A Review of Retrospective Cost Analyses

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Introduction

Since 1981, the US federal government has required benefit–cost analyses for its proposed rulemakings. The systematic review of benefit–cost analyses by the Office of Management and Budget (OMB) and their release for public comment have elevated their relative importance in the decision-making process. While informative of the anticipated effects of a regulation, benefit–cost analyses are conducted ex ante: "The point when we know the least, precisely because the regulations are untested" (Greenstone 2013; available at https://www.brookings.edu/testimonies/eliminating-unnecessary-and-costly-red-tape-through-smarter-regulations/). Thus, they cannot inform the question of whether a regulation delivers the promised benefits at the expected costs. Retrospective analyses—ex post examinations of the effects of promulgated rules—are designed to provide such information but are conducted relatively infrequently (Aldy 2014).[1] Without such information, it is difficult to identify regulations in need of strengthening, modification, or even elimination based on actual costs and benefits.

In this article, we review 28 ex post studies of the costs of 13 US Environmental Protection Agency (EPA) regulations. We organize the review around the following four cost components: compliance strategies, permit or other prices, unit compliance cost, and aggregate cost. For each component, we assess the quality of the underlying data and methods of analysis. We

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The views expressed in this paper are those of the authors and do not necessarily reflect the views or policies of the US Environmental Protection Agency or Resources for the Future. The authors thank Dick Morgenstern, Nathalie Simon, Terry Dinan, Dominic Mancini, Al McGartland, and participants of a workshop on retrospective review of regulation for their thoughtful comments and suggestions. Art Fraas also acknowledges partial support from the Smith Richardson Foundation.

[1]Every administration since President Carter has initiated efforts urging agencies to reassess existing regulations (Aldy 2014). Agencies are also directed to conduct periodic reviews of regulations under some statutes. In addition, the Foundations for Evidence-Based Policymaking Act of 2018 (US House of Representatives 2019) requires that agencies submit to the OMB a plan for retrospective review of agency programs, including what data they intend to collect, use, or acquire.

Online enhancements: appendixes.

Electronically published March 8, 2023

Review of Environmental Economics and Policy, volume 17, number 1, winter 2023.
 https://doi.org/10.1086/723595

then investigate common sources of differences between ex ante and ex post estimates for each cost component identified for the regulations in our sample. In a few cases, the evidence also suggests the direction of difference—that is, whether per-unit costs are over- or underestimated. Finally, we discuss lessons learned for improving future ex ante or ex post analyses of EPA rules.

Many prior retrospective reviews of compliance costs focus on whether costs are under- or overestimated and provide few insights into what drives those differences. In addition, many of these reviews are not peer-reviewed and encompass a relatively small and overlapping sample of regulations and studies. For example, OMB's (2005) retrospective review included 18 EPA regulations but was based on only three studies, one of which was not peer-reviewed. Ex post costs of regulation in these reviews are also often only roughly approximated. For example, Putnam, Hayes, & Bartlett Inc. (1980) focuses exclusively on capital expenditures rather than including all compliance costs, Anderson and Sherwood (2002) use an indirect proxy for ex post costs, OMB (2005) includes relatively small regulations (e.g., only 5 of the 18 EPA regulations are economically significant), and Morgenstern (1997) includes several studies that rely on ex ante instead of ex post cost information.

In contrast, EPA (2014) conducted original ex post assessments of costs for five regulations promulgated between 1995 and 2005 using a systematic framework to assess key drivers of identified differences between ex ante and ex post estimates. Wolverton, Ferris, and Simon (2019) follow the same protocol. Resources for the Future also commissioned new ex post evaluations, including two that examined the costs of EPA regulations promulgated between 1992 and 2010 (Morgenstern 2018). Aldy et al. (2022) review quasi-experimental or structural evidence of the benefits, costs, or economic impacts relative to a counterfactual for rules promulgated under the Clean Air Act. Because few studies of ex post compliance costs meet their criteria for inclusion, Aldy et al. (2022) discuss evidence of costs for only four rules. We have included the relevant case studies from these recent efforts in our review.

While the literature has identified a variety of factors that could potentially introduce differences between ex ante and ex post cost estimates (table 1), there has been no systematic attempt to gauge their relevance in practice. This article also attempts to fill this gap.

