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A Retrospective Review of Retrospective Cost Analyses

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ABSTRACT: In this paper, we identify the main factors that drive differences between ex ante and ex post cost estimates. The paper reviews evidence from peer-reviewed studies of the realized costs of 13 significant EPA regulations to develop lessons for the design of future ex ante and ex post analyses of rules. Most of the retrospective studies address realized compliance strategies, though some also offer insights into specific elements of per-unit compliance costs. Only a few shed light on the total cost of the regulation studied. All the studies have data limitations, but in general, more insight was obtained when detailed facility-level data (e.g., power plants) were available. In spite of data and methodological limitations, as well as the narrow focus of some studies, we identify several common sources of differences between ex ante and ex post estimates. For example, these studies reveal that firms adopted substantially different compliance strategies than anticipated in ex ante analysis for nearly 70 percent of the regulations. Other key drivers of differences include reliance on engineering models, misspecification of the baseline, and failure to anticipate the role of new technologies.

To improve future ex ante cost analysis, we recommend better characterization of baseline conditions, sensitivity analysis of highly uncertain parameters, greater use of economic models of the regulated sector to better reflect firm decisionmaking, and analysis of phase-in periods. For ex post analyses, we recommend developing plans for future study at the time the regulation is adopted. Aside from opportunistic cases, it will be difficult to conduct thorough retrospective evaluations without a plan in place ex ante that identifies endpoints of interest, methods of analysis, and data needs.

KEYWORDS: benefit-cost analysis, regulatory analysis, retrospective evaluation

JEL CODES: Q52, L6, D61

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The views expressed in this paper are those of the author(s) and do not necessarily represent those of the U.S. Environmental Protection Agency (EPA). In addition, although the research described in this paper may have been funded entirely or in part by the U.S EPA, it has not been subjected to the Agency's required peer and policy review. No official Agency endorsement should be inferred.

1. Introduction[1,2,3]

Since 1981, a series of executive orders (EOs) have required that proposed US federal rulemakings be accompanied by benefit-cost analysis (BCA). The systematic review of these BCAs by the Office of Management and Budget and their release for public comment have increased their relative importance in the federal decision-making process. However, while informative regarding the anticipated effects of a regulation, BCAs are conducted ex ante—"the point when we know the least, precisely because the regulations are untested" (Greenstone 2013). These ex ante BCAs cannot inform the question of whether a regulation has delivered the promised benefits at the expected costs. Retrospective analyses, ex post examinations of the effects of a rule once it is in place, are designed to provide such information, but these analyses are conducted relatively infrequently (Aldy 2014).

Policymakers have long attempted to better integrate retrospective review and analysis into federal decision-making. Every administration since President Carter has initiated efforts urging

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[3] The authors thank Dick Morgenstern, Nathalie Simon, Terry Dinan, Dominic Mancini, and Al McGartland, as well as participants in an RFF workshop on conducting retrospective reviews of regulation, for their thoughtful comments and suggestions.

agencies to reassess existing regulations (Aldy 2014).[4] Agencies also are directed to conduct periodic reviews of regulations under some statutes.[5]

The Administrative Conference of the United States offered "recommendations designed to promote a culture of retrospective review at agencies," including how to plan for them at the initial stage of regulation and criteria for identifying regulations that should be subject to review (ACUS 2014). The Foundations for Evidence-Based Policymaking Act of 2018 requires that agencies submit a plan to the Office of Management and Budget that includes discussion of what data they "intend to collect, use, or acquire to facilitate the use of evidence in policymaking." A bipartisan bill, Setting Manageable Analysis Requirements in Text (SMART) Act, introduced by Senators Lankford and Sinema in May 2019 to improve the regulatory development process, goes even further by requiring agencies to conduct an analysis of the realized costs and benefits of significant regulations after they have been implemented and to present a plan for how that analysis will be conducted at the time the original rule is promulgated. These efforts reflect a thirst for greater understanding of when regulation works well and when it does not. Without such information, it is difficult to prioritize regulations ripe for strengthening, modification, or even elimination based on actualized costs and benefits.

[4] Most recently, President Obama called for retrospective review in EOs 13563, 13579 and 13610. President Trump issued EO 13771, directing agencies to cut two existing rules for each new rule issued and to offset costs imposed by new rules. While retrospective analysis is not explicitly required, agencies identified existing regulations to repeal or revise and then quantified the expected cost savings from them.

[5] For instance, the Regulatory Flexibility Act requires review of regulations with "a significant economic impact upon a substantial number of small entities" within 10 years of promulgation. Also, under Section 812 of the 1990 Clean Air Act Amendments, EPA conducted one retrospective review and a couple of prospective reviews. For more information, see https://www.epa.gov/clean-air-act-overview/benefits-and-costs-clean-air-act.

In this paper, we review 28 ex post analyses in the peer-reviewed literature of the costs of 13 individual significant EPA regulations.[6] All the studies have data limitations, but in general, more information can be obtained for regulations affecting industries that report detailed facility-level data (e.g., power plants). In spite of data and methodological limitations, as well as the narrowness in scope of some studies, we find that many of the studies provide insights on realized compliance strategies. Some also offer a greater appreciation of factors affecting specific elements of per-unit compliance costs (e.g., capital expenditures for a subset of entities). Only a few shed light on overall per-unit compliance costs, and even fewer speak to the total cost of the regulation studied.

Most prior reviews of retrospective cost analyses largely focus on a discussion of whether compliance costs tend to be under- or overestimated. We contribute to the literature on the role of retrospective analysis in several ways: We develop a systematic framework identifying the key elements affecting differences in realized compliance costs for each study. We then build on this assessment to identify common sources of differences between ex ante and ex post estimates across regulations. These differences include the failure to account for significant exogenous factors in the baseline, the role of compliance flexibilities, and how innovation affects both compliance choices and costs. In some cases, the study findings suggest the direction of

[6] Executive Order (EO) 12866 requires agencies to assess potential costs and benefits for "significant" rules. The term *significant* refers to policy actions that "(1) have an annual effect on the economy of $100 million or more or adversely affect in a material way the economy, a sector of the economy, productivity, competition, jobs, the environment, public health or safety, or State, local, or tribal governments or communities; (2) create a serious inconsistency or otherwise interfere with an action taken or planned by another agency; (3) materially alter the budgetary impact of entitlements, grants, user fees, or loan programs or the rights and obligations of recipients thereof; or (4) raise novel legal or policy issues arising out of legal mandates, the President's priorities, or the principles set forth in this Executive order." Also, see OMB (2003).

difference—that is, whether per-unit costs were over- or underestimated. Finally, we discuss what lessons our results offer for designing future ex ante or ex post analyses of EPA rules.

The paper is organized as follows. Section 2 briefly discusses prior literature reviews of retrospective analyses and attempts to systematically survey the evidence. It also considers reasons why ex ante and ex post costs might be expected to differ. Section 3 presents an overview of the 28 studies included in our sample. We categorize each study based on the methodological approach, breadth, and whether it makes explicit comparison with EPA's ex ante analysis. Section 4 describes our approaches to assessing which aspects of compliance costs the studies can inform and identifying common sources of differences. Section 5 presents our findings. Section 6 concludes and looks at lessons learned to improve both ex ante and ex post cost analyses going forward.

2. Existing Literature

An important policy question is how different environmental regulatory policies have performed in practice. Ex post analyses have focused on evaluating changes in risk, health impacts, environmental outcomes, competitiveness, production, plant location decisions, and employment effects, among others. A subset of these studies examine ex post evidence of the abatement strategies used to comply with a regulation and the cost of implementation, which is the focus of our review.

Even fewer ex post cost studies include a systematic comparison with the ex ante analysis, and many of these exist only in the gray literature. The relatively small number and narrow scope of published ex post cost studies are often a direct result of data limitations. For instance, many of the ex post cost studies are opportunistic in nature; researchers examine evidence on compliance costs where the data are available. In practice this means that retrospective cost evaluations are dominated by studies of regulations in the electric utility sector because of the availability of detailed boiler-level data collected by government agencies and of price information from regulatory agencies, as well as market-based regulation to support the analysis of the cost of abatement.

Retrospective reviews of environmental regulations promulgated in the first two decades of EPA's existence (i.e., prior to 1996) suggest that ex ante estimates tended to overstate compliance costs more often than understate them.[7] However, these conclusions are largely suggestive. Many of these reviews are unpublished, they include both published and unpublished studies, and they encompass a relatively small and often overlapping sample of regulations and studies.[8] In addition, ex post costs of regulation are often only roughly approximated. For example, reviews focus on only a subset of compliance costs (e.g., Putnam, Hayes, & Bartlett [1980] examine capital expenditures), use an indirect proxy for ex post costs (e.g., Anderson and Sherwood [2002] examine real price changes), include relatively small regulations (e.g., only 5 of the 18 EPA regulations included in OMB [2005] were economically significant), or at times include ex ante instead of ex post cost information (e.g., several of the studies in Morgenstern [1997] are primarily discussions of ex ante estimates).[9]

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[7] See Putnam, Hayes, & Bartlett (1980); Harrington et al. (2000b); Anderson and Sherwood (2002); OMB (2005).

[8] For example, OMB (2005), a retrospective review of the costs and benefits of 18 EPA regulations, is based on three studies. An unpublished study was the basis for 13 of them, while Harrington et al. (2000b) informed review of 9 of the regulations.

[9] Also, see Ramsden (1997), Nichols (1997), and Anderson and Rykowski (1997). Ex ante compliance cost estimates are also used in broader statute-wide retrospective assessments. See, for example, EPA's retrospective analysis of the benefits and costs of the Clean Air Act from 1970 to 1990 (EPA 1997).

In contrast to these early forays into retrospective review of compliance costs, two more recent efforts conducted original ex post assessments of EPA regulations. EPA (2014) conducted retrospective analyses of the costs of five regulations promulgated between 1995 and 2005. In each case, it uses a systematic framework to assess whether ex ante and ex post estimates differed and attempts to identify key drivers of identified differences. An additional case study completed after the release of the EPA report (Wolverton et al. 2019) follows the same protocol. As part of its Regulatory Performance Initiative, Resources for the Future commissioned several ex post evaluations of the benefits or costs of rules or requirements across multiple agencies, including eight EPA regulations promulgated between 1992 and 2010 (Morgenstern 2018). Of these, only two examine costs ex post. Relevant case studies from both efforts are included in our review.

2.1. Hypotheses from the Literature on Factors Contributing to Differences in Ex Ante versus Ex Post Cost Estimates

While the main focus of many ex post cost evaluations is to determine the direction and magnitude of the differences between ex ante and ex post estimates, Harrington et al. (2000b), Simpson (2014), Morgenstern (2018), and Hahn (2004) suggest a variety of reasons for such differences. Table 1 groups these explanations into six broad categories and discusses the likely direction of the bias each introduces. Note that differences between ex ante and ex post estimates may be driven by more than one factor (Harrington et al. 2000b). We briefly describe these hypotheses in this section.

Table 1. Reasons Proposed in the Literature for Cost Misestimation Ex Ante

Possible reasons	Examples	Direction of bias ex ante	Sources
Regulators' approach to cost estimation leads to errors	Use conservative (or optimistic) cost assumptions; less effort when benefits greatly exceed costs	Either	Hahn, H, S
Long promulgation process	Exogenous factors change; cheaper compliance options developed than those analyzed	Either	H, S, M
Does not account for technological innovation	Technologies in development may cost less than those already in use	Mainly overestimated	H, S, M
Unaccounted-for costs	Short-run adjustment costs; uncertainty in sources of pollution	Mainly underestimated	Hahn, H, M
Misspecified baseline	Failure to account for state regulation; incorrect growth assumptions (e.g., energy prices)	Either	H, S, M
Compliance errors	Rule less effective than expected	Either	H, S, M

Note: Hahn = Hahn (2004); H = Harrington et al. (2000b); S = Simpson (2014); M = Morgenstern (2018).

There are several ways in which a regulator's strategic approach to cost estimation may bias ex ante estimates. Policymakers and analysts may want the regulation to look as net beneficial as possible, which could lead them to employ optimistic input assumptions that understate costs or overstate benefits (Hahn 2004). On the other hand, regulators may purposely use conservative input assumptions, leading to a larger estimate of costs as a way of protecting the agency from court challenges (Harrington et al. 2000b), to avoid controversy in the face of industry opposition, or because benefits are so large that the regulation is likely to pass the benefit-cost test regardless of how much effort is put into refining cost estimates (Simpson 2014). While gross underestimation of costs is likely to be raised by the regulated community during the public comment period, Harrington et al. (2000b) contend that there is not nearly as strong of an incentive to identify gross overestimation. Reliance on industry-provided information may further emphasize conservative assumptions, as industry is unlikely to invest resources in identifying the best way to comply with a regulation prior to promulgation. Finally, it is often the case that governing statutes direct EPA to identify what technologies are feasible and already in use by a subset of entities (e.g., Best Available Control Technology [BACT] and Maximum Achievable Control Technology [MACT] standards). Cost estimates are then typically predicated on these identified technologies. However, since these regulations do not prescribe the method of compliance, identified technologies are used only if they are the cheapest option available.

It is also possible that the promulgation process may be drawn out over many years, which makes it more likely that ex post costs will differ from those ex ante because of unanticipated developments such as changes in fuel prices, production levels, or other regulatory requirements. Delays could also give the regulated industry more time to develop cheaper compliance options than were available when the analysis occurred (Harrington 2000b).[10]

Failure to adequately account for technological innovation is a commonly acknowledged reason for misestimation of costs ex ante. Analyses often assume that compliance obligations will be met through use of known technologies, but if industry finds cheaper ways to comply, costs will be lower than anticipated. Learning-by-doing may also lower compliance costs after a regulation is in place. While it may be reasonable to expect that compliance costs will decline after a regulation is in place, Harrington et al. (2000b) note that the rate at which costs decline is a key uncertainty. Underestimation of compliance costs is also possible when analysts incorporate overly optimistic assumptions regarding the availability of future technology to meet compliance requirements (Simpson 2014; Morgenstern 2018).

The ex ante assessment may be an underestimate of realized costs when it omits some types of costs entirely. Morgenstern (2018) points out that the long-run focus of benefit-cost analysis

[10] Simpson (2014) notes that comments from key stakeholders could result in changes in the scope or relative stringency of the rule compared with the options originally analyzed. We restrict ourselves to analyses of final rules, which makes this reason less relevant for our sample.

ignores shorter-run adjustment costs such as infrastructure needs (Harrington et al. 2000b). In addition, multiple sources of error likely underlie ex ante cost estimates because of inherent uncertainties about who is affected, how they will comply, and the effectiveness of abatement strategies. Some types of costs may be omitted when they are hard to quantify or sources of pollution are more uncertain. As Hahn (2004) observes, EPA analyses often restrict themselves to compliance costs, but a social cost measure would also consider costs related to behavioral change or forgone opportunities, such as lost profits or the diversion of funds away from more productive investments.

