this void, but we still do not know, *ex post*, the direct compliance costs of most regulations issued under the CAA.

6.2 *The Evolution of the Retrospective Literature and the Research Frontier*

In our review of the CAA retrospective literature, the application of quasi-experimental methods to estimate the causal impacts of air quality regulations began with scholarship published in the 1990s. This CAA literature built on and extended the empirical techniques developed for program evaluation in labor and public economics. We close with some insights about the evolution of the data and methods used in retrospective analysis, the prospects for applying innovations in big data and empirical methods going forward, and opportunities for advancing this research frontier.

6.2.1. *The Data Revolution*

A defining characteristic of the CAA retrospective analysis literature has been the reliance on non-EPA data for evaluating the performance of EPA regulations. It is common in this literature for a retrospective analysis to use only the most basic information about an EPA regulation—such as the dates it is in effect and the entities or regions that it covers—and rely on non-EPA data to estimate economic costs and health impacts. For example, power plant analyses typically rely on Energy Information Administration data compiled through various annual surveys of the electricity sector (e.g., Carlson et al. 2000). Manufacturing sector analyses typically rely on Census Bureau data from the Annual Survey of Manufactures and Economic Census (e.g., Greenstone 2002). Estimating the mortality and morbidity impacts of CAA regulations may require information generated by the National Center for Health Statistics. Increasingly, researchers studying CAA regulations are demonstrating creativity

in finding and connecting various datasets to enable empirical evaluation of EPA rules.

In more recent years, researchers have drawn from proprietary datasets to assess the impacts of CAA regulations. Understanding the impacts of fuel content standards on gasoline prices, for example, requires market-specific, high-frequency price data (Brown et al. 2008). Exploring how lower ambient air pollution concentrations reduce defensive investments requires high-frequency, location-specific pharmaceutical expenditure data (Deschênes et al. 2017).

Administrative records have also enabled further examination of the CAA. For example, analyses using the LEHD database at the Census Bureau shed light on labor market dynamics for workers in industries affected by CAA regulations and help identify the effects of early childhood pollution exposure on individuals' later labor force participation and earnings (Walker 2013; Isen, Rossin-Slater, and Walker 2017). The Quarterly Workforce Indicators dataset, based on the LEHD, serves as the basis for labor market analysis of the NO_x Budget Trading Program (Curtis 2018).

The ongoing data revolution represents a potentially major step forward in the kinds of information scholars can exploit to assess the CAA. Ambient levels of air pollution have long been measured by government-installed monitors—raising issues of spatial coverage, monitor outages, and nonrandom placement—but today, new, more comprehensive pollution data sources are available. Satellite-based data enable a richer understanding of fine particulate matter pollution across the country. Some Google street-view vehicles track and map street-level pollution. The dramatic decline in costs of drone and monitoring technologies could provide even more opportunities for measuring pollution with a high degree of spatial and temporal resolution.

The growing opportunities for analyzing administrative records data can lay the foundation for further CAA research. Recent research on the mortality and health expenditure impacts of air pollution exposure, based on the Medicare records of millions of individuals age 65 and older, illustrates how such data could serve future analyses of the contributions of specific CAA regulations on these health outcomes and, importantly, the distribution of outcomes. Internal Revenue Service tax return data have been used to analyze returns to education, economic mobility, and racial differences in economic attainment (e.g., Chetty et al. 2020). These data could also facilitate further investigations into the impacts of CAA regulations.

The availability of economic activity and online activity data can also enrich future CAA scholarship. Residential property value data from Zillow and Corelogic, high-frequency mobility data from cell phones, Google search activity, and internet-connected appliance use data could be used in estimating the impacts of CAA regulations. The emergence of new data enables both a richer set of empirical strategies and a broader set of outcomes that scholars can study.

6.2.2. *The Methods Evolution*

Much of the early CAA retrospective analysis literature employed a difference-in-differences empirical strategy—exploiting the spatial variation in the timing and stringency of specific CAA regulations—or an instrumental variables strategy in which the CAA regulation often served as the instrument. In implementing statistical models that exploited exogenous variation in the key variable of interest, these approaches distinguished themselves from an epidemiology literature, largely focused on associations in estimating air quality and health outcomes, and from a business literature, largely focused on case studies, in estimating productivity, labor, and related firm and market outcomes.