The remainder of the paper is organized as follows. "Methodology" summarizes the studies in our sample. "Overview of Our Sample" describes the approach we take to assess which aspects of compliance costs the studies can inform as well as common sources of differences. "Findings" presents our findings. "Conclusions and Lessons Learned" concludes with lessons learned to improve ex ante and ex post cost analyses.

Methodology

The studies included in our review address specific components of the costs of regulation, and we organize our review around the following main four: compliance strategies adopted by regulated entities, permit or other prices to proxy for marginal cost of compliance, unit compliance cost, and aggregate cost. Identifying compliance strategies used by regulated entities is a key component of cost estimation. If EPA does not accurately predict which abatement technologies firms will use, then aggregate costs may also be inaccurate, particularly when there are large differences in unit costs across compliance options. We use the term "unit compliance

Table 1 Reasons proposed in the literature for cost misestimation ex ante

Possible reason	Example(s)	Direction of bias ex ante	Sources
Regulators' approach to cost estimation	Conservative (or optimistic) cost assumptions, less effort when benefits greatly exceed costs	Either	Harrington, Morgenstern, and Nelson 2000; Hahn 2004; Simpson 2014
Long promulgation process	Changes in exogenous factors, cheaper compliance options than analyzed	Either	Harrington, Morgenstern, and Nelson 2000; Simpson 2014; Morgenstern 2018
Inadequate consideration of technological innovation	Technologies in development that lower costs relative to those already known/in use, learning by doing	Mainly overestimated	Harrington, Morgenstern, and Nelson 2000; Simpson 2014; Morgenstern 2018
Unaccounted-for costs	Behavioral change, opportunity costs, and short-run adjustment costs; uncertainty in sources of pollution or effectiveness of abatement strategies	Mainly underestimated	Harrington, Morgenstern, and Nelson 2000; Hahn 2004; Morgenstern 2018
Misspecified baseline	Failure to account for state regulation or exogenous factors that affect future production, prices, and demand; uncertainty on which control measures are in place	Either	Harrington, Morgenstern, and Nelson 2000; Simpson 2014; Morgenstern 2018
Compliance errors	Less effective rule than expected	Either	Harrington, Morgenstern, and Nelson 2000; Simpson 2014; Morgenstern 2018

cost" broadly to refer to average cost per unit of production or consumption, average cost per unit of emissions abated, or average cost per plant or model type.

For each of the four cost components, we assess the following 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 extent to which the analysis controls for confounding factors. We assign each element a score from one to three, increasing in degree of formality and rigor, so that a study's maximum potential total score for each of the four cost components is 15 (see appendix A [appendixes A–C are available online] for the scoring methodology and results for each study). While we adopt a systematic evaluation approach to enhance transparency, we recognize that it is inherently subjective given wide variation in data, methods, and scope across studies. In addition, because small differences in scores may not be meaningful, we collapse the scores into five broader categories, indicating the degree to which we can infer how ex ante and ex post costs differed.

We then undertake an in-depth review of the retrospective studies to investigate the main factors that drive differences between ex ante and ex post estimates for the cost components identified for each rule. We revisit the ex ante EPA regulatory impact analyses (RIAs) as needed to understand underlying assumptions and other factors. 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 the misestimation of one or more components of compliance cost. Within each broad category, we note how the identified reasons for differences between ex ante and ex post cost estimates compare with the hypotheses from the literature (summarized in table 1).

We attempt to judge in general terms the degree to which the reported outcomes can inform identified differences between ex ante and ex post cost estimates, giving greater weight to findings of higher-scoring studies. In a few cases, we are able to suggest whether per-unit or aggregate costs were likely over- or underestimated ex ante. This last exercise is the most speculative given the difficulty in making apples-to-apples comparisons between ex ante and ex post estimates, the data limitations, and the narrow focus of many ex post studies in our sample.

Overview of Our Sample

We identify 28 peer-reviewed, published studies (from 52 potentially relevant papers) that focus on ex post evaluation of compliance choices or costs for 13 final EPA regulations. Papers are omitted from the sample because of the qualitative nature of a study, publication prior to 2000, lack of peer review, or limited to no discussion of the ex post experience. In a few cases, however, we rely on excluded studies for supplementary insights.