Even when per-plant cost estimates are accurate, all four papers note that the aggregate compliance costs from the regulation could be misestimated due to inaccurate assumptions regarding a rule’s effectiveness or misspecification of the baseline. With regard to rule effectiveness, if plants invested in abatement strategies that did not deliver the promised reductions, this could imply no change in costs but fewer benefits (Harrington et al. 2000b). It is also possible that some plants do not comply with regulatory requirements (or plants may shut down for reasons unrelated to the regulatory requirements), meaning the cost of abatement was not incurred.

With regard to misspecifying the baseline, if plants have lower emissions in the baseline than EPA projected, fewer emissions reductions are needed to meet regulatory requirements, and the total costs of regulation will be less than estimated ex ante. Conversely, if plants have higher emissions than EPA projected, and thus more abatement is needed to meet requirements, then total costs will be higher. There are several reasons why analysts might misspecify the baseline. First, there is often substantial uncertainty about the regulated universe. Second, macroeconomic factors unrelated to the rule could cause future production, prices, or demand to be lower (or higher) than anticipated ex ante (Simpson 2014; Morgenstern 2018). Third, it is possible that the baseline is inaccurate because EPA underestimated (or overestimated) the extent to which abatement activities were already in place or would have occurred absent regulation due to preexisting international, state, and local initiatives or other exogenous factors (Morgenstern 2018; Harrington et al. 2000b).

3. Methodology

We begin our review by assessing the specific components of compliance cost addressed by the 28 studies included in our review. We organize review around four cost components: compliance strategies adopted by regulated entities, permit or other prices as a proxy for marginal cost of compliance, unit compliance cost, and aggregate cost. As described in this section, we adopt a systematic evaluation approach to enhance transparency but recognize that such an assessment will inherently include a subjective element, given wide variation in data, methods, and scope for the studies in our sample. Based on the results of this assessment, we further investigate and attempt to identify the main factors that drive differences between ex ante and ex post estimates for each cost component identified in the studies.

Identifying the compliance strategy used by regulated entities is a key component of cost estimation. Before estimating the unit cost, an analyst must first understand the main methods of compliance. If regulators do not accurately predict which technologies firms will use to abate pollution, then aggregate ex ante costs may also not be accurate predictors, particularly when there are large differences in unit costs across possible compliance options. Most of the studies in our sample provide insights on the control strategies regulated entities actually adopted to comply with a regulation; some then use this information to develop ex post cost estimates.

Changes in product (or allowance) prices in response to a new regulation can serve as possible indicators of the costs of compliance. The extent to which they reflect marginal compliance cost will depend on what other contemporaneous factors also affect prices as well as the ability of producers to pass along compliance costs to customers. For instance, in the presence of market power, producers may shift prices around among their products to encourage shifts in consumption that minimize losses in revenue, or they may absorb some of the increase in costs by reducing profits such that there is no longer a direct correspondence between changes in prices and regulatory costs. In an allowance market, flexibilities (e.g., banking and borrowing) and restrictions on trading may also create a wedge between the marginal cost of compliance and the allowance price (Bialek and Shrader 2019). With these caveats in mind, in the absence of direct information on compliance costs, prices may still offer some insight into the overall efficiency of the market (e.g., whether firms appear to be cost minimizing when complying with regulation) and may indicate whether the costs of compliance were markedly different from ex ante expectations.

Unit compliance cost represents the cost per unit to implement abatement technologies, methods, and processes to meet regulatory requirements. The cost per unit is interpreted broadly for our purposes, given wide variation in how and what ex post assessments report; it may refer to average cost per unit of production or consumption, cost per unit of emissions abated, or even cost per plant or model type. It is also important to understand how unit costs vary with heterogeneity across regulated entities (e.g., plant age, size, the type of production processes used, and abatement controls already in place). While typically information is available only on the average cost of compliance, understanding how it varies across plants may also allow one to draw inferences regarding the marginal cost of compliance.

Finally, we are interested in understanding whether the total cost of regulation was notably different from what was expected ex ante and identifying the key factors that drive these differences. Ideally, this would encompass not just aggregate compliance costs but all social costs—direct and indirect—imposed by a rule. In reality, it is exceptionally rare to have either ex ante or ex post estimates of social cost. While ex ante analyses of regulation provide an aggregate compliance cost estimate, it is often difficult to estimate costs ex post because of data limitations (e.g., information is often available for only a subset of the regulated entities, which may not be representative of the universe).

For each of the four cost components, we assess five elements related to the data and methods used in the study: data type, data coverage, unit of observation, method of obtaining the result, and the extent to which the analysis controls for confounding factors. For each element, we assign the study a score ranging from 1 to 3, with the score increasing in degree of formality and rigor. For example, a score of 1 for data type indicates the use of primarily informal data (e.g., informal self-reporting, industry association report, expert opinion), while a score of 3 indicates the study relies primarily on verifiable, formal data sources (e.g., observed, measured, required self-reporting to federal agencies). When the scores are summed over all five elements, a study's maximum potential total score for each of the four cost components is 15. (See Appendix A for additional details on the scoring methodology and the results for each study in our sample.)

Using the results of this assessment, we next determine the key factors that led to differences in ex ante versus ex post results with the objective of identifying important themes. To accomplish this task, we first undertake an in-depth review of each retrospective study. We revisit the ex ante information from EPA final regulatory impact analyses (RIAs) in several instances to better understand underlying assumptions and other factors for the specific regulation of interest. In some cases, we supplement our review with other, mainly qualitative, studies in the literature.

Next, we classify the sources of the differences identified from the in-depth review based on whether the evidence points to a misspecified baseline, the use of different control strategies than anticipated, or misestimation of one or more components of compliance costs. Within each broad category, we also note how the identified reasons for differences between ex ante and ex post cost estimates compare with the hypotheses already mentioned in the literature.

Finally, to inform recommendations for improving future ex ante analyses, one needs to determine whether an identified difference substantially affected the cost estimate and the extent to which the source of such difference could even be analyzed or addressed ex ante. Based on the information available in the identified studies and EPA ex ante regulatory analyses, we attempt to judge in general terms how much the identified differences likely mattered for the final cost estimates (i.e., a lot, a little, not much). In some cases, we also find it possible to suggest the likely direction of the difference—that is, whether per-unit cost or aggregate costs were likely over- or underestimated in the ex ante analysis. This last exercise is the most speculative, given the difficulty in making apples-to-apples comparisons between ex ante and ex post estimates as well as the data limitations and narrow focus of many ex post studies in our sample.

4. Overview of Our Sample

We limit our sample to peer-reviewed, published studies that focus on an ex post evaluation of compliance choices or key cost elements of individual, final EPA regulations. From 52 potentially relevant papers, we focus on 28 "primary" studies of ex post compliance strategies or costs of past EPA regulations. In a few cases, we rely on other studies, drawn from the larger set of identified studies, for supplementary insights with regard to the regulations covered by this review—although they are not stand-alone ex post studies. The remaining papers identified by the literature search have been omitted from our review for a variety of reasons, such as the qualitative nature of the study, publication prior to 2000, being unpublished at the time of our review, or including limited discussion of the ex post experience.[11]

4.1. Overview of Included Regulations

Table 2 describes the regulations that are the focus of our review. While the 28 studies evaluating ex post compliance strategies or costs were all published between 2000 and 2018, the 13 regulations they evaluate were promulgated over a much longer time frame. The earliest regulation included in our review is the phasedown of lead in gasoline, first promulgated in 1979 but subject to several updates (in 1982 and 1985). The newest regulation included is the renewable fuels standard required under the 2007 Energy Independence and Securities Act (RFS2), promulgated in 2010. For eight regulations, only a single available study meets our criteria for inclusion in the review. We have multiple studies for the remaining five regulations: 2 each for the boutique fuels program, cluster rule, and renewable fuels standard; 4 studies for the nitrogen oxide (NO_x) budget program, and 11 studies for the Title IV Sulfur Dioxide (SO_2) Trading Program.[12]

[11] Ryan (2012) finds a sizable increase in the costs of entry in the Portland cement industry post-1990, which he interprets as evidence that Title V permit and reporting requirements caused significant additional barriers to entry, allowing existing firms to increase prices. However, it is unclear why these requirements—estimated to cost less than $10,000 per plant—would induce such a large change. Ryan's policy variable is a post-1990 dummy, but other preexisting regulations (such as new source review) were also enforced more stringently over this time and are not accounted for in the study. Ryan also notes marked changes in international competition over the same time frame but does not investigate its role. Since we are not convinced that the study isolates the effect of the Title V requirements from other policy and market changes, we did not include it in our sample.

[12] Note that the total does not add up to 28 because one study, Morgan et al. (2014), covers two regulations.

Table 2. Regulations Included in Our Review

EPA rule	Promulgation years	Averaging, banking, or trading?	Primary studies included in review
Lead Phasedown in Gasoline	1979, 1982, 1985	Y	Kerr and Newell (2003)
CFC Phaseout	1988, 1992, 1993	Y	Hammitt (2000)
Boutique Fuels (RFG, RVP, & OXY)	1989, 1990, 1992, 1994	N	Brown et al. (2008); Chakravorty et al. (2008)
Title IV SO_2 Trading Program	1992	Y	Carlson et al. (2000); Ellerman et al. (2000); Swift (2001); Arimura (2002); Popp (2003); Swinton (2002, 2004); Busse and Keohane (2007); Frey (2013); Cicala (2015); Chan et al. (2018)
Enhanced Vehicle Emissions I&M	1992	N	Harrington et al. (2000a)
NO_x Budget	1998	Y	Linn (2008); Popp (2010); Fowlie (2010); Fowlie and Muller (2019)
Locomotive Emission Standards	1998	Y	Kopits (2014)
Cluster Rule for Pulp and Paper	1998	N	Morgan et al. (2014); Elrod and Malik (2017)
MACT II for Pulp and Paper	2001	Y	Morgan et al. (2014)
Arsenic in Drinking Water Regulations	2001	N	Morgan and Simon (2014)
Light-Duty Vehicle Surface Coating NESHAP	2004	N	Wolverton et al. (2019)
MBr Annual Critical Use Exemptions	2004-2008	N	Wolverton (2014)
RFS2	2010	Y	Lade et al. (2018a, 2018b)

Note: CFC = chlorofluorocarbon; RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel; NESHAP = National Emission Standards for Hazardous Air Pollutants.

Most of the rules covered in our review are air program rules; we also include two water program rules (arsenic in drinking water and cluster rule) and one pesticide rule (methyl bromide [MBr] phaseout). In addition, as expected, the types of regulations represented in our sample are not representative of the larger universe of significant EPA regulations. Regulations that pertain to fuels (e.g., lead phaseout, boutique fuels, RFS2) are likely overrepresented. Moreover, a substantial number of the regulations that have been studied ex post include mechanisms, such as averaging, banking, or trading, designed to give regulated entities additional flexibility in meeting the standard. In some cases, the degree of flexibility may be relatively limited (e.g., bubble strategies allowed under MACT II). In other cases, the regulations rely extensively on market-based approaches that include one or more of these mechanisms (e.g., Title IV SO_2 Trading Program, chlorofluorocarbon [CFC] tradable permits). Moreover, many environmental programs established through federal regulation are implemented by the states (e.g., boutique fuels, enhanced emissions inspection and maintenance [I&M], arsenic in drinking water, and NO_x budget, among others); this adds an element of uncertainty to ex ante cost estimation. (See Appendix B for a description of the regulatory requirements associated with each regulation.)

4.2. Overview of Included Studies

The 28 studies included in our review vary considerably but can be loosely grouped into two general methodological categories. The first set of studies consists of those that use a bottom-up accounting strategy to develop expenditure estimates by component and to build up a cost estimate from these components. While some of these studies offer a qualitative discussion of exogenous factors, they typically do not control for such factors. Because of data limitations, these studies often rely on expert opinion, subjective synthesis, or direct reports from regulated entities. The second set of studies comprises those that use econometric approaches to identify an effect after attempting to control for other exogenous factors.

Table 3 provides an overview of each study in our sample. It is evident that the bottom-up studies (shaded gray) tend to have a broader focus and often aim to identify key drivers of differences between the ex ante analysis and ex post estimates of costs. The econometric studies (unshaded) often evaluate narrower questions. For example, several examine the role of specific factors in compliance decisions, while others focus on adoption of a specific technology or compliance behavior. In addition, the econometric studies typically provide less explicit comparisons of their ex post estimates with the original ex ante analysis than the bottom-up studies.

The econometric studies also vary somewhat in approach. While most of them rely on panel data, allowing for use of fixed effects, only five are quasi-experimental (designated by * in Table 3). The ability to perform econometric analysis is predicated on the availability of detailed, disaggregated data. The electric utility sector is blessed with extensive, publicly available data on plant operations from federal agencies; EPA collects emissions data; and the Energy Information Agency (EIA) and Federal Energy Regulatory Commission (FERC) have detailed data on plant design and operational costs. Not surprisingly, then, 14 of the studies—almost all econometric—address the effects of the Title IV SO_2 Trading and NO_x Budget Programs on electric utility sector operations. Two studies by Popp, one for each of these same programs, also leverage patent data. Five additional econometric studies address the effects of regulations on fuel additives on fuel prices—boutique fuels, lead phasedown, and RFS2. These use a combination of state and federal sources of data on refinery operations and privately available price data. Data limitations restrict some of these econometric studies to a subset of facilities.