More recently, researchers have adapted these standard program evaluation identification tools and refined them, given both the CAA context and improvements in the empirical methods literature. Some scholars have modified difference-in-differences by using a matching estimator that selects a sample of controls, which better ensures comparable pre-trends between treatment and control groups (Ferris, Shadbegian, and Wolverton 2014). The insights from atmospheric science have also informed new empirical strategies. To address measurement issues associated with the location of pollution monitors, an instrumental variables approach using wind direction as the instrument has enabled causal identification of the mortality impact of particulate matter exposure (Deryugina et al. 2019). Accounting for pollution transport, a spatial regression discontinuity estimator has enabled rigorous estimation of the adverse health impacts of lead exposure near race-tracks where cars were fueled with leaded gasoline (Hollingsworth and Rudik 2021).

Future applications of empirical methods could also draw on approaches considered beyond the standard program evaluation toolkit. As noted in section 6.1, few studies estimate the costs of CAA regulations. Ryan's (2012) evaluation of the costs of the CAA on the Portland cement industry is a notable exception. Ryan estimates the costs of the regulation by building a structural model of the industry that accounts for imperfect competition and market dynamics and uses it to model the CAA and counterfactual policies. Given the extent of imperfectly competitive industries subject to CAA regulation, such an empirical framework could complement reduced-form program evaluation strategies and enrich our understanding of industry impacts under the CAA. Given the extensive application of structural industrial organization models to the automobile manufacturing sector, these approaches could be used to evaluate tailpipe emissions standards. This

may also build on a large literature on fuel economy standards—based on structural and reduced-form analyses—that could have important implications for the CAA, given recent actions by the EPA and the Department of Transportation to simultaneously regulate tailpipe CO₂ emissions and fuel economy.

The emergence of large datasets also highlights the potential for machine learning to improve our understanding of the CAA. Such tools may help extract information signals from large datasets, enable assessments of the distribution of impacts across space and time, and illustrate the underlying mechanisms driving CAA impacts. Recent innovations in machine learning could leverage the benefits of machine learning with big datasets in a causal inference framework.

6.2.3. *Opportunities to Advance the Research Frontier*

Exploiting the advances in novel datasets and empirical methods for evaluating such data provides new opportunities for evaluating CAA regulatory performance. We highlight a few of these opportunities below. Some are specific to the CAA, while others could inform ex post regulatory evaluations in other regulatory contexts.

First, scholars could partner with regulators in the design of regulations and associated evaluation frameworks. This could take several forms. Researchers could collaborate with regulators to develop a rule that randomizes implementation across affected entities.⁶⁹ Such randomization may be difficult to justify legally under the CAA, but it may be possible to explore opportunities for learning through randomized treatments for information disclosure activities

undertaken by the EPA. This could include the fuel economy labels for new automobiles (which include a raft of information about local air pollutants and greenhouse gas emissions), the EnergyStar labeling program, and the Toxic Release Inventory.

An alternative approach would be for researchers to work with regulators on evaluation plans for new regulations (Aldy 2014; Cropper, Morgenstern, and Rivers 2018). This would involve planning for an ex post regulatory analysis at the time of regulatory development. Such efforts would involve establishing data collection protocols, constructing empirical strategies, and implementing the regulation to ensure the exogenous variation necessary to identify regulatory impacts. The rich literature surveyed above provides guidance on the data, sources of regulatory variation, and empirical methods that could inform regulatory evaluation plans. This could serve as a cornerstone of how the EPA implements the Foundations for Evidence-Based Policymaking Act of 2018 as it relates to the core activity of the agency: environmental regulation.