The 13 regulations included in our sample were promulgated from 1979 to 2010 (table 2). Fourteen studies examine either the Title IV SO_2 Trading Program or the NO_x Budget Trading Program, for which detailed, disaggregated facility-level data for the electricity sector are available. Five studies address the effects of fuel additive regulations—boutique fuels, lead phasedown, and the Renewable Fuel Standard (RFS2)—on fuel prices. These studies use a combination of state and federal sources of data on refinery operations and privately available price data. Another two studies look at the Cluster Rule, and for each of the remaining seven rules, only a single study meets our criteria for inclusion.

While most of the regulations covered in our review are air rules, we also include the Arsenic Rule and Cluster Rule (which regulate drinking water and air and water discharges, respectively) and the critical use exemptions for methyl bromide (MBr), a pesticide. Relative to the larger universe of significant EPA regulations, those that pertain to fuels are overrepresented. A substantial number of the regulations in our sample give regulated entities additional flexibility in meeting regulatory requirements, ranging from more limited "bubble"-based strategies (e.g., Maximum Achievable Control Technology Standards [MACT II]) to extensive reliance on tradable permits (e.g., Title IV SO_2 Trading Program, phaseout of chlorofluorocarbons [CFCs]). Finally, many environmental programs established through federal regulation (including boutique fuels, enhanced vehicle emissions inspection and maintenance [I/M] programs, the Arsenic Rule, and the NO_x Budget Trading Program) are implemented by the states, which adds an element of uncertainty to ex ante cost estimation (see appendix B for a brief description of each regulation).

The studies included in our review vary considerably but can be grouped into two general methodological categories (table 3). One set of studies uses bottom-up accounting to develop expenditure estimates by component and builds a cost estimate from these components. While some of these studies qualitatively discuss exogenous factors, they typically do not control for them. Because of data limitations, these studies often rely on expert opinion,

Table 2 Regulations included in review

EPA rule	Promulgation year(s)	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 fuel regulations	1989, 1990, 1992, 1994	N	Brown et al. 2008; Chakravorty, Nauges, and Thomas 2008
Enhanced vehicle emissions I/M programs	1992	N	Harrington, McConnell, and Ando 2000; Harrington, Morgenstern, and Nelson 2000
Title IV SO_2 Trading Program	1992	Y	Carlson et al. 2000; Ellerman et al. 2000; Swift 2001; Arimura 2002; Swinton 2002, 2004; Popp 2003; Busse and Keohane 2007; Frey 2013; Cicala 2015; Chan et al. 2018
Cluster Rule	1998	N	Morgan, Pasurka, and Shadbegian 2014; Elrod and Malik 2017
Locomotive emission standards	1998	Y	Kopits 2014
NO_x Budget Trading Program	1998	Y	Linn 2008; Fowlie 2010; Popp 2010; Fowlie and Muller 2019[a]
Arsenic Rule	2001	N	Morgan and Simon 2014
MACT II	2001	Y	Morgan, Pasurka, and Shadbegian 2014
Light-duty vehicle surface coating NESHAP	2004	N	Wolverton, Ferris, and Simon 2019
MBr critical use exemptions	2004–2008	N	Wolverton 2014
RFS2	2010	Y	Lade, Lawell, and Smith 2018a, 2018b

[a]We also consult Fowlie and Muller (2013), the unpublished precursor to Fowlie and Muller (2019), because it contains a more explicit representation of the NO_x Budget Trading Program than the published paper.

subjective synthesis, or direct reporting from regulated entities. The second set of studies uses econometric approaches to identify an effect after controlling for exogenous factors. While most of the econometric studies use panel data, only five are quasi-experimental (i.e., where a nontreated group or time period acts as a counterfactual).

While the bottom-up studies lack empirical sophistication and cannot control for other important drivers or isolate effects relative to a counterfactual, they tend to have a broader focus and often aim to identify key drivers of differences between ex ante and ex post estimates of costs. In contrast, the econometric studies often evaluate narrower questions, such as the role of specific factors in compliance decisions, adoption of a specific technology, or compliance behavior. In addition, the econometric studies typically provide less explicit comparisons of ex post estimates with the original ex ante analyses.