Table 3. Overview of Focus of Each Study

EPA rule (study)	Focus of study
CFC Phaseout (Hammitt 2000)	Compares ex ante vs ex post marginal control cost
Enhanced I&M (Harrington et al. 2000a)	Compares ex ante vs. ex post cost per vehicle and identifies key drivers; AZ program only
Title IV Phase I (Swift 2001)	Examines performance of the SO_2 trading program and compliance behavior
Locomotive (Kopits 2014)	Compares ex ante vs. ex post cost and identifies key drivers
Arsenic (Morgan and Simon 2014)	Compares ex ante vs. ex post cost and identifies key drivers
MBr Phaseout (Wolverton 2014)	Compares ex ante vs. ex post cost and identifies key drivers
Surface Coating (Wolverton et al. 2019)	Compares ex ante vs. ex post cost and identifies key drivers
Cluster (Morgan et al. 2014)	Compares ex ante vs. ex post cost and identifies key drivers
Cluster (Elrod and Malik 2017)*	Estimates extent of product mix shifts as a compliance strategy
MACT II (Morgan et al. 2014)	Compares ex ante vs. ex post cost and identifies key drivers
Lead Phaseout (Kerr and Newell 2003)	Estimates impact of trading on technology adoption (isomerization) relative to performance std.
Boutique Fuels (Brown et al. 2008)	Estimates impact of RFG and RVP and market segmentation on wholesale gasoline prices
Boutique Fuels (Chakravorty et al. 2008)	Examines effect of fragmented gasoline markets and RFG and OXY on wholesale gasoline prices
NO_x Budget (Linn 2008)*	Examines impact on compliance via smaller-scale boiler modifications relative to CAC
NO_x Budget (Popp 2010)	Examines linkages between innovation and adoption of NO_x pollution control techniques
NO_x Budget (Fowlie 2010; Fowlie & Muller 2019)	Examines how heterogeneity in electricity market regulation affected compliance methods
RFS2 (Lade et al. 2018a, 2018b)	Examines effect on value of compliance obligation, commodity markets, and value of biofuel firms
Title IV Phase I (Carlson et al. 2000)	Develops ex ante cost prediction; estimate how actual costs compare with ex ante prediction
Title IV Phase I (Swinton 2002, 2004)	Examines whether abatement costs converged across plants (2002: FL only; 2004: US)
Title IV Phases I & II (Frey 2013)	Examines how characteristics, regulatory structure, installation costs affected scrubber adoption
Title IV Phase I (Popp 2003)	Examines innovation in scrubber technology across SO_2 CAC and cap-and-trade regimes
Title IV Phase I (Busse and Keohane 2007)*	Examines effect of SO_2 trading on the market for low-sulfur coal
Title IV Phase I (Arimura 2002)	Examines utilities' SO_2 compliance responses and the role of local and state regulations
Title IV Phase I (Ellerman et al. 2000)	Describes and evaluate performance and behavior of markets for first three years of program
Title IV Phase I (Cicala 2015)*	Examines how deregulating electricity markets affected scrubber technology adoption
Title IV Phase II (Chan et al. 2018)*	Estimates compliance costs for coal-fired units to counterfactual uniform performance standard

Note: Gray shading indicates bottom-up study approach; unshaded studies are econometric. RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel; CAC = command and control. * Uses quasi-experimental study design.

Many of the bottom-up studies attempt to speak to compliance strategies and costs for the program as a whole, but data constraints prevented them from accomplishing this goal. For instance, Harrington et al. (2000a) use data on inspection and repair costs from one county in Arizona to examine the enhanced I&M program. Wolverton (2014) focuses on methyl bromide critical use exemptions, relying on published reports on operating costs for representative California strawberry farms.[13]

Table 4 summarizes the type of data available for each study. Studies in gray use panel data, which means that they have information on compliance strategies or costs for multiple years and are often able to include fixed effects to control for plant-specific factors. A red *X* indicates that only partial information was available for a study. For example, data may have been available for only one state or one type of source, such as coal-powered electricity plants.

In general, most studies tend to have disaggregated information about control strategies, supplemented by other source-level data. However, many of the studies that have such information cannot claim that the data available are representative of the regulated universe. This appears to be a problem shared by both bottom-up and econometric studies. Far fewer studies have disaggregated source-level information on control costs, and when available, it is always partial. Several studies in our sample also use information on product prices as a potential indicator of compliance costs.

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[13] Also, Morgan and Simon (2014) use cost data collected from EPA demonstration projects and information on compliance strategies from compliance assistance engineering firms, independent associations, and a subset of state agencies to examine the arsenic rule. Kopits (2014) uses information primarily provided by a single industry expert, augmented by trade association information and federal market level data, to examine the locomotive rule. To help overcome data gaps, Wolverton et al. (2019) designed a survey to collect data from nine automotive manufacturing plants on the costs of complying with the surface coating rule.

Table 4. Types of Data Used, by Study

EPA rule (study)	Regulated source-level data			Market data		Other input cost data
	Control strategy	Control cost	Other	Permit price	Product prices	
CFC Phaseout (Hammitt 2000)					X	
Enhanced I&M (Harrington et al. 2000a)	X	X	X			
Title IV SO_2 Phase I (Swift 2001)	X			X	X	X
Locomotive (Kopits 2014)					X	
Arsenic (Morgan and Simon 2014)	X	X	X			
MBr Phaseout (Wolverton 2014)	X	X			X	X
Surface Coating (Wolverton et al. 2019)	X	X	X			X
Cluster (Morgan et al. 2014)	X		X			X
Cluster (Elrod and Malik 2017)*	X		X			
MACT II (Morgan et al. 2014)			X			X
Gasoline Lead Phaseout (Kerr and Newell 2003)	X		X			X
Boutique Fuels (RFG & RVP) (Brown et al. 2008)					X	
Boutique Fuels (RFG & OXY) (Chakravorty et al. 2008)					X	
NO_x Budget (Linn 2008)*	X		X			
NO_x Budget (Popp 2010)	X		X			
NO_x Budget (Fowlie 2010; Fowlie and Muller 2019)	X		X			
RFS2 (Lade et al. 2018a, 2018b)				X	X	
Title IV SO_2 Phase I (Carlson et al. 2000)	X		X		X	X
Title IV SO_2 Phase I (Swinton 2002, 2004)	X		X		X	
Title IV SO_2 Phases I & II (Frey 2013)	X	X	X			
Title IV SO_2 Phase I (Popp 2003)	X	X	X	X	X	
Title IV SO_2 Phase I (Busse and Keohane 2007)*	X		X		X	
Title IV SO_2 Phase I (Arimura 2002)	X		X		X	
Title IV SO_2 Phase I (Ellerman et al. 2000)	X	X	X	X	X	
Title IV SO_2 Phase I (Cicala 2015)*	X		X			
Title IV SO_2 Phase II (Chan et al. 2018)*	X		X	X	X	

Note: Gray shading indicates bottom-up study approach; unshaded studies are econometric; a red *X* indicates availability of only partial data. RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel. * Uses quasi-experimental study design.

5. Findings

Our results are organized into three subsections. Section 5.1 discusses which elements of compliance costs are informed by the available ex post studies. Section 5.2 describes identified differences between ex ante and ex post cost estimates and examines possible sources of these differences. Section 5.3 evaluates the extent to which our results can be used to identify the direction of ex post costs relative to EPA ex ante estimates.

5.1. Elements of Compliance Costs Informed by the Studies

Table 5 summarizes our assessment of what components of compliance costs the studies inform. Each cell in the table indicates the extent to which a study provides insights on the realized effects of the regulation, based on its total score across the five elements described in Section 3. The higher the total score, the darker the cell; the lower the score, the lighter the cell, indicating less certainty in the study’s ability to inform that aspect of costs. Black indicates a score of 14–15; dark gray, a score of 11–13; medium gray, a score of 8–10; and light gray, a score of 5–7. No shading indicates that the study does not address that specific component of cost (i.e., a score of less than 5). We also include columns to indicate whether the study is relatively broad or narrow in focus and whether it includes an explicit comparison with the ex ante analysis of the regulation.

Table 5. Elements of Realized Compliance Costs Informed by the Studies

EPA rule (study)	Scope of study	Compares with RIA?	Extent to which study provides insights on realized:			
			Compliance strategies	Permit/ other prices	Unit compliance cost	Aggregate cost
CFC Phaseout (Hammitt 2000)	Broad	Explicit				
Enhanced I&M (Harrington et al. 2000a)	Broad	Explicit				
Locomotive (Kopits 2014)	Broad	Explicit				
Arsenic (Morgan and Simon 2014)	Broad	Explicit				
MBr Phaseout (Wolverton 2014)	Broad	Explicit				
Surface Coating (Wolverton et al. 2019)	Broad	Explicit				
MACT II (Morgan et al. 2014)	Broad	Explicit				
Cluster (Morgan et al. 2014)	Broad	Explicit				
Cluster (Elrod and Malik 2017)	Narrow	Partial				
Gasoline Lead Phaseout (Kerr and Newell 2003)	Narrow					
Boutique Fuels (RFG & RVP) (Brown et al. 2008)	Narrow					
Boutique Fuels (RFG & OXY) (Chakravorty et al. 2008)	Narrow					
RFS2 (Lade et al. 2018a, 2018b)	Narrow	Partial				
NO_x Budget (Linn 2008)	Narrow	Partial				
NO_x Budget (Popp 2010)	Narrow					
NO_x Budget (Fowlie 2010; Fowlie and Muller 2019)	Narrow	Partial				
Title IV SO_2 Phase I (Carlson et al. 2000)	Broad	Explicit				
Title IV SO_2 Phase I (Ellerman et al. 2000)	Broad	Explicit				
Title IV SO_2 Phase I (Swift 2001)	Broad	Explicit				
Title IV SO_2 Phase I (Arimura 2002)	Narrow	Partial				
Title IV SO_2 Phase I (Popp 2003)	Narrow					
Title IV SO_2 Phase I (Swinton 2002, 2004)	Broad	Partial				
Title IV SO_2 Phase I (Busse and Keohane 2007)	Narrow					
Title IV SO_2 Phases I & II (Frey 2013)	Narrow					
Title IV SO_2 Phase I (Cicala 2015)	Narrow					
Title IV SO_2 Phase II (Chan et al. 2018)	Broad	Partial				

Note: Shading corresponds to score: black = 14–15; dark gray = 11–13; medium gray = 8–10; light gray = 5–7; unshaded = <5. RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel.

Several observations are evident based on this compiled information. First, many of the studies in our sample provide insights into the actual compliance strategies used by regulated entities. A few studies examine the effect of the regulation on market prices, which in some cases may yield insights into the marginal cost of compliance. Some go a step further to examine a specific element of per-unit compliance costs (e.g., capital expenditures for a subset of regulated entities), but only a few have enough ex post data to be able to estimate overall per-unit compliance costs. Unfortunately, even fewer studies provide insights into the total cost of a regulation.

Overall, studies in our sample suggest that realized cost components frequently differed from EPA estimates. For example, compliance strategies differed from ex ante expectations for 10 of the 13 rules in our study. Shifts in capital intensity represent one important category of differences. For the electricity generating sector, rate-regulated utilities shifted toward more capital-intensive controls than projected, while those in competitive markets shifted away from them (i.e., NO_x Budget and Title IV SO_2 Trading Programs).[14] In addition, regulated entities in private markets shifted to less capital-intensive control approaches than anticipated for five other rules in our sample (surface coating, arsenic, cluster, MACT II, and locomotive). We explore possible reasons for these differences in the next section.

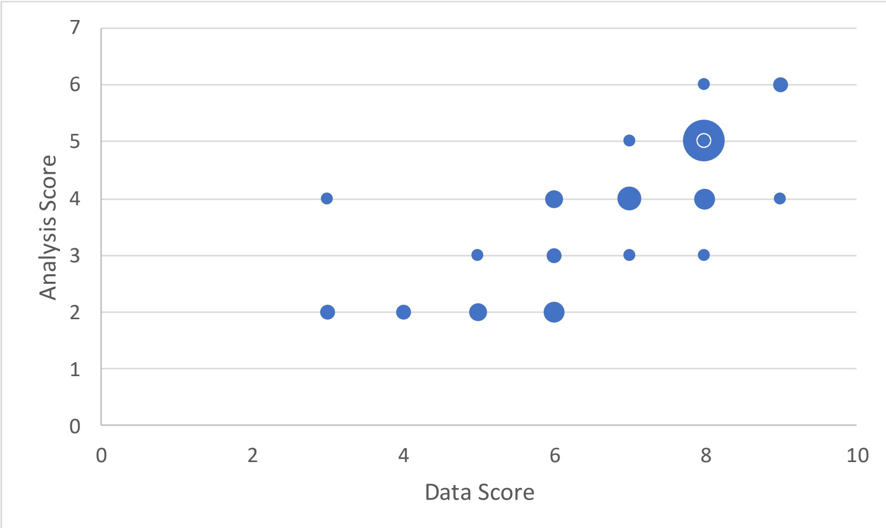
While Section 5.2 focuses on sources of differences and their possible implications for costs, a few studies find substantial agreement between ex ante and ex post estimates for specific inputs or components of costs. In the case of methyl bromide critical use exemptions, Wolverton (2014) reports that the strawberry prices assumed by EPA ex ante were consistent with both historic and

[14] This behavior is consistent with the Averch-Johnson effect, where rate-regulated utilities can ensure recovery of capital costs by including them in the rate base (Fowlie 2010).

contemporaneous prices received by California growers. Likewise, for surface coating, Wolverton et al. (2019) note that the ex ante unit cost estimates for reformulating topcoats and basecoats were within the ex post range. For the Title IV SO_2 Trading Program, though many differences between ex ante and ex post compliance strategies and unit costs have been identified, the few available estimates of realized aggregate costs are not vastly different from EPA's ex ante estimates. In the case of CFCs, Hammitt (2000) finds that the EPA ex ante estimates (under the higher of the two cost scenarios presented) were quite similar to the revealed marginal cost of control (as estimated by the market price for CFC permits) for consumption reductions of about 50 percent achieved in 1990 and 1991.

Figure 1 adds to our understanding of the shading results in Table 5 by showing the correlation between the type of data used and analysis performed. Specifically, the figure plots the combined data scores versus analysis scores assigned to each study for each cost component assessed. The combined data score is the sum of the numerical scores for the three elements that describe the data used for the study: data type, coverage, and unit of observation. The combined analysis score is the sum of the numerical scores for the two elements that pertain to the type of analysis performed in the study: method of obtaining result and extent of control for other factors. (See Appendix A for more discussion of each of these elements.)

Figure 1. Type of Data and Analysis Performed for Each Study



Each data point displayed in the graph is sized proportionately to the number of studies that received the same combined scores.[15] As discussed in Appendix A, the numerical categories were ordered in such a way that an increase in the degree of formality or rigor leads to a higher numerical score for each element. Thus the same can be said of the combined data and analysis scores displayed in Figure 1. Unsurprisingly, the resulting plot shows that the more formal, complete, and disaggregated data used, the more rigorous the analysis.