Second, scholars could advance efforts to bridge the divide between estimating pollution dose-response functions and estimating the impacts of specific CAA regulatory actions. The vast majority of the EPA's RIAs for CAA regulations rely on epidemiological dose-response functions that are neither causal nor based on variation induced by the regulation (or similar regulation) in question. Much of the economics literature—including some of what is synthesized in Currie and Walker (2019)—addresses the first issue through quasi-experimental methods, but does not necessarily connect the change in pollution to specific regulations. Understanding the performance of a regulation—especially given the complexity of atmospheric chemistry, overlapping policies, and changing economic structure over time—often requires an explicit assessment

⁶⁹For a related example, Duffo et al. (2018) worked with the environmental regulator in an Indian state to randomize environmental inspections so as to determine the effect of greater likelihood of an audit on regulatory compliance. In this case, the regulation was common across covered entities, but its enforcement was randomized.

of how a regulation changes pollution and how this change in pollution affects various outcomes of interest, including public health and firm costs.

Such efforts could also expand the scope of public health impacts studied to address an array of nonfatal health risks associated with air pollution exposure. Both the epidemiological and the economics literatures have focused more attention on air pollution-related premature mortality. The underlying evidence for some of the nonfatal health benefits, worker productivity, and school absences identified in CAA RIAs could be updated with more recent, credibly estimated relationships. Moreover, every CAA RIA includes a list of nonmonetized benefits that could be quantified and monetized in future analyses if the research literature addresses these often-overlooked impacts.

Third, spatially disaggregated data can enable much richer evaluations of the distributional impacts of CAA policies. Given presidential guidance through executive orders requiring regulatory agencies to compare benefits and costs in their RIAs and the emphasis of our discipline on social welfare, it is natural that both EPA *ex ante* analyses of regulations and academic *ex post* evaluations have focused their attention on net social benefits. This also reflects some of the historical limitations in data and methods. With advances on both fronts, there are many opportunities for evaluating the distribution of benefits and costs of CAA regulations across sociodemographic characteristics, regions, and industries.

Fourth, the gradual blurring of environmental and energy policy in the context of mitigating greenhouse gas emissions creates challenges and opportunities for evaluating climate change policies going forward. The EPA has begun implementing regulations focused on greenhouse gas emissions, and these overlap with Department of Energy regulations on appliance efficiency,