In general, most studies use disaggregated information about control strategies supplemented by other source-level data. However, many of the studies—both bottom-up and econometric—cannot claim that the data available are representative of the regulated universe. For instance, Harrington, McConnell, and Ando (2000) use Arizona inspection and repair costs to

Table 3 Types of methods and data used, by study

EPA rule (study)	Regulated source-level data			Market data		Other input cost data
	Control strategy	Control cost	Other	Permit prices	Product prices	
Lead phasedown in gasoline (Kerr and Newell 2003)	✓		✓			✓
CFC phaseout (Hammitt 2000)					**✓**	
Boutique fuel regulations (Brown et al. 2008; Chakravorty, Nauges, and Thomas 2008)					✓	
Enhanced vehicle emissions I/M programs (Harrington, McConnell, and Ando 2000)	***P***	***P***	***P***			
Title IV SO_2 Trading Program, phase I (Arimura 2002)	✓		✓		✓	
Title IV SO_2 Trading Program, phase I (Busse and Keohane 2007)[a]	✓		✓		✓	
Title IV SO_2 Trading Program, phase I (Carlson et al. 2000)	*P*		*P*		✓	✓
Title IV SO_2 Trading Program, phase II (Chan et al. 2018)[a]	✓		✓	✓	✓	
Title IV SO_2 Trading Program, phase I (Cicala 2015)[a]	*P*		*P*			
Title IV SO_2 Trading Program, phase I (Ellerman et al. 2000)	**✓**	***P***	**✓**	**✓**	**✓**	
Title IV SO_2 Trading Program, phases I and II (Frey 2013)	*P*	*P*	✓			
Title IV SO_2 Trading Program, phase I (Popp 2003)	*P*	*P*	✓	✓	✓	
Title IV SO_2 Trading Program, phase I (Swift 2001)	**✓**			**✓**	**✓**	**✓**
Title IV SO_2 Trading Program, phase I (Swinton 2002, 2004)	*P*		*P*		✓	
Cluster Rule (Elrod and Malik 2017)[a]	✓		✓			
Cluster Rule (Morgan, Pasurka, and Shadbegian 2014)	***P***		**✓**			**✓**
Locomotive emission standards (Kopits 2014)					***P***	
NO_x Budget Trading Program (Fowlie 2010; Fowlie and Muller 2019)	✓		✓			
NO_x Budget Trading Program (Linn 2008)[a]	*P*		✓			
NO_x Budget Trading Program (Popp 2010)	✓		✓			
Arsenic Rule (Morgan and Simon 2014)	***P***	***P***	***P***			
MACT II (Morgan, Pasurka, and Shadbegian 2014)			**✓**			**✓**
Light-duty vehicle surface coating NESHAP (Wolverton, Ferris, and Simon 2019)	***P***	***P***	**✓**			**✓**
MBr critical use exemptions (Wolverton 2014)	***P***	***P***			***P***	**✓**
RFS2 (Lade, Lawell, and Smith 2018a, 2018b)				✓	✓	

Note: Studies with a bottom-up study approach are shown in bold; studies not shown in bold are econometric. *P* indicates availability of only partial data.

[a]Uses quasi-experimental study design.