5.2. Sources of Differences between Ex Ante and Ex Post Cost Estimates

In this section, we further investigate underlying sources of differences between ex ante and ex post estimates for each regulation (see Table 6).[16] We group sources of differences into eight categories: (1) inadequate or incorrect baseline specification (e.g., due to changes in exogenous

[15] For example, the largest circle in the graph corresponds to nine studies that received a combined data score of 8 and an analysis score of 5. By contrast, the smallest circles in the graph correspond to scores received by only one study in our sample, a data score of 3 and an analysis score of 4.
[16] Note that while Table 5 summarizes areas where the studies provide insights about realized cost components (including differences or similarities to ex ante estimates), this section focuses on understanding differences. Hence not all shaded cells in Table 5 have a corresponding entry in Table 6.

factors); (2) missed behavioral responses due to sole reliance on engineering models; (3) not accounting for how industry structure affects compliance; (4) inadequate consideration of technological innovation; (5) inadequate consideration of regulatory flexibilities (e.g., banking or trading) to meet compliance obligations; (6) not accounting for transition or implementation costs; (7) changes to the regulation itself after the analysis was conducted; and (8) unspecified reasons. While many of these are consistent with hypotheses raised in the literature (Harrington et al. 2000b; Simpson 2014; Morgenstern 2018), categories 2, 3, and 5 are new to this study and highlight the importance of considering behavioral response when estimating compliance costs.[17]

For all but one regulation in our sample, we identify at least one factor that likely contributed to differences between ex ante and ex post estimates of one or more cost components. The most common factors identified were an inaccurate ex ante accounting of baseline conditions (for eight rules) followed by inadequate consideration of technological innovation (for six rules). In most cases, multiple factors were found to contribute to differences.

[17] We do not explore hypotheses related to the motives of EPA decisionmakers and analysts (i.e., adopting a deliberately conservative approach to cost estimation, estimating costs with less precision when benefits substantially exceed costs, or asymmetric correction of errors in the estimation). While this is an important area for future research, these hypotheses are untestable based on the data and information available from the studies in our sample.

Table 6. Identified Sources of Differences between Ex Post and Ex Ante Cost Estimates

Sources of differences between ex ante and ex post estimates	Compliance approach		Prices	Unit cost	Total cost
	Different mix/usage than anticipated	Different controls than anticipated			
Inadequate/incorrect baseline	NO_x Budget, MBr, Surface Coating, SO_2		RFS2	Locomotive, I&M, SO_2	Cluster, Surface Coating
Missed behavioral responses due to sole reliance on engineering models	Arsenic, Locomotive	Arsenic, Cluster NO_x Budget			
Lack of accounting for effect of industry structure*	Surface Coating, SO_2		Boutique Fuels		Surface Coating
Inadequate consideration of technological innovation	RFS2, Surface Coating, MBr	Arsenic, Locomotive, SO_2	RFS2	SO_2, MBr	
Inadequate consideration of flexibility provisions	MACT II		SO_2	MACT II	SO_2
Lack of analysis of transition/implementation†	Surface Coating, MBr		RFS2		
Ex post rule changes	Locomotive		CFCs, RFS2	I&M	
Reason unspecified	NO_x Budget, Surface Coating	Lead	CFCs	Arsenic, Cluster, Locomotive, MBr, I&M	

Note: The identified sources of difference are based on primary studies in our sample.
* Supplementary studies suggest that this source of differences was also relevant for the CFC regulation.
† Supplementary studies suggest that this source of differences was also relevant for the lead phasedown in gasoline regulations.

The purpose of most primary studies in our sample is not to shed light on all relevant factors that cause differences between ex ante and ex post estimates. Some studies find a difference between ex ante and ex post costs but did not explore the underlying reason for the difference. Some are able to identify relevant factors for only a subset of their results. Even when identifying drivers of differences between ex ante and ex post costs was the express purpose of a study, a lack of data often limited the authors' ability to examine all potential sources of differences. Thus, for most of the regulations in our sample, at least some sources of differences between ex ante and ex post estimates remain unknown (i.e., fall into the "reason unspecified" category).

To provide a deeper appreciation for the sources of differences between ex ante and ex post estimates, we discuss each of the eight categories in the following subsections and highlight a few specific examples, drawing mainly from the primary studies in our sample. Additional studies that provide broad context and qualitative discussion or suggest possible drivers of differences in cost estimates are occasionally referenced as supplementary support. (A more complete discussion is provided in Appendix C.)

5.2.1. Incorrect Baseline Specification

A major challenge when developing an ex ante cost estimate of a regulation is constructing a defensible baseline. How the world will evolve absent (or in spite of) the standard is not observable ex ante and therefore inherently uncertain. Ex post, however, it is possible to directly observe changes in some relevant exogenous conditions, such as changes in demand or supply conditions unrelated to the imposition of the regulation. The studies we review found evidence of inadequate accounting for key exogenous factors in the baseline for eight regulations. In some cases, the implications of these exogenous factors could have been evaluated ex ante, which we discuss in Section 6.

Energy prices and demand are notoriously difficult to forecast but are nonetheless important for understanding the effects of many environmental regulations. One example where an inaccurate forecast of energy markets contributed to differences between ex ante and ex post estimates is in regard to RFS2. EPA used a single forecast of future fuel prices in its ex ante analysis; it did not explore how the inherent unpredictability of energy prices could affect costs. Specifically, it used projections that implied the wholesale gasoline price would be almost two times higher than for ethanol on a per-gallon basis in 2022. Given this large gap, EPA estimated that the ethanol mandate would yield substantial cost savings as low-cost ethanol was substituted for gasoline. In fact, wholesale gasoline and ethanol prices have tracked each other relatively closely, with only a small gap to reflect differences in the energy density of the two fuels (Lade et al. 2018a).

Another example of an exogenous factor that is important for the baseline is the effect of preexisting regulations or initiatives. In the case of methyl bromide exemptions, Wolverton (2014) finds that the ability of farmers to switch to some alternatives was hindered by existing state-level restrictions on how some fumigants could be combined because of concerns about worker safety. Likewise, international initiatives played a role in vehicle manufacturers' adoption of low-emitting coatings prior to the National Emission Standards for Hazardous Air Pollutants (NESHAP) for surface coating (Wolverton et al. 2017). EPA accounted for some of these regulations and initiatives ex ante and discussed others qualitatively but nonetheless likely underestimated their effect on compliance strategies.

5.2.2. Missed Behavioral Responses due to Sole Reliance on Engineering Models

EPA typically uses the estimated cost of installation, operation, and maintenance for one or more specific control technologies as the compliance cost, holding all else constant. This "engineering" approach does not typically account for the behavioral responses of a regulated entity to the new requirement. Failure to account for such responses may result in errors when predicting control strategies, which then has implications for the cost of compliance. We found four examples in our sample of 13 rules where such behavioral responses were not considered in the ex ante analysis.

One possible type of firm behavioral response is to alter its production process to reduce the amount of pollution emitted and therefore reduce the extent to which it is subject to abatement requirements. In this case, the regulated entity still incurs costs, but they are likely lower than the cost of installing and maintaining abatement equipment. For example, Elrod and Malik (2017) find that some mills subject to the cluster rule substantially altered their product mix away from bleached paper products in response to the new regulatory requirements. This shift in production reduced the need to install abatement technologies to reduce releases into the water from the bleaching process, which then reduced the capital cost of complying with the rule. The implications for total costs are unclear, since Elrod and Malik did not examine the additional costs of these shifts in production.

The locomotive rule is another example where behavioral responses to the regulation may have resulted in different costs than anticipated. EPA estimated that most line-haul locomotives in the existing fleet would be rebuilt to meet the standards over the 10-year period following issuance of the rule. This estimate reflected current practices at the time: the overhaul of line-haul locomotives every eight years and the rebuild of engines at least once over the lifetime of the engine. Kopits (2014) reports that only 6 percent of line-haul engines were rebuilt, suggesting that a strategic decision may have been made to delay costly rebuilds and instead absorb additional operational costs.

5.2.3. Lack of Accounting for Effect of Industry Structure

It is relatively common for EPA to assume that the markets affected by regulation are perfectly competitive and that compliance decisions are made at the unit (e.g., plant, boiler unit, engine) level. However, if regulated entities exercise market power, are subject to existing regulations that restrict behavior (e.g., electric utilities in cost-of-service states), or share the same ownership structure (e.g., one firm owns multiple plants), this can influence how they respond to regulatory requirements. Within our sample, we identified three regulations where an inadequate accounting for industry structure likely contributed to differences in compliance strategies or costs relative to ex ante estimates. We also find suggestive evidence that industry structure may have played a role based on supplementary sources (i.e., those that do not explicitly estimate costs ex post) for a fourth regulation.[18]

In the case of surface coating, Wolverton et al. (2019) find greater uniformity in compliance strategies across plants within a firm than anticipated ex ante—with a strong preference for coating reformulation over end-of-pipe controls—due to the pursuit of corporate-wide compliance strategies. This yielded substantial economies of scale as the firm negotiated directly with its paint supplier to reformulate coatings for its plants. Administrative costs also were lower than anticipated, as database development occurred at the firm instead of the plant level.

Environmental regulations also can potentially alter the number of firms and degree of market power within regulated sectors due to economies of scale or new barriers to entry. Brown et al.

[18] In the case of CFCs, EPA's ex ante analysis acknowledged that production was concentrated among a few firms but did not analyze its effect. Subsequent studies noted that firms may have used the regulation to increase market share via patents of technology (Harrington et al. 2000b). An excise tax imposed after the Montreal Protocol also was meant to prevent the industry from retaining scarcity rents created by the CFC phaseout (Schmalensee and Stavins 2019).

(2008) find that fuel content (Reid vapor pressure and reformulated gasoline) requirements increased wholesale gasoline prices significantly relative to unregulated markets. The limited number of competitors and geographic isolation of some regulated markets contributed to even larger increases in city-specific wholesale gasoline prices. These results suggest that geographically differentiated requirements may have increased the ability of refiners to exercise market power (also see Chakravorty et al. 2008). In the case of the Title IV SO_2 Trading Program, ex post evidence suggests that market power allowed railroads to impose higher low-sulfur fuel prices on power plants in isolated markets, increasing the cost of compliance (Busse and Keohane 2007). In both cases, EPA did not analyze how market power might affect costs ex ante.[19]

5.2.4. Inadequate Consideration of Technological Innovation

Innovations that expand the range of strategies available to regulated firms for meeting regulatory requirements can lower compliance costs relative to the case where firms rely only on well-established abatement technologies. While it is not possible to anticipate the role of a new, unforeseen abatement technology developed after a regulation is in place, it may still be possible to account for some level of technological innovation ex ante, such as when more cost-effective technologies are under development but not yet widely available at the time a rule is promulgated. We identified six regulations in our sample where EPA's ex ante analysis failed to adequately consider how technological innovation could influence the policy scenario.[20]

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[19] For example, Anderson and Rykowski (1997) report that while the RIA for boutique fuels included a technical analysis of refiner costs, it did not examine the effects of the regulations on market competitiveness.

[20] Note that while the instances identified in our sample pertain to innovations in the abatement sector, technological advances that are completely exogenous to the regulation can also affect compliance strategies and costs. This type of technological change should be reflected in the baseline of the analysis.

EPA often relies on available demonstrated control technologies as the basis for setting standards. This, in turn, influences its economic analysis: ex ante cost estimates are frequently based on available controls even when more cost-effective alternatives are under development. In the case of arsenic, Morgan et al. (2014) report significant use of iron-based adsorptive media to comply with requirements. However, because iron adsorption technology was in a pilot research phase at the time of the rulemaking, it was not used as a basis for standard setting or included in EPA's ex ante analysis as a compliance option. Wolverton et al. (2019) also find evidence that EPA underestimated the extent of technological innovation already underway and the pace at which it could affect compliance choices for the light-duty surface coating rule. Several major manufacturers (as well as paint suppliers) were already cooperatively exploring low-HAP coating formulations prior to promulgation, in part to respond to increased competition and what were anticipated to be formidable technical challenges to developing low-emissions technologies. While EPA acknowledged that it would be cheaper to comply with the surface coating requirements through reformulation, it nonetheless anticipated that a majority of plants would use the more expensive end-of-pipe technology.

On the other hand, when EPA incorporates nascent technologies into its ex ante assessments, it runs the risk of underestimating compliance costs. In the case of the RFS2, EPA substantially overestimated the extent to which future cellulosic ethanol production would come online (Lade et al. 2018a; Gies 2014).[21] As a result, compliance with the RFS2 has resulted in significant

[21] Cellulosic ethanol, which converts cellulose from grasses and agricultural waste into fuel, has long held promise as a way to meet the advanced renewables mandate while emitting fewer greenhouse gases than alternatives.

additional volumes of diesel biofuel and imported sugarcane ethanol to meet the mandate (Lade et al. 2018b).

5.2.5. Inadequate Consideration of Flexibility Provisions

For many EPA regulations, flexibilities such as averaging, banking or trading are available to reduce compliance costs. How and when firms use these flexibilities can have important implications for the estimated cost of regulation. For two regulations in our sample, we find evidence that accounting for these types of flexibility provisions in the analysis would have altered EPA's ex ante estimates. Suggestive evidence based on supplementary studies also points to a third case where accounting for flexibility provisions would have affected costs.[22]

MACT II gave regulated pulp mills the option of reducing particulate matter at any of their individual units to meet a mill-specific "bubble" limit instead of a unit-specific limit. However, EPA did not evaluate the implications of the compliance bubble strategy in its ex ante analysis. Morgan et al. (2014) find that about 25 percent of regulated mills used this compliance strategy, obviating the need to update air controls at some mills. As a result, EPA overestimated capital costs ex ante.

In the case of the Title IV SO_2 Trading Program, EPA failed to consider reasons why firms might not fully utilize available flexibilities. Because firms relied less on interfirm trading than anticipated (Ellerman et al. 2000), marginal abatement costs were not equalized across plants (Carlson et al. 2000; Swinton 2004). However, intrafirm strategies such as banking and use of

[22] In the case of the phasedown of lead in gasoline, Newell and Rogers (2007) and Hahn and Hester (1989) note the robust use of trading and banking to meet requirements and suggest that EPA's ex ante estimates of cost savings due to banking were likely underestimated. However, neither study estimates ex post costs.

substitution and compensation units played an important role in keeping unit compliance costs and allowance prices low (Swift 2001).

5.2.6. Lack of Analysis of Transition/Implementation

For three regulations in our sample, studies find evidence of transition or implementation issues that EPA's ex ante analysis did not consider.[23] In the case of the methyl bromide phaseout, Wolverton (2014) suggest that unanticipated complications (i.e., new diseases) after switching away from methyl bromide may have slowed the transition to some alternatives in California.