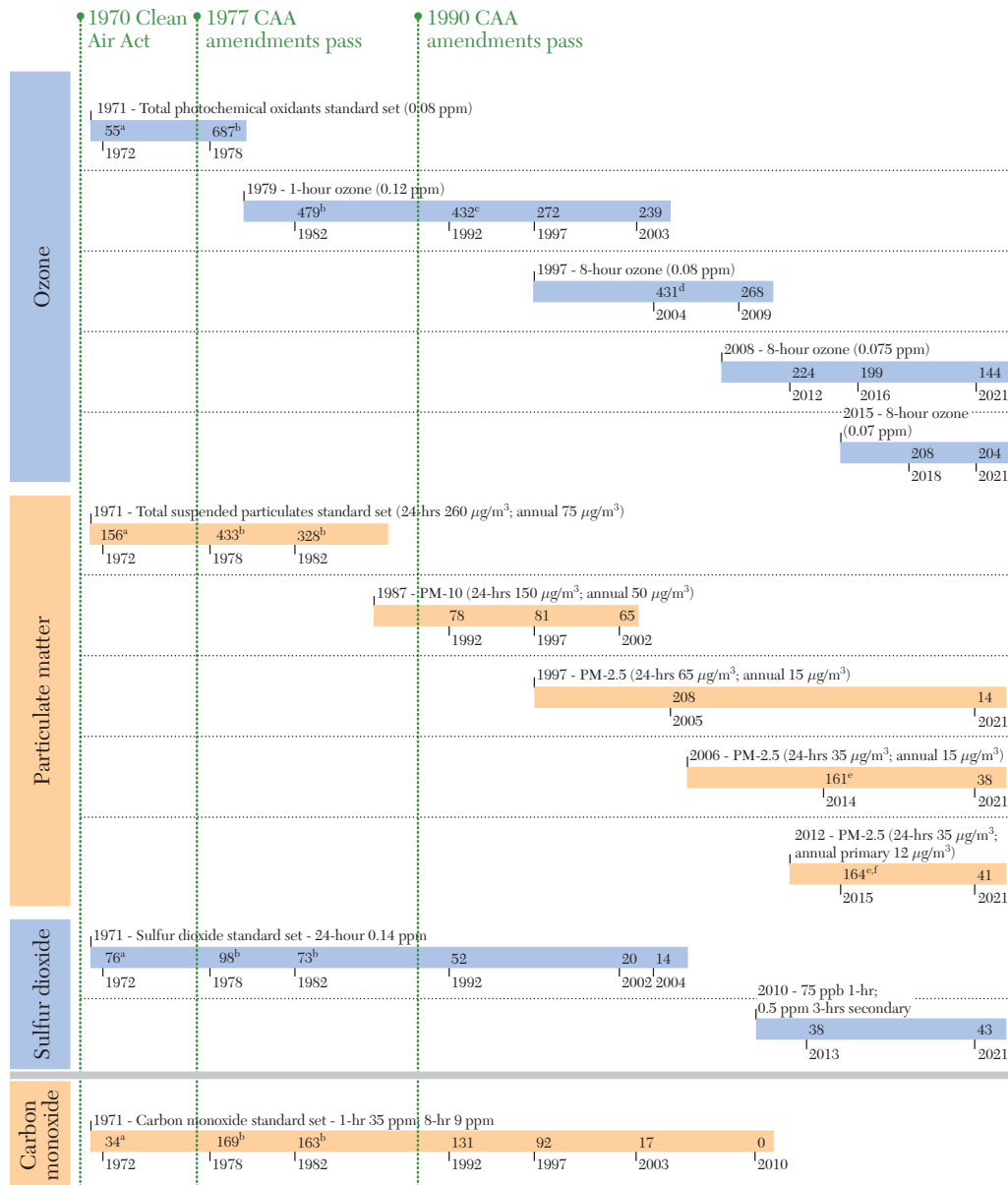
Department of Transportation regulations on fuel economy, and a variety of tax expenditures for low- and zero-emissions technologies. The EPA's regulations also overlap with state-level policies on greenhouse gas emissions, renewable power mandates, and low-carbon fuel standards. The patchwork policy landscape may complicate efforts to statistically identify the impacts of specific CAA regulations, but they may also heighten the social value of such analyses, given the potential welfare losses that may emerge in this complex, generally uncoordinated policy approach to climate change.

Shapiro and Walker (2018) illustrate an approach for addressing this multiple, overlapping policy challenge in their assessment of the decline in air pollution among US manufacturing industries. They develop a structural model that includes an effective pollution tax that represents the shadow cost of all federal and state air pollution regulatory burdens manufacturing facilities bear. This enables them to distinguish the roles of regulation, trade shocks, and productivity shocks on the changes in air pollution over time. Future work could build on this foundation to examine the broad scope of climate-oriented environmental and energy policies and explore ways to decompose this regulatory shadow cost on a regulation- and policy-specific basis.

Finally, we encourage scholars to evaluate, replicate, and extend the existing literature. Replicating aspects of the current knowledge base can further promote its use in the EPA's future CAA regulatory developments and analyses. New data and methods may provide alternative identification strategies for evaluating existing and past regulations. Given the often intense policy debates over the future of air quality regulations, expanding the rigorous evidence basis for such debates could promote welfare-improving, cost-effective, and distributionally beneficial environmental policies.

APPENDIX

FIGURE A1
 NUMBER OF AIR QUALITY CONTROL REGIONS OR COUNTIES OUT OF ATTAINMENT WITH NATIONAL AMBIENT AIR QUALITY STANDARDS



Notes: Nonattainment status was defined by Air Quality Control Region (AQCR) until 1978 and by county thereafter. The figure reports AQCRs out of attainment in 1972 and counties out of attainment beginning in 1978. Unless otherwise noted, nonattainment county figures for 1992 and subsequent years come from US EPA's NAYRO dataset retrieved in November 2021; (a) 37 FR 10841; (b) Greenstone 2002; (c) 56 FR 56694; (d) US EPA. Green Book; (e) 79 FR 31565; (f) 79 FR 31565 and NAYRO dataset for 2015.

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