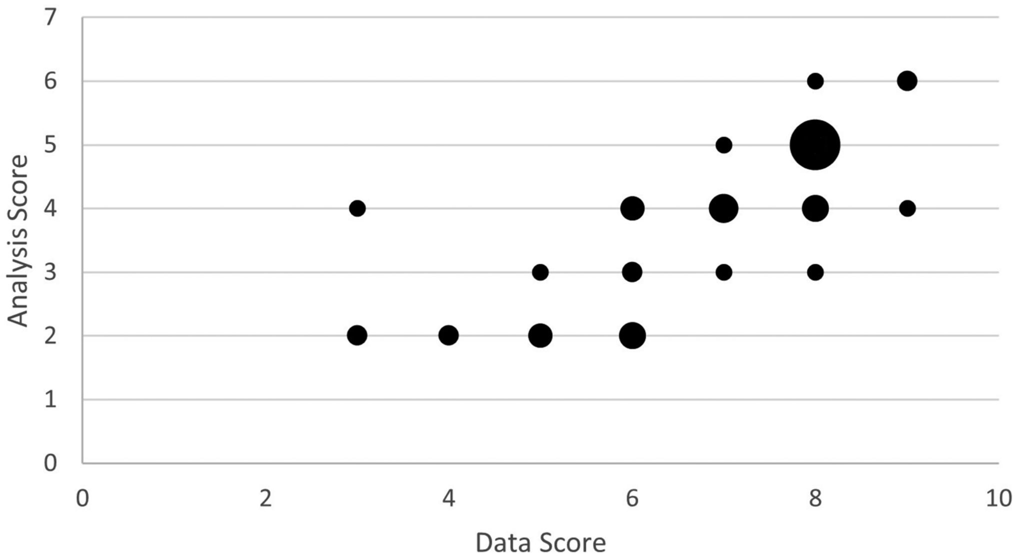

Figure 1 Type of data and analysis performed for each study. Data score is the sum of the scores for data type, coverage, and unit of observation. Analysis score is the sum of the scores for method of obtaining the result and extent of control for other factors. Each data point in the plot is sized proportionately to the number of studies with the same score. An increase in formality or rigor corresponds to a higher numerical score.

examine enhanced vehicle emissions I/M programs, while Wolverton (2014) relies on data from typical California strawberry farms to examine the costs of MBr critical use exemptions. Far fewer studies have disaggregated source-level information on control costs, and when available, it is always partial. While information is typically available on only the average cost of compliance, understanding how it varies with key characteristics (e.g., plant or equipment age, size, type of production process, abatement controls already in place) sometimes also allows for inferences regarding the marginal cost of compliance. We find that more formal, complete, and disaggregated data are positively correlated with more rigorous analysis in our sample (figure 1).

Several studies in our sample use product or allowance prices as an indicator of compliance costs. The extent to which market prices proxy for marginal compliance costs ex post likely varies, in part because of the presence of market power. In an allowance market, banking, borrowing, and restrictions on trading may also cause the marginal cost of compliance and allowance price to differ (Bialek and Shrader 2019). As a result, some price effects may reflect the distributional effects of a policy rather than its costs, though it is difficult to pull the two apart.

Findings

As previously mentioned, published studies that examine ex post evidence of the abatement strategies used to comply with a regulation and the cost of implementation are relatively small in number and narrow in scope. Many ex post cost studies are opportunistic in nature. Retrospective cost studies of electric utility regulations dominate because of the availability of price information and detailed boiler-level data. Few ex post cost studies include a systematic comparison with ex ante analysis. With these limitations in mind, we now discuss which elements of compliance costs are informed by available ex post studies. Later in this section, we identify differences between ex ante and ex post cost estimates, their possible sources, and the extent to which we can identify the direction of ex post costs relative to EPA ex ante estimates.

Elements of Compliance Costs Informed by the Studies

Table 4 summarizes our assessment of which components of compliance costs a study informs based on its total score across the five elements described in "Methodology." Studies that examine only a specific aspect of per-unit compliance costs receive a lower score. We have listed scores ranging from 5–7 (lower score) to 14–15 (highest score) to reflect the degree to which findings from the studies in our sample allow us to draw conclusions from ex ante and ex post comparisons of various cost components.

Many of the studies in our sample identify changes in the actual compliance strategies adopted (thus, receiving a score of 11–13 or 14–15). Fewer studies examine the effect of regulation on market prices. Some studies examine only a specific element of unit compliance costs, and very few speak to overall unit compliance costs. Only four studies examine the total cost of a regulation, but the extent to which they inform ex ante and ex post differences varies (ranging from a score of 5–7 to 11–13).

Overall, we find 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 sample. In many instances, EPA accurately identified the available compliance strategies but erred in its prediction of their relative mix. In a few cases, EPA failed to anticipate the strategies that firms used to comply. For the electricity sector, rate-regulated utilities shifted toward more capital-intensive controls than projected, while those in competitive markets shifted away from them. Entities operating in private markets tended to shift to less capital-intensive controls than anticipated in response to EPA regulations.