In the case of RFS2, Lade et al. (2018a) argue that explicit consideration of implementation challenges related to the "blend wall," how much ethanol can be combined or blended into conventional gasoline given existing restrictions on maximum ethanol content, would have greatly increased EPA's ex ante cost estimate of the mandate. Because of blend wall issues, along with failure to produce cellulosic ethanol at commercial scale, EPA has had to revise the mandated cap levels for several categories of renewable fuels—a process that has proved to be disruptive to the renewable identification number (RIN) credit market (Lade et al. 2018b).

5.2.7. Ex Post Rule Changes

Retrospective analysis of the costs of a regulation can be complicated by revisions to requirements over time that affect its implementation. For example, if a future revision to a rule is announced shortly after promulgation, it could affect regulated entities' decisions of how best to comply and hence the rule's realized compliance costs. When this occurs, it is difficult to

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[23] Supplemental studies also offer suggestive evidence that transition or implementation issues were a source of difference between ex ante and realized costs for other regulations. For example, Newell and Rogers (2007) discuss the unexpected high administrative and enforcement burden caused by the output-based nature of the lead phasedown trading program. (See Appendix C for more discussion.)

isolate the effects of the regulation as envisioned ex ante from other regulatory changes. Among the 13 regulations in our sample, we identified four cases where EPA changed the requirements after the rule was finalized. This makes drawing conclusions from a comparison of ex post and ex ante cost estimates more difficult.

In the case of the I&M rule, EPA estimated the costs of a stringent design-based program that limited state flexibility. Three years later, it revised the rule in the face of political pressure to provide states with additional options (Ramsden 1997). Harrington et al. (2000a) evaluate the ex post costs of Arizona's I&M program and find that failure rates were much lower than EPA's ex ante estimate. They attribute the lower failure rate in part to changes in the Arizona program allowed after the initial I&M rule was promulgated. In the case of the CFC phaseout, Hammitt (2000) acknowledges that underestimation of costs in EPA's ex ante analysis was likely explained in part by subsequent passage of the 1990 and 1992 Montreal Protocol amendments, which set an accelerated schedule for reductions in HFCs relative to EPA's 1988 rule.[24]

5.2.8. Reason Unspecified

For nine regulations in our sample, studies find evidence that ex ante and ex post cost estimates differed but did not offer or were unable to identify the sources of these differences. For instance, to meet NO_x budget program requirements, EPA projected that an end-of-pipe selective noncatalytic reduction (SNCR) technology would account for two-thirds of installed control capacity and an alternative end-of-pipe technology, selective catalytic reduction (SCR), would account for around 30 percent. Fowlie (2010) and Fowlie and Muller (2019) find that SCR was

[24] EPA examined 40 percent and 70 percent reductions in CFCs by 1994 and 1998, respectively, but these reductions were achieved by 1990 and 1993.

actually the dominant control technology adopted, while SNCR accounted for less than 10 percent. EPA (2008) also reports that SCR dominated ex post for coal-fired generators of electricity. Possible reasons for these differences are not explored. In the case of the phasedown of lead in gasoline, EPA projected that planning costs associated with adding capital equipment would preclude the adoption of one control technology, isomerization, for two to three years, yet isomerization ended up being adopted by refineries during this time. Again, no explanation for this discrepancy is offered by the ex post study.

5.3. What Sources of Differences Imply for Ex Post Compliance Costs

Realized compliance costs may not align with ex ante projections for a variety of reasons. In this section, we first discuss what insights regarding ex post compliance costs, if any, can be gleaned from differences between ex ante and actual compliance strategies alone. We then look at the possible combined influence of all identified sources of differences on the direction of ex post compliance costs (i.e., over- or underestimated) compared with ex ante expectations.

5.3.1. What Do We Learn from Differences in Compliance Strategies?

Compliance strategies are a critical building block in developing ex ante cost estimates. Table 6 indicates that for 10 of the 13 rules covered in our review, available studies find evidence of differences between anticipated compliance strategies and what actually occurred, and for 9 of the rules, we are able to identify possible sources of these differences. This is a striking result because a better characterization ex ante of compliance strategies should yield better estimates of ex post costs.

Nevertheless, in only three cases is it possible to identify the directional influence of changes in compliance strategies on ex post compliance costs, all else equal. In the case of RFS2, the technological innovation needed to produce substantial volumes of cellulosic ethanol at low cost failed to materialize. While studies do not explicitly quantify the extent to which this resulted in higher compliance costs, the direction of the effect—at least in aggregate—is reasonably well established (e.g., Lade et al. 2018b). In the case of MACT II, failure to consider how the availability of a "bubble" reduced unit costs at mills that adopted this strategy also likely resulted in an overestimate of compliance costs for these mills (Morgan et al. 2014).[25]

While several factors likely contributed to differences in compliance strategy for the surface coating rule, they all lowered realized compliance costs relative to ex ante expectations. Some plants introduced reformulation earlier than anticipated, sometimes in response to preexisting initiatives that were not always accounted for by EPA. In addition, corporatewide approaches to compliance likely made reformulation even more dominant as an abatement strategy, which allowed firms to take advantage of economies of scale, further reducing costs. Finally, realized costs were also lower than anticipated due to EPA's ex ante assumptions regarding the order in which controls would be applied at plants—that is, the adoption of more expensive end-of-pipe controls before lower-cost process-based options.

For the remaining rules in our sample, it is not possible to draw conclusions about ex post unit costs based on shifts in compliance strategy alone.[26] In some instances (arsenic, cluster, and NO_x budget), this is because either the retrospective study sheds light on compliance strategies for only a small subset of regulated entities or the identified sources of differences in compliance

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[25] Morgan et al. (2014) note that this conclusion is valid only if the EPA ex ante control cost estimates were reasonably accurate for the end-of-pipe controls installed at these mills.
[26] For three rules—boutique fuels, CFCs, and enhanced I&M—the studies in our sample offer little (or no) insight into how compliance strategies differed between ex ante and ex post.

strategies are not sufficient for understanding its implications for realized compliance costs.[27] In other cases (methyl bromide exemptions, locomotives, and Title IV SO_2 Trading Program), multiple sources of differences in compliance strategy make an assessment of their net directional influence on ex post costs challenging.[28]

5.3.2. Are Ex Post Costs Lower or Higher Than Ex Ante Estimates?

In this section, we discuss how realized costs—whether aggregate cost, unit compliance cost, or some proxy for the marginal cost of compliance—compare with ex ante projections based on the combined influence of all identified sources of differences. Table 7 shows the likely direction of differences between ex ante and ex post cost estimates for each regulation. We restrict our assessment to conclusions that can be drawn directly from the primary studies in our sample. A blank cell in the table indicates that no primary studies are available to inform ex post estimates for a particular rule and cost type. Because of the relatively small number of regulations for which ex post cost information is available, as well as the limited scope of many of these studies,

[27] For the arsenic rule, while some entities avoided or reduced compliance costs through behavioral and process changes (Morgan and Simon 2014), we do not know how the costs of these changes compare with ex ante estimates. For the cluster rule, some mills shifted away from production of bleached products, reducing or eliminating the cost of complying (Elrod and Malik 2017). While this strategy must have been cheaper than if product mix had remained unchanged, it is not clear what this implies for realized compliance costs relative to ex ante. For the NO_x Budget Program, Linn (2008) find that precombustion modifications were widely used to lower emissions rates at plants that did not use end-of-pipe controls but do not discuss how this affected costs relative to ex ante.

[28] While there is broad consensus that the Title IV SO_2 Trading Program resulted in more cost-effective reductions than anticipated, the directional influence of changes in compliance strategies alone on costs is less clear. The program induced greater-than-expected levels of technological innovation (Bohi and Burtraw 1997; Swift 2001; Popp 2003), which unambiguously reduced compliance costs relative to ex ante expectations. However, reliance on corporate instead of plant-level decisionmaking and intrafirm trading (Swinton 2002, 2004; Carlson et al. 2000) resulted in less trading and thus higher compliance costs than ex ante expectations (e.g., Bohi and Burtraw 1997; Swift 2001; Ellerman et al. 2000). Differences in compliance strategies due to exogenous baseline changes had an indeterminate effect on compliance costs. For MBr, preexisting state regulations and the unanticipated emergence of new diseases slowed adoption of alternatives, increasing compliance costs relative to what was expected. However, innovations that improved the performance of new formulations of existing fumigants reduced costs relative to ex ante estimates (Wolverton 2014). For locomotives, the number of remanufactured locomotives complying with the rule was lower than anticipated, which would reduce compliance costs. However, some evidence suggests higher-than-anticipated usage rates for certain technologies to minimize the fuel economy penalty from the rule, which may have increased compliance costs (Kopits 2014).

we are not able to reach a conclusion on whether ex post costs in general tend to be greater or less than ex ante estimates produced by EPA.

Table 7. Direction of Difference between Ex Ante and Ex Post Compliance Cost Estimates

EPA rule	Aggregate costs	Unit cost	Costs as reflected in permit or market prices
Lead Phasedown in Gasoline			
CFC Phaseout			Relatively accurate initially, unclear after 1990
Boutique Fuels (RFG, RVP, & OXY)			Likely underestimated for some markets
Title IV SO_2 Trading Program	Relatively accurate for initial years of Phase I	Likely overestimated for both Phases I and II	
Enhanced Vehicle Emissions I&M		Likely underestimated, Arizona only	
NO_x Budget			
Locomotive Emission Standards		Likely underestimated for some locomotive types	
Cluster Rule for Pulp and Paper	Likely overestimated, at least capital costs	Indeterminate	
MACT II for Pulp and Paper		Likely overestimated, for capital cost of plants using bubble	
Arsenic in Drinking Water Regulations		Indeterminate	
Light-Duty Vehicle Surface Coating NESHAP	Likely overestimated	Likely overestimated	
MBr Annual Critical Use Exemptions		Likely overestimated, in California	Reasonably accurate, in California for strawberries
RFS2			Likely underestimated

Note: Blank cells indicate that available studies do not inform or offer insights into a particular element of realized compliance costs. RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel.

We are able to identify the direction of difference between ex ante and ex post aggregate compliance costs estimates for only three rules: cluster, Phase I of the Title IV SO_2 Trading Program, and the light-duty surface coating NESHAP.[29] In two of these cases (cluster and light-duty NESHAP), studies find that compliance costs were likely overestimated ex ante. In the remaining instance (SO_2), ex ante estimates were consistent with ex post evidence on costs.[30] However, it is important to note that these conclusions are based on partial coverage (i.e., subset of cost categories, regulated entities, or years). Recall that in Table 5, we classified the extent to which the studies provide insights with regard to aggregate compliance costs as medium gray for the Title IV SO_2 Trading Program and light gray for the cluster and light-duty NESHAP rules.

Wolverton et al. (2019) conclude that ex ante compliance costs were likely substantially overestimated for the light-duty surface coating NESHAP. The dominant compliance strategy for the subset of plants surveyed—reformulating coatings instead of installing expensive abatement control technology—likely applied to most of the automobile sector. And many companies implemented reformulation across all their plants, not just at those surveyed. In addition, fewer plants were subject to the new requirements than anticipated (e.g., some went out of business for reasons unrelated to the regulation). For the cluster rule, Morgan et al. (2014) find that aggregate capital costs to meet regulatory requirements were 55 percent lower than anticipated. Use of alternate baseline assumptions produced qualitatively similar results, with realized costs

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[29] In at least one case, broader lines of evidence also suggest that aggregate costs differed substantially from ex ante estimates. For RFS2, EPA projected substantial cost savings based on increased use of ethanol in place of gasoline. However, gasoline and ethanol prices have been closely correlated, substantially reducing the price gap between the two fuels relative to what was projected. Thus, cost savings from substituting ethanol for gasoline were also likely considerably smaller (Lade et al. 2018a).

[30] Ellerman et al. (2000) and Carlson et al. (2000) estimate that aggregate annual compliance costs were about $700 million to $900 million in 1995 and 1996; annualized ex ante estimates produced by EPA were $700 million to $1.5 billion (converted to the same dollar year, 1995).

estimated as 30–100 percent lower than ex ante estimates. The authors note that they had no ex post information on two rule provisions or on variable compliance costs.

Carlson et al. (2000) and Ellerman et al. (2000) estimate the aggregate compliance costs of Phase I of the Title IV SO_2 Trading Program, but only for the first few years of the program. While the extent to which plants relied on compliance flexibilities differed from ex ante expectations, ex post costs were largely in line with EPA estimates for the initial years. However, we reach a somewhat different conclusion regarding the unit compliance costs of the Title IV SO_2 Trading Program based on evidence from a longer time period.

Information is available for a larger set of rules regarding the likely direction of difference between ex ante and ex post unit compliance cost estimates. However, ex ante estimates were not uniformly biased in one direction. While our sample of studies suggests four cases (surface coating, SO_2 trading, MBr, and MACT II) where EPA likely overestimated unit compliance costs for at least a subset of regulated entities, in at least two cases (enhanced I&M and locomotive) it likely underestimated them for at least a subset of regulated entities. It is difficult to draw conclusions regarding the direction of the difference between ex ante and ex post unit compliance costs based on available evidence for the arsenic and cluster rule cases.[31]

Recall from Table 5 that our ability to glean insights about ex post unit compliance costs from existing studies is strongest for surface coating and the Title IV SO_2 Trading Program (dark

[31] For the arsenic rule, though Morgan and Simon (2014) had some limited information on unit operating and maintenance costs for two treatment technologies, they were not able to come to a conclusion regarding how realized per-unit costs differed from ex ante expectations. In addition, they note a high level of heterogeneity in compliance strategies across regulated systems and a lack of information on capital costs and on the costs of other treatment technologies as analytic challenges. Morgan et al. (2014) had some limited unit cost information for a small subset of firms from their SEC filings, which they describe as anecdotal, but even for these firms, the data were mixed when comparing ex ante and ex post costs, making it difficult to draw firm conclusions.

gray), followed by enhanced I&M (medium gray). Locomotive, MACT II, MBr, arsenic, and cluster are all classified using the lightest color (light gray). We briefly discuss each case in turn, beginning with those where unit compliance costs were likely overestimated for the subset of regulated entities for which there are data.

In addition to the factors identified in Section 5.3.1, failure to account for flexibilities aside from trading that were afforded to plants through the implementation of the Title IV SO_2 Trading Program caused EPA to overestimate ex ante unit compliance costs. While firms did not rely on interfirm trading to the extent anticipated, they made great use of substitution and compensating units, as well as banking provisions. These flexibilities, along with higher-than-anticipated levels of technological innovation and cheaper access to low-sulfur coal, resulted in both lower-than-anticipated allowance prices and unit compliance costs (e.g., Ellerman et al. 2000; Carlson et al. 2000; Swift 2001; Chan et al. 2018).[32] For surface coating, unit compliance costs were much lower than anticipated because firms chose to reformulate coatings instead of installing end-of-pipe technologies that were markedly more expensive.

For MACT II, Morgan et al. (2014) observe that the use of a bubble strategy for particulate matter allowed some firms to spread compliance activities over a wider range of plant activities. Thus, capital costs were estimated to be about 25 percent lower ex post at these plants, since they no longer had to upgrade or replace air pollution controls in some units. As long as operating costs were not vastly different from expectations, this decrease in capital costs implies that the unit cost of meeting MACT II was also lower at these plants. Morgan et al. (2014) are not able to

[32] The only study to speak to ex post costs for Phase II of the Title IV SO_2 Trading Program is Chan et al. (2018).

determine the extent to which unit costs at plants that continued to use controls differed from ex ante expectations.

In the case of methyl bromide, the effect on farmer (net) operating costs of not being granted an exemption was likely overestimated ex ante as a result of overly conservative assumptions for strawberry yields per acre in California. EPA substantially underestimated yields in the baseline because of its reliance on a national average instead of accounting for the greater productivity of California farms. Evidence also suggests that yield loss due to switching from MBr was likely lower than anticipated.

Next, we turn to the two cases where unit compliance costs were likely underestimated, at least for the subset of regulated entities for which there is information. While the enhanced I&M program in Arizona, as implemented, was less stringent than what was analyzed ex ante by EPA, which would imply lower unit compliance costs all else equal, Harrington et al. (2000a) find that actual fuel cost savings were substantially lower than projected, baseline control equipment was more effective and durable than expected, and repairs were less effective and less durable than expected.[33] These differences led to higher compliance costs than anticipated. What these differences in costs imply for programs in other states is unclear. While some differences are driven by factors that are unlikely to be specific to the Arizona program, other differences may

[33] Harrington et al. (2000a) find substantially longer wait times for repairs than anticipated by EPA. Direct comparisons of this cost category are complicated by use of different wage rates. EPA used a substantially higher wage rate in its ex ante analysis than the ex post study. (Harrington et al. [2000a] used an Arizona-specific wage rate, while EPA relied on a national rate.) However, no information is provided on the extent to which the rate used by EPA in its ex ante analysis was an accurate reflection of ex post labor costs across all states that implemented the program.

not generalize (e.g., it is possible that wait times in other states were similar to or shorter than EPA's ex ante estimate).

In the case of the locomotive rule, all else equal, realized unit compliance costs for some types of locomotives were likely higher than EPA's ex ante estimates because of two identified differences. First, the larger number of remanufacturing systems certified and larger number of suppliers than expected likely increased the fixed costs of compliance for remanufactured locomotives. Second, increased usage rates for some technologies caused variable costs for remanufactured locomotives to be higher than anticipated for most model types. Third, the operating costs per locomotive (new or remanufactured) were likely higher, since actual fuel prices were much higher than anticipated (Kopits 2014).

For the retrospective studies that examine the market price effects of regulation but lack other compliance cost information, there are two cases, boutique fuels and RFS2, where the results indicate that compliance costs may have been underestimated. Additionally, there is one case, CFCs, where it is difficult to infer much about potential underestimation of costs after 1990 because the retrospective study does not quantitatively estimate the influence of the passage of the 1990 and 1992 Montreal Protocol amendments, which accelerated the HFC reduction schedule relative to EPA's 1988 rule.

For the remaining case where a retrospective study examines market price effects of the MBr exemptions, EPA's forecast of national strawberry grower prices was reasonably accurate. However, other evidence suggests that compliance costs were likely overestimated by EPA. Taken together, one might infer that compliance costs did not significantly affect prices, all else equal. MBr is also identified in Table 5 as dark gray with respect to market prices.

6. Conclusions and Lessons Learned

In this paper, we have reviewed 28 ex post analyses from the published literature that offer insights into the compliance costs of 13 significant EPA regulations. Specifically, we assess which elements of compliance costs are informed by each study, discuss possible sources of identified differences between ex ante and ex post cost estimates, and then evaluate the extent to which our results indicate the direction of difference between ex post costs relative to EPA's ex ante estimates.

Even though our sample comprises a very small subset of EPA regulations, our review provides useful insights on the realized costs of regulations and offers lessons for future analysis. First, we find that many of the studies provide insights on realized compliance strategies relative to ex ante expectations. For example, in a number of cases, we found that—with the exception of rate-regulated electric utilities—regulated firms tended to adopt less capital-intensive compliance strategies than EPA anticipated ex ante. Second, some studies also offer insights into specific elements of per-unit compliance costs (e.g., capital expenditures) for a subset of entities, but only a few shed light on unit compliance costs. Third, even fewer speak to the total cost of the regulation. Finally, while all the studies have data limitations, in general more information is available for regulations affecting industries that are required to report detailed facility-level data (e.g., power plants).

In spite of data and methodological limitations, as well as the narrow scope of some studies, we have been able to identify several common sources of differences between ex ante and ex post estimates. The most common factor identified is an inaccurate ex ante accounting of baseline conditions, followed by inadequate consideration of technological innovation. In most cases, multiple factors are found to have contributed to differences.

Only in a few cases does the combined influence of all identified sources of differences allow us to discern how the realized cost—whether aggregate cost, unit compliance cost, or some proxy for the marginal cost of compliance—differed from ex ante projections. Even where we have information, we are able to make only partial statements about costs being likely under- or overestimated (e.g., for a subset of regulated entities, years). Because of the relatively small number of regulations covered and the limited scope of many of these studies, we are not able to reach a conclusion as to whether ex post costs in general tend to be greater or less than ex ante estimates produced by EPA.

The ultimate objective of retrospective analysis is to assess the extent to which a regulation delivered the promised benefits at the expected costs. We have limited this study to a retrospective assessment of costs but recognize the importance of a future study that conducts a similar exercise comparing ex ante and ex post estimates of benefits for the 13 regulations in our study.

6.1. Lessons for Conducting Ex Ante Cost Analysis

While the published literature examining the cost of environmental regulation retrospectively is relatively limited in scope, several valuable lessons can still be taken from an assessment of the differences between ex ante and ex post estimates to inform improvements in the way ex ante analyses are conducted going forward. First, we find that several of the sources of differences identified in Section 5 stem from failure to use an economic framework or model. For instance, differences in cost estimates stemmed from not accounting for the effect of industry structure, flexibility provisions, transition/implementation issues, or compliance/enforcement difficulties. In cases where firms owned multiple plants or had some degree of market power (e.g. automobile companies in the case of surface coating or electric utilities in the case of the Title IV SO_2 Trading Program), firms opted for compliance strategies that differed from what was implied under perfect competition or for individually owned plants. In addition, EPA often evaluated costs and benefits in only one or more years after the regulatory requirements were fully implemented. In some cases (e.g., RFS2, MBr), it would have been informative to also examine costs in the initial phase-in years of the program due to supply constraints, input shortages, and training requirements.

Second, in several cases, improved forecasts or sensitivity analysis of key inputs and assumptions based on data that are typically available prior to rule promulgation would have yielded more accurate ex ante projections of the cost of regulation. For example, for some rules (e.g., RFS2, locomotives), the assumption for future energy prices were a key driver of differences between ex post costs and ex ante cost estimates. The typical RIA approach is to focus on the EIA reference price projections for energy prices. However, EIA also provides high and low energy price scenarios, which can serve as the basis for sensitivity analysis where energy prices are likely to have an important effect on cost. Moreover, better accounting for existing regulations, known but emerging technologies, and other factors could improve the forecast of the baseline scenario for the ex ante analysis. In some cases, enough information may be available to explore alternative assumptions about the effect of technological innovation on cost. For example, in the case of surface coating and arsenic, the EPA analysis failed to fully reflect the extent of technological innovation already underway and the pace at which these changes could be introduced into the marketplace—a key factor that reduced the cost of the rule.

In the case of RFS2, however, EPA was overly optimistic regarding the potential development of low-cost cellulosic ethanol, a key factor that increased the cost of the rule.

That said, some sources of differences are essentially unforecastable and will likely remain difficult to account for in ex ante analysis. This may be the case, for example, for some types of significant technological breakthroughs or major institutional changes that emerge after a rule has been issued. In cases where a change is anticipated but with a high level of uncertainty, particularly over a long time frame, it may be worth conducting a revised benefit-cost analysis to evaluate the extent to which such anticipated changes affected the costs (and benefits) of the rule.

6.2. Lessons for Conducting Ex Post Cost Analysis

Without adopting an evaluation plan ex ante, it is difficult to conduct thorough and systematic retrospective evaluation. To date, retrospective analysis has mainly occurred opportunistically, where data happen to be available and it is possible to identify a group or time period to act as a counterfactual (i.e., what might have happened absent the regulation). The relatively small number of studies where some element of the cost to comply with a specific environmental regulation has been evaluated ex post is a telling indicator of the scale of the problem. Efforts to improve the ability to conduct a high-quality retrospective cost analysis should therefore focus on enhancing data collection efforts, including information that can be used to construct a defensible counterfactual. Without increased attention to these issues, the ability to draw more general conclusions ex post about the realized cost of regulation will continue to be limited.

EPA could help facilitate a greater level of retrospective review of its regulations, however. One possible way this could be accomplished is by laying out plans for future ex post study in the final rule. Plans for future study could specify the measurable outcomes to be chosen for retrospective analysis (perhaps with greater attention to the most uncertain elements of the ex ante analysis), the time period for evaluation, quantitative methods to be used, identification of a control group (and baseline), and possible approaches to resolving key uncertainties, which could then serve as basis for identifying data needs and putting in place plans for ex post data collection. Making these data publicly available would allow academic researchers and other interested parties to conduct their own retrospective reviews.

For rules where regulatory analysis occurs well before full implementation (e.g., Title IV SO_2 Trading Program, RFS2), laying out explicit plans for an ex post evaluation at an appropriate interval after promulgation (e.g., the final rule for greenhouse gas emissions standards in light-duty vehicles announced and followed through on a midterm review several years after promulgation) could be informative and allow for potential midcourse corrections in policy design or stringency. These types of look-backs could also yield insights that are informative for other rulemaking processes.

Finally, EPA could give special attention to the opportunity to design a quasi-experimental analysis with an effective counterfactual. Such opportunities could arise, for example, where a rule adopts differential phase-in schedules or regional requirements or establishes a critical threshold (e.g., for size). In addition, there may be instances where EPA could undertake pilot studies to understand the likely cost implications of a rulemaking.

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Appendix A: Additional Details on Study Methods and Data

This appendix provides additional details on the scoring methodology and the detailed results for each study in our sample. Table A.1 describes the three categories and associated scores for each of the five elements assessed. Category numbers are assigned in such a way that within each element, an increase in the degree of formality or rigor leads to a higher number. Thus the same can be said of the total score when summing across the five elements.

Table A.1. Description of Element Scoring Scheme

Element	Score	Category description
Data type	1	Primarily informal (e.g., informal self-reporting, industry association report, expert opinion)
	2	Mix of informal and more formal (e.g., observed data on one or few key inputs)
	3	Primarily formal (e.g., observed, measured, required self-reporting to EPA, EIA, FERC)
Coverage	1	Anecdotal, model plant
	2	Partial, nonrepresentative sample
	3	Full/census, representative sample
Unit of observation	1	Primarily industry/national or state level (or data for broadly defined markets)
	2	Mix of market/industry-wide and source-level data (or data for precisely defined markets)
	3	Primarily source-level/regulated entity
Method of obtaining result	1	Primarily subjective synthesis, expert opinion
	2	Estimated/revealed
	3	Observed/stated directly by affected sources (few additional steps to get to endpoint)
Extent of control for other factors	1	Descriptive, no controls
	2	Associative, with control variables
	3	Causal, counterfactual or panel fixed effects and control variables

Table A.2 provides an example of the application of this scoring scheme. Specifically, it shows our assessment of how Linn (2008) provides insights on compliance strategies used in the NO_x Budget Program, a cap-and-trade program to limit summer NO_x emissions from power plants in eastern states. Linn's focus is to examine how important smaller-scale boiler modifications were in reducing emissions. He does this by limiting his sample to those electricity generating units (EGUs) that did not install capital-intensive control equipment (e.g., SNCR or SCR) and uses the geographic and temporal coverage of the program to construct a control group that is observably quite similar to the treatment group. He finds that emissions rates of the plants subject to the regulation (treatment group) were approximately 10–15 percent lower than the plants in the control group. Because of the difference-in-difference estimation approach's ability to control for all other confounding factors, Linn concludes that these reductions were the result of smaller-scale modifications. Table A.2 summarizes the scores we assigned to each of the five elements for this study.

Table A.2. Example of Application of Scoring Scheme

Element	Assessment	Score
Data type	Observed/self-reported data on emissions reductions and whether capital investment was made	3
Coverage	Sample limited to EGUs that did not make capital investments	2
Unit of observation	Primarily source-level (EGU-specific) data	3
Method of obtaining result	Estimated via regression analysis	2
Extent of control for other factors	Panel data with fixed effects; difference-in-difference allows causal inference	3
Total		*13*

Note: This example applies the scoring scheme in Table A.1 to the analysis by Linn (2008) of NOx Budget Program compliance strategies.

The Linn (2008) study was assigned a score of 3 for both data type and unit of observation, since all the data needed to construct the EGU subsamples and estimate the regressions (i.e., data on emissions, boiler characteristics, the installation of capital-intensive control technologies, location) were EGU-specific and obtained from formal EPA and DOE data sources. It was assigned a 2 for coverage since the study examines the compliance strategies of only a subset of all EGUs subject to the rule. Finally, for the two methods-related elements, it was assigned a 2 for being estimated via regression and a 3 for controlling for confounding factors with a difference-in-difference estimation approach.

We repeated this exercise for each study for all four cost components. Table A.3 reports the resulting numeric scores for each of the studies in the sample.