A few studies find substantial agreement between ex ante and ex post estimates for specific inputs or cost components. For MBr critical use exemptions, ex ante strawberry prices are consistent with those received by California growers (Wolverton 2014). For the light-duty vehicle surface coating National Emission Standards for Hazardous Air Pollutants (NESHAP), ex ante per-gallon cost estimates for reformulated coatings are within the ex post range (Wolverton, Ferris, and Simon 2019). Realized aggregate costs in the early years of the Title IV SO_2 Trading Program are also not substantially different from EPA ex ante estimates (though many differences between ex ante and ex post compliance strategies and unit costs have been identified). In the case of CFCs, EPA ex ante estimates (under the higher cost scenario) were similar to revealed marginal control costs, as proxied by permit prices for 1990 and 1991 reductions (Hammitt 2000).

Sources of Differences between Ex Ante and Ex Post Cost Estimates

We group sources of differences into the following eight categories: (1) inadequate or incorrect baseline specification, (2) inadequate consideration of behavioral responses due to sole reliance on engineering models, (3) failure to account for the effect of industry structure on compliance, (4) inadequate consideration of technological innovation, (5) inadequate consideration

Table 4 Elements of realized compliance costs informed by the studies

EPA rule (study)	Scope of study	Comparison with RIAs?	Extent to which study provides insights into realized			
			Compliance strategies	Permit/other prices	Unit compliance cost	Aggregate cost
Lead phasedown in gasoline (Kerr and Newell 2003)	Narrow		11–13			
CFC phaseout (Hammitt 2000)	Broad	Explicit		8–10		
Boutique fuels (Brown et al. 2008)	Narrow			11–13		
Boutique fuels (Chakravorty, Nauges, and Thomas 2008)	Narrow			8–10		
Enhanced vehicle emissions I/M programs (Harrington, McConnell, and Ando 2000)	Broad	Explicit			8–10	
Title IV SO_2 Trading Program, phase I (Arimura 2002)	Narrow	Partial	11–13	11–13		
Title IV SO_2 Trading Program, phase I (Busse and Keohane 2007)	Narrow			11–13		
Title IV SO_2 Trading Program, phase I (Carlson et al. 2000)	Broad	Explicit				11–13
Title IV SO_2 Trading Program, phase II (Chan et al. 2018)	Broad	Partial	14–15		11–13	
Title IV SO_2 Trading Program, phase I (Cicala 2015)	Narrow		11–13			
Title IV SO_2 Trading Program, phase I (Ellerman et al. 2000)	Broad	Explicit	11–13	8–10	8–10	8–10
Title IV SO_2 Trading Program, phases I and II (Frey 2013)	Narrow		11–13		11–13	
Title IV SO_2 Trading Program, phase I (Popp 2003)	Narrow				11–13	
Title IV SO_2 Trading Program, phase I (Swift 2001)	Broad	Explicit	11–13	11–13	8–10	
Title IV SO_2 Trading Program, phase I (Swinton 2002, 2004)	Broad	Partial	14–15		11–13	
Cluster Rule (Elrod and Malik 2017)	Narrow	Partial	11–13			

Table 4 (*Continued*)

EPA rule (study)	Scope of study	Comparison with RIAs?	Extent to which study provides insights into realized			
			Compliance strategies	Permit/other prices	Unit compliance cost	Aggregate cost
Cluster Rule (Morgan, Pasurka, and Shadbegian 2014)	Broad	Explicit	11–13		5–7	5–7
Locomotive emission standards (Kopits 2014)	Broad	Explicit	5–7		5–7	
NO_x Budget Trading Program (Fowlie 2010; Fowlie and Muller 2019)	Narrow	Partial	14–15			
NO_x Budget Trading Program (Linn 2008)	Narrow	Partial	11–13			
NO_x Budget Trading Program (Popp 2010)	Narrow		11–13			
Arsenic Rule (Morgan and Simon 2014)	Broad	Explicit	5–7		5–7	
MACT II (Morgan, Pasurka, and Shadbegian 2014)	Broad	Explicit	11–13		5–7	
Light-duty vehicle surface coating NESHAP (Wolverton, Ferris, and Simon 2019)	Broad	Explicit	11–13		11–13	5–7
MBr critical use exemptions (Wolverton 2014)	Broad	Explicit	8–10	11–13	5–7	
RFS2 (Lade, Lawell, and Smith 2018a, 2018b)	Narrow	Partial	14–15	11–13		

Note: A blank cell indicates that a study does not inform or offer insights into a particular element of realized compliance costs.

of regulatory flexibilities, (6) failure to account for transition or implementation costs, (7) changes to the regulation after the analysis was conducted, and (8) unspecified reasons (table 5). While many of these are consistent with the hypotheses raised in the literature (see table 1), categories 2, 3, and 5 are new to this study and highlight the importance of considering behavioral response when estimating compliance costs. In addition, for the compliance approach component, we distinguish between cases where EPA accurately identified the available compliance strategies ex ante but erred in its predictions of their relative mix or usage and cases where EPA did not anticipate a compliance option that was ultimately used.

For all regulations except the lead phasedown, 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 are inaccurate ex ante accounting of baseline conditions (for seven rules) followed by inadequate consideration of technological innovation (for six rules). Failure to account for behavioral response due to reliance on an engineering-based approach, not accounting for industry structure, or failure to consider the use of averaging, trading, and banking opportunities also contributes to differences between ex post and ex ante cost estimates (for eight rules, taken together). In most cases, multiple factors contribute to differences. To provide a deeper appreciation for the sources of differences between ex ante and ex post estimates, we discuss each category and highlight a few specific examples (table 5 includes a complete listing, and appendix C discusses how each source of difference applies for each rule in our sample).

Incorrect baseline specification

A major challenge when developing ex ante cost estimates is constructing a defensible baseline. How the world will evolve absent the standard is not observable ex ante and is therefore inherently uncertain. We find evidence of incorrect baseline specification due to the role of exogenous factors for seven regulations. In many cases, the effects of these exogenous factors could have been evaluated ex ante.

Two important exogenous factors affecting the baseline for many environmental regulations are energy markets and preexisting regulations or initiatives (other exogenous factors identified are described in appendix C). For example, the projections underlying EPA ex ante cost estimates for RFS2 implied that wholesale gasoline prices would be almost two times higher than ethanol prices on a per-gallon basis; thus, the ethanol mandate was expected to yield substantial cost savings. In fact, wholesale gasoline and ethanol prices have tracked relatively closely, with only a small gap to reflect differences in energy density (Lade, Lawell, and Smith 2018a). In the case of MBr critical use exemptions, ex ante and ex post estimates differed in part because existing state-level restrictions on how some fumigants could be combined hindered the ability of farmers to switch to alternatives (Wolverton 2014).

Missed behavioral responses due to sole reliance on engineering models

EPA typically uses the estimated cost of installation, operation, and maintenance for specific control technologies as the compliance cost, holding all else constant. This “engineering” approach does not account for the behavioral responses of a regulated entity to the new requirement, which can affect the estimated cost of compliance. Table 5 identifies four cases where behavioral responses were not considered ex ante; we highlight two examples below.

Table 5 Identified sources of differences between ex post and ex ante cost estimates

Sources of differences between ex ante and ex post estimates	Compliance approach: Different mix/usage than anticipated	Compliance approach: Different controls than anticipated	Price	Unit cost	Total cost
Inadequate/incorrect baseline	MBr critical use exemptions, Title IV SO_2 Trading Program, light-duty vehicle surface coating NESHAP		RFS2	Enhanced vehicle emissions I/M programs, locomotive emission standards, Title IV SO_2 Trading Program, light-duty vehicle surface coating NESHAP	Cluster Rule, light-duty vehicle surface coating NESHAP
Missed behavioral responses due to sole reliance on engineering models	Arsenic Rule, locomotive emission standards	Arsenic Rule, Cluster Rule, NO_x Budget Trading Program			
Lack of accounting for effect of industry structure[a]	Title IV SO_2 Trading Program, light-duty vehicle surface coating NESHAP, NO_x Budget Trading Program		Boutique fuel regulations	Light-duty vehicle surface coating NESHAP	Light-duty vehicle surface coating NESHAP
Inadequate consideration of technological innovation	MBr critical use exemptions, RFS2, light-duty vehicle surface coating NESHAP	Arsenic Rule, locomotive emission standards, Title IV SO_2 Trading Program	RFS2	MBr critical use exemptions, Title IV SO_2 Trading Program	
Inadequate consideration of flexibility provisions	MACT II		Title IV SO_2 Trading Program	MACT II	Title IV SO_2 Trading Program