Table A.3. Detailed Results of Scoring Exercise

		CFC (Hammitt 2000)	I&M (Harrington et al. 2000a)	Locomotive (Kopits 2014)	Arsenic (Morgan and Simon 2014)	MBr Phaseout (Wolverton 2014)	Surface coating (Wolverton et al. 2019)
Compliance strategy	Data type			1	2	2	3
	Coverage			1	1	2	2
	Unit of obs.			1	2	2	3
	Method			1	1	2	3
	Controls			1	1	1	1
Permit or other prices	Data type	3				3	
	Coverage	3				3	
	Unit of obs.	1				2	
	Method	2				2	
	Controls	1				1	
Unit compliance cost	Data type		2	1	1	2	2
	Coverage		2	1	1	1	2
	Unit of obs.		2	1	2	1	3
	Method		2	1	1	1	3
	Controls		1	1	1	1	1
Aggregate cost	Data type						1
	Coverage						2
	Unit of obs.						2
	Method						1
	Controls						1
Compliance strategy	Total	0	0	5	7	9	12
Permit or other prices	Total	10	0	0	0	11	0
Unit compliance cost	Total	0	9	5	6	6	11
Aggregate cost	Total	0	0	0	0	0	7

Table A.3 (*continued*)

		MACT II (Morgan et al. 2014)	Cluster (Morgan et al. 2014)	Cluster (Elrod and Malik 2017)	Gasoline Lead (Kerr and Newell 2003)	Boutique Fuels (Brown et al. 2008)	Boutique Fuels (Chakravorty et al. 2008)	RFS2 (Lade et al. 2018a, 2018b)
Compliance strategy	Data type	2	2	3	2			
	Coverage	3	3	2	2			
	Unit of obs.	3	3	3	3			
	Method	3	3	2	2			
	Controls	1	1	3	3			
Permit or other prices	Data type					3	3	3
	Coverage					2	2	3
	Unit of obs.					2	1	1
	Method					2	2	2
	Controls					2	2	2
Unit compliance cost	Data type	1	2					
	Coverage	2	2					
	Unit of obs.	2	1					
	Method	1	1					
	Controls	1	1					
Aggregate cost	Data type		1					
	Coverage		2					
	Unit of obs.		1					
	Method		2					
	Controls		1					
Compliance strategy	Total	12	12	13	12	0	0	0
Permit or other prices	Total	0	0	0	0	11	10	11
Unit compliance cost	Total	7	7	0	0	0	0	0
Aggregate cost	Total	0	7	0	0	0	0	0

Table A.3 (*continued*)

		NO_x Budget (Linn 2008)	NO_x Budget (Popp 2010)	NO_x Budget (Fowlie 2010)	SO_2 Title IV (Carlson et al. 2000)	SO_2 Title IV (Ellerman et al. 2000)	SO_2 Title IV (Swift 2001)	SO_2 Title IV (Arimura 2002)
Compliance strategy	Data type	3	3	3		3	3	3
	Coverage	2	3	3		2	3	2
	Unit of obs.	3	2	3		3	3	3
	Method	2	2	3		3	3	3
	Controls	3	3	3		1	1	2
Permit or other prices	Data type					3	3	3
	Coverage					2	3	2
	Unit of obs.					1	1	2
	Method					3	3	2
	Controls					1	1	2
Unit compliance cost	Data type			1		1	2	
	Coverage			1		2	2	
	Unit of obs.			1		3	2	
	Method			2		3	1	
	Controls			2		1	1	
Aggregate cost	Data type				3	2	2	
	Coverage				2	2	2	
	Unit of obs.				3	2	2	
	Method				2	1	1	
	Controls				3	1	1	
Compliance strategy	Total	13	13	15	0	12	13	13
Permit or other prices	Total	0	0	0	0	10	11	11
Unit compliance cost	Total	0	0	7	0	10	8	0
Aggregate cost	Total	0	0	0	13	8	8	0

Table A.3 (*continued*)

		SO_2 Title IV (Popp 2003)	SO_2 Title IV (Swinton 2002, 2004)	SO_2 Title IV (Busse and Keohane 2007)	SO_2 Title IV (Frey 2013)	SO_2 Title IV (Cicala 2015)	SO_2 Title IV (Chan et al. 2018)
Compliance strategy	Data type		3		3	3	3
	Coverage		2		2	2	3
	Unit of obs.		3		3	3	3
	Method		3		2	2	3
	Controls		3		3	3	3
Permit or other prices	Data type			3			
	Coverage			2			
	Unit of obs.			3			
	Method			2			
	Controls			3			
Unit compliance cost	Data type	3	3		3		3
	Coverage	2	2		2		2
	Unit of obs.	3	3		3		3
	Method	2	2		2		2
	Controls	3	3		3		3
Aggregate cost	Data type						
	Coverage						
	Unit of obs.						
	Method						
	Controls						
Compliance strategy	Total	0	14	0	13	13	15
Permit or other prices	Total	0	0	13	0	0	0
Unit compliance cost	Total	13	13	0	13	0	13
Aggregate cost	Total	0	0	0	0	0	0

Appendix B: Additional Details on Included Regulations

Table B.1. Regulations Analyzed by Studies in Our Sample

EPA rule	Promulgation years	Regulatory requirement
Lead Phasedown in Gasoline	1979, 1982, 1985	Individual facility refinery performance standards followed by trading program
CFC Phaseout	1988, 1992, 1993	Tradable permit program for CFC consumption plus excise tax with eventual phaseout (to implement provisions of the Montreal Protocol)
Boutique Fuels Program (RFG, RVP, & OXY)	1989, 1990, 1992, 1994	Fuel emissions standards for regions with local air quality problems; in some cases, states allowed to adopt unique fuel programs
Title IV SO_2 Trading Program	1992	Two-phased cap-and-trade program for SO_2 emissions from power plants
Enhanced Emissions I&M Program	1992	Requirements for enhanced vehicle inspection; maintenance programs for metropolitan areas with high levels of ozone or carbon monoxide (CO)
NO_x Budget Program	1998	Cap-and-trade program to limit summer NO_x emissions in eastern states from power plants and other sources
Locomotive Emission Standards	1998	Emissions standards (for HC, CO, NO_x, PM, smoke) and test procedures for new and remanufactured locomotives
Cluster Rule	1998	BAT and effluent guidelines for wastewater and MACT standards for HAP emissions from pulp and paper mills
MACT II	2001	NESHAP for Chemical Recovery Combustion Sources at Kraft, Soda, Sulfite and Stand-Alone Semichemical Pulp Mills
National Primary Drinking Water Regulations for Arsenic	2001	Drinking water BAT standard for residential and nonresidential systems
Light-Duty Surface Coating NESHAP	2004	MACT standard for HAP air emissions from vehicle paint shops
Methyl Bromide Phaseout	2004–2008	Critical use exemption from ban on MBr use for agricultural production
Renewable Fuels Standard 2	2010	Volume requirements for renewable fuel to replace (via blending) petroleum-based fuel

Note: RFG = reformulated gasoline; RVP = Reid vapor pressure; OXY = oxygenated fuel; HC = hydrocarbons; PM = particulate matter; BAT = best available technology; HAP = hazardous air pollutants.

Appendix C: Additional Discussion of Findings from Included Studies

C.1. Baseline Issues

With regard to the NO_x Budget Program, EPA did not consider the effect of differences in state regulation of electricity rates in modeling electricity generating unit (EGU) compliance strategy decisions ex ante.[34] Fowlie (2010) finds that state rate-regulated and publicly owned and operated EGUs were more likely to select a capital-intensive compliance approach than were EGUs operating in competitive/restructured electricity markets.

In the case of RFS2, EPA used a single forecast of future fuel prices (the EIA reference projections for energy prices) in its ex ante analysis. However, forecasts of future energy prices are notoriously inaccurate. Since EIA also provides high and low energy price scenarios, these alternatives could have served as the basis for sensitivity analysis. In fact, world oil prices and the price of wholesale gasoline and ethanol have behaved in a way that differs significantly from the projected prices underlying EPA's ex ante analysis. Lade et al. (2018a) report that gasoline and ethanol prices have tracked relatively closely, with only a minor gap between them. The gap likely reflects the difference in energy density of the two fuels. The virtual elimination of the gap between wholesale ethanol and gasoline prices means that there is a negligible cost savings associated with substituting ethanol for gasoline.

In addition, EPA projected annual increases in gasoline demand out to 2022. Lade et al. (2018a) note that gasoline demand declined over the 2009–13 period, returning to 2009 levels only in

[34] EPA qualitatively discussed the effect of restructuring on electricity prices in its ex ante analysis, noting that identifying the owners of the affected units and projecting the way in which public utility commissions would treat the additional costs associated with the NO_x budget program are particularly difficult. As a result, EPA did not carry forward any implications of the effect of restructuring on compliance choice by EGUs.

2015. As a result, the RFS2 mandate exceeded the blend wall over the 2012–16 period, bringing to a head issues with the blend wall. Lade et al. argue that explicit consideration of blend wall issues "would have revealed the inherent costly nature of the mandates beyond the blend wall."

Concerning enhanced I&M, EPA's ex ante baseline assumed a higher incidence of test failures than actually occurred in the Arizona program. Harrington et al. (2000a) report that manufacturer improvements in the reliability/durability of vehicles' original control equipment, made beginning in the late 1980s, reduced the incidence of test failures.[35]

For the cluster rule, Morgan et al. (2014) assert that issues associated with the establishment of a baseline posed an important challenge to assessing ex post costs. For instance, they find evidence that control of dioxin and furan in the baseline was likely greater than anticipated because of a combination of state regulations and public pressure. The RIA adopted a baseline based on equipment in place as of mid-1995. Announced projects that had not been completed by mid-1995 were included as part of the projected RIA costs of the rule.[36]

Morgan et al. (2014) construct a pre–cluster rule baseline using the average air and water capital expenditures for the years 1995–97. They assume that all increases in air and water expenditures for 1998–2001 relative to this baseline reflected the incremental capital cost of the cluster rule.[37] Using this approach, Morgan et al. conclude that industry capital expenditures were only 45

[35] This improvement reflected better technology and manufacturer response to changes in warranty equipment. Note that the Arizona program also adopted less stringent cut points—a change reflecting the political difficulty of adopting the more stringent program required by the 1992 rule. Harrington et al. (2000a) also suggest that manufacturer improvements in control may have also reflected a response to the 1992 I&M rule.

[36] The RIA included the announced costs of additional controls not underway as of July 1, 1995.

[37] If capital expenditures in one of the years during the 1998–2001 period fell below the pre-rule baseline level, Morgan et al. assumed that there were no capital costs associated with the cluster rule in that year.

percent of the ex ante EPA estimate.[38] EPA also projected that 9 mills would shut down for reasons unrelated to the rule. These mills were treated as baseline closures and were not included in the estimate of capital costs imposed by the rule. Morgan et al. report that 18 mills shut down prior to the effective date of the final rule for reasons unrelated to the rule (excess capacity and changes in demand).

In the case of LDV surface coating, Wolverton et al. (2019) note that the regulated universe was smaller than expected because many plants closed before 2007 for reasons unrelated to the regulation, such as changes in vehicle demand and the overall financial health of the firms. In addition, the ex post analysis finds that process changes were introduced in the baseline to a greater extent than anticipated by the ex ante analysis. Further, reformulation of solvent-based coatings prior to the rule was mainly driven by global firm-level initiatives.

Regarding exemptions to the MBr phaseout, Wolverton (2014) reports that adoption of some MBr alternatives were hindered by preexisting state-level restrictions (e.g., California limits the ways in which some existing fumigants can be combined because of concerns about worker safety). EPA accounted for some of these regulatory issues ex ante and discussed others qualitatively but nonetheless likely underestimated their effect, particularly for new combinations. Moreover, EPA likely underestimated baseline strawberry yields through its reliance on national averages, as California is substantially more productive than other states.

[38] Results using 1996 and 1997 as alternative baselines yielded similar results—capital expenditures were only 33 percent and 57 percent, respectively, of ex ante RIA estimates. Note that Morgan et al. (2014) report that for an earlier period—the substantial capital investment in the early 1990s—they were not able to determine whether the industry undertook this investment in anticipation of the cluster rule or was responding to state and local toxics regulations.

However, yields likely vary by farmer, and it is possible that farmers seeking exemptions were less productive than the California average.

In Phases I and II of the Title IV SO_2 Trading Program, factors such as railroad deregulation and investment by utilities in mining and transportation infrastructure made low-sulfur coal cheaper than anticipated, which resulted in its greater use as a compliance option (Ellerman et al. 2000; Carlson et al. 2000; Swift 2001; Busse and Keohane 2007). State-level public utility commission regulations and cost recovery rules also led to a different mix of compliance strategies (Arimura 2002; Swift 2001; Frey 2013). Differences between ex ante and ex post estimates in capacity, retirements, and additions were largely driven by exogenous changes in electricity supply and demand (Carlson et al. 2000).

For the locomotive rule, the baseline used in EPA's ex ante analysis reflected current conditions for several key inputs rather than being a forecast of future conditions in absence of the regulation. In particular, actual locomotive fuel prices were more than double EPA's ex ante constant fuel price estimate over 2000–2009. Given that fuel costs constituted a large share of per-locomotive operating costs, this input assumption could have contributed to differences between ex ante and ex post per-unit cost estimates. As discussed in Kopits (2014), given the lack of additional data, it is difficult to estimate the extent to which higher fuel prices could have been offset by changes in other factors (e.g., rising fuel prices may have incentivized even greater investment in fuel efficiency improvements absent the regulation). Similarly, EPA estimated the number of newly manufactured and remanufactured locomotives based on the existing fleet and production, remanufacture, and retirement rates. When projecting newly manufactured locomotives, the ex ante analysis did not discuss many potential exogenous factors that could influence the size of the regulated universe, such as demand-side factors that could shift railroad market share relative to trucking and hence the number of new locomotives purchased.

Concerning the CFC phaseout, supplementary studies that do not explicitly estimate costs ex post still offer insights into potential drivers of differences between ex ante and ex post estimates. Industry research and development efforts for CFC alternatives, dating back to the late 1970s, were likely influenced by the presumption of an eventual phaseout.

C.2. Reliance on Engineering Models (versus Economic Models)

In the case of the NO_x Budget Program, Linn (2008) finds that some EGUs used low-cost combustion modification approaches to achieve NO_x reductions rather than purchase NO_x allowances or adopt the high-capital-cost control equipment identified by EPA.

With regard to the cluster rule, Elrod and Malik (2017) point to one possible explanation for why capital costs were overestimated: some regulated mills substantially altered their product mix and output away from bleached products in response to requirements, which would have reduced the need to install end-of-pipe abatement technologies.

For the locomotive rule, Kopits (2014) finds some evidence to suggest higher-than-anticipated usage rates for certain technologies (e.g., EFI and split cooling). An industry expert stated that firms may have been incentivized to adopt these technologies to minimize the fuel economy penalty associated with the rule, not because they were needed to achieve required emissions reductions. Kopits also notes that the number of remanufactured locomotives complying with the rule was lower and the number of new locomotives was higher than EPA anticipated. These trends could have reflected strategic firm behavior in response to the regulation, as railroads may have found it cheaper to delay rebuilds or to retire early and buy new locomotives rather than remanufacture older models to meet the new emissions standards.

Concerning the arsenic rule, Morgan and Simon (2014) find that behavioral nontreatment options were used to comply with the standards. For example, some water systems chose to meet the arsenic limits, or avoid being subject to the rule, by blending with low-arsenic or arsenic-free water, turning off wells with elevated levels of arsenic, using selective well screening to draw water from regions of the aquifer with low arsenic levels, or connecting to municipal water sources. These types of nontreatment strategies were not considered by EPA when forecasting regulated entities' compliance choices.

C.3. Lack of Accounting for Industry Structure

In the case of surface coating, Wolverton et al. (2019) report that there was greater uniformity in compliance strategies across plants than anticipated; feedback from auto manufacturers indicates that this may have been driven by firms' decisions to pursue a corporate-wide compliance strategy. EPA evaluated each plant's compliance strategy as if it were independent from other plants within the same firm. Pursuing a corporate-level reformulation approach was described as attractive because it yielded substantial economies of scale. Administrative costs were lower than anticipated since database development also occurred at the firm instead of the plant level.

For the Title IV SO_2 Trading Program, ex post evidence suggests a preference for a within-firm compliance strategy that led to less extensive trading, which meant that marginal abatement costs were not equalized across plants (Bohi and Burtraw 1997; Ellerman et al. 2000; Carlson et al. 2000; Swift 2001; Swinton 2002, 2004). In addition, industry structure came into play with regard to the role of railroad deregulation: single-plant firms saw higher low-sulfur fuel prices in isolated markets (Busse and Keohane 2007).

Regarding boutique fuels, Brown et al. (2008) find that RVP and RFG requirements increased wholesale gasoline prices significantly relative to prices in unregulated markets. Further, they report evidence that the number of competitors and the geographic isolation of some regulated markets contributed to even larger increases in city-specific wholesale gasoline prices. These results suggest that geographically differentiated requirements resulted in the segmentation of these markets, increasing the ability of refiners to exercise market power.[39]

In the case of the CFC phaseout, EPA acknowledged that production of CFCs was concentrated among a few firms but did not incorporate this into its ex ante analysis. However, there is suggestive evidence that firms holding patents on promising substitutes viewed the regulation as a way to increase market share (Harrington et al. 2000b).

C.4. Technological Innovation

For surface coating, EPA acknowledged ex ante that process change would be the cheaper way to comply but nonetheless anticipated that most plants would pursue the more expensive end-of-pipe technology strategy. Wolverton et al. (2019) find evidence that EPA underestimated the technological innovation already underway and the pace at which these changes could be introduced into the marketplace. Several major manufacturers (as well as paint suppliers) were already cooperatively exploring low-HAP paint formulations prior to promulgation of the

[39] Chakravorty et al. (2008) also report that boutique fuels rules created "regulatory islands," increasing the market power of firms in these markets, and increased gasoline prices. Anderson and Rykowski (1997) argue that EPA's ex ante analysis was long on engineering analysis (i.e., technical analysis of refiner costs) but short on economic analysis, including the effects of the regulations on competitiveness.

NESHAP, in part as a response to increased competition by foreign automobile manufacturers and in anticipation of formidable technical challenges to developing low-emissions technologies to meet eventual requirements under the 1990 Clean Air Act Amendments. Moreover, the automotive coatings industry is fairly concentrated; while coating specifications are unique to a manufacturer, paint suppliers received similar requests from multiple manufacturers to develop compliant coatings. This may have allowed other manufacturers that did not engage in early R&D to nonetheless adopt coatings that were low in volatile organic compounds (VOCs) relatively quickly.

Concerning the MBr phaseout, while EPA generally anticipated the most viable MBr alternatives, some of these options may have become available more quickly than anticipated as a result of the improved performance of new formulations of existing chemical fumigants (Wolverton 2014).

The Title IV SO_2 Trading Program may have stimulated technological innovation that allowed for more fuel-blending options, heat rate improvements, repowering of boilers, and greater scrubber efficiency than anticipated, lowering the cost of compliance relative to ex ante expectations (Bohi and Burtraw 1997; Swift 2001; Popp 2003).

With regard to RFS2, EPA projected cellulosic ethanol production would increase from less than 10 million gallons in 2011 to 4.25 billion gallons in 2016 and 16 billion gallons by 2022. Cellulosic ethanol production fell well short of these projected volumes (Lade et al. 2018a). As a result, RFS2 forced the use of significant additional volumes of higher-cost diesel biofuel and imported sugarcane ethanol to meet the mandated advanced renewable volume requirements (Lade et al. 2018b).

In the case of the locomotive rule, Kopits (2014) report that EPA correctly predicted the potential to substitute nonroad engines for locomotive engines in switch locomotives, but did not foresee that the use of batteries or several smaller nonroad engines in place of a single larger one was the preferred approach for the remaining companies in the switch locomotive market.

For the arsenic rule, Morgan and Simon (2014) find that there was significant use of iron-based adsorptive media to comply with the requirements, but because the technology was in a pilot research phase at the time of the rulemaking, this compliance option was not considered by EPA in its ex ante analysis.

C.5. Implementation/Transition Dynamics

While EPA accounted for many preexisting R&D efforts to reduce paint shop HAPs in its ex ante analysis, the surface coating rule may have accelerated technological change already underway in the industry. In particular, a 1999 data request may have prompted firms to begin introducing reformulated coatings earlier than they would have otherwise, though given uncertainty regarding the stringency of the standard, these anticipatory actions were limited to reformulation of new colors.

For the MBr phaseout, Wolverton (2014) find evidence that unanticipated complications after switching away from MBr, such as new diseases, may have slowed the transition to some alternatives in California.

In the case of RFS2, Lade et al. (2018b) argue that lack of consideration of transition issues exacerbated implementation challenges, such as those associated with the "blend wall" and the failure of cellulosic ethanol to reach projected production levels. These issues forced EPA to revise the mandated cap levels in 2013–17 for several categories of renewable fuels—a process that has proved disruptive to the RIN market.

Concerning the phasedown of lead in gasoline, EPA's ex ante analysis did not consider how the design of the program would result in additional entrants into the trading program and added enforcement complications and costs (see, e.g., Newell and Rogers [2007] for a discussion).

C.6. Flexibility Provisions

With regard to MACT II, Morgan et al. (2014) find that EPA overestimated capital costs ex ante. The primary driver of the overestimate was that EPA did not evaluate the use of the PM compliance bubble strategy, which was utilized by about 25 percent of the regulated mills. Use of this strategy obviated the need to update air controls at some mills.

In the Title IV SO_2 Trading Program, firms relied on less interfirm trading than anticipated (Bohi and Burtraw 1997; Swift 2001; Ellerman et al. 2000). Ex post evidence shows that intrafirm strategies such as banking and the use of substitution and compensation units played an important role in keeping compliance costs low. These provisions allowed utilities the flexibility to reduce emissions using cheaper compliance strategies, to overcomply (SO_2 emissions were about 30 percent below the cap by the end of Phase I), and to bank allowances for future years when requirements would be more stringent (11.6 million allowances were banked for Phase II) (Swift 2001).

In the case of the phasedown of lead in gasoline, supplementary studies note the robust use of trading and banking to meet requirements. However, it is unclear whether EPA considered trading when estimating ex ante costs for the 1982 rulemaking (Nichols 1997). EPA's RIA for the 1985 rule did not try to take into account cost savings from trading, and it is likely that ex ante estimates of cost savings due to the banking provision were underestimated (Hahn and Hester 1989).

While they do not explicitly estimate ex post costs, Schmalensee and Stavins (2019) note that through mid-1991, there were 34 participants in the market and 80 trades in the CFC trading program, yet no studies have been conducted to estimate the cost savings associated with these provisions.

C.7. Ex Post Rule Changes

In the case of RFS2, issues associated with the "blend wall" and failure of cellulosic ethanol to reach projected production levels forced EPA to revise the mandated cap levels in 2013–2017 for several categories of renewable fuels—a process that has proved to be disruptive in the RIN markets, with sharp changes in RIN prices and collateral volatility in the markets for the marginal compliance fuels and for the share value of advanced biofuel firms (Lade et al. 2018b).

EPA's ex ante analysis of the 1992 enhanced I&M rule evaluated a stringent design-based program that limited state flexibility. However, EPA subsequently revised its rule in 1995 to provide states with additional options (and Congress added to this flexibility via legislation) (Ramsden 1997). Harrington et al. (2000a) evaluate Arizona's program as implemented in the mid-1990s, a less stringent program consistent with the revised 1995 rule.

With regard to the locomotive rule, the tiers of emissions standards set by the 1998 rule were phased in such that they fully took effect in 2008. Since another rule was promulgated in 2008 (issuing Tier 3 and 4 standards) for locomotives remanufactured or newly built in 2010 and on, the 1998 rule ended up only applying to locomotives built or remanufactured between 2000 and 2009. While the analysis period was 2000–2009 in the review of the 1998 rule by Kopits (2014), the retrospective assessment could still have been influenced by the later rule, given the 2004 publication of EPA's Advance Notice of Proposed Rulemaking for Tiers 3 and 4. For instance, the significantly higher number of new locomotives over the 2000–2009 time period compared with ex ante expectations could have been due to demand-side factors (e.g., railroads gained market share compared with trucks in the face of increasing fuel prices), as well as to regulated entities moving forward purchases to avoid the more stringent standards coming into effect a few years later or opting for new locomotives rather than facing the high compliance costs of remanufacturing older ones. Significant data limitations did not allow Kopits to disentangle the relative influence of these two factors.

Concerning the CFC phaseout, Hammitt (2000) find that realized costs were likely influenced by the 1990 and 1992 Montreal Protocol amendments (announced after EPA's ex ante analysis for the original 1988 rule was completed). These amendments accelerated the CFC phaseout. Supplementary studies of the CFC program also consider some of the implications of the post-1988 program changes. For example, Cook (1996) discusses how the way EPA set up the program helped lower administrative costs and made it flexible enough to adapt quickly to Montreal Protocol amendments. (Rulemakings to implement the amendments only took one year each to develop.)

C.8. Misestimation for Other/Unspecified Reason

In the case of surface coating, EPA expected that paint shops would predominantly rely on expensive end-of-pipe control of spray booth exhaust for compliance, but the reason for this expectation is not clear. The ex ante cost estimates identified reformulation of coatings as the cheapest way to comply, but EPA assumed that plants would not use this option until after end-of-pipe controls were applied. Wolverton et al. (2019) report that facilities largely relied on the use of reformulated low-VOC coatings to comply with MACT limits—an approach that significantly reduced the cost of compliance.

For exemptions to the MBr phaseout, Wolverton (2014) finds some evidence that yield losses may have been substantially less than EPA originally anticipated. EPA reportedly used conservative assumptions of yield loss in its ex ante analysis because the literature available at the time contained a wide range of estimates and gave little detail on what types of impacts were included. Subsequent evidence narrowed this range.

Regarding the NO_x Budget Program, EPA projected ex ante that the SNCR abatement technology would account for two-thirds of the installed control capacity, and that SCR would account for around 30 percent.[40] Ex post, Fowlie (2010) and Fowlie and Muller (2019) report that SCR was the dominant control technology adopted by EGUs, and that SNCR accounted for less than 10 percent of installed control capacity.[41] However, the literature does not offer an ex post explanation for the widespread adoption of SCR control in place of SNCR. Fowlie (2010) and Fowlie and Muller (2013, 2019) attribute variation in control strategies across states to electricity rate regulations (which affect the ability to recover capital costs). Specifically, they find that utilities in rate-regulated states shifted toward more capital-intensive controls (i.e., SCR) than projected, while those in competitive markets shifted away from them (i.e., toward SNCR).

Concerning enhanced I&M, EPA projected ex ante that the fuel economy of failed vehicles would improve by 12.6 percent with required repair; Harrington et al. (2000a) estimate ex post

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[40] EPA (1998), 6-2.
[41] EPA (2007) also reports that SCR dominated ex post for coal-fired generators of electricity.

an improvement in fuel economy after required repair of only 3.5 percent. In addition, Harrington et al. report that repaired vehicles had a high rate of repeat failure even after repair; EPA implicitly assumed that repaired vehicles would perform as well as vehicles that were never tagged for repair. A more recent study by Merel et al. (2014) provides a similar estimate of the incidence of repeat failure for repaired vehicles.

For the locomotive rule, Kopits (2014) finds that the number of suppliers and, especially, the number of different Tier 0 remanufacturing systems developed were higher than EPA anticipated. EPA estimated that a total of 11 remanufacturing systems from three suppliers would be developed and certified for Tier 0 locomotive models. In 2005, certification data showed that 37 remanufacturing systems from four suppliers had been certified. The industry expert interviewed concluded that this difference alone suggested that total costs of certification of Tier 0 remanufacturing systems were probably about double the EPA estimate, even if the cost per remanufactured system certified were somewhat lower than anticipated. However, the industry expert did not reveal the underlying driver of this difference.

In a subset of 24 mills subject to the cluster rule (out of 155), Morgan et al. (2014) find evidence that EPA accurately predicted capital costs for about 8 mills, while it overestimated capital costs ex ante for the remainder. Why EPA overestimated capital costs for these mills is not discussed.

With regard to the arsenic rule, Morgan and Simon (2014) report that capital costs were lower (higher) than expected for demonstration projects at systems with lower (higher) design flow/average flow for two control technologies, greensand filtration and ion exchange. For both technologies, the operating and maintenance costs for the demonstration projects were higher than EPA's ex ante predictions. Morgan and Simon (2014) cannot speak to the underlying driver of the difference.

In the case of the CFC phaseout, while Hamitt (2000) notes that ex ante and ex post cost estimates differed, he does not investigate the underlying drivers of these differences.

For the lead in gasoline phasedown, Kerr and Newell (2003) report that EPA overestimated planning costs associated with adopting isomerization, so it projected that this technology would be adopted more slowly than it actually was. The reasons costs were lower than anticipated are not discussed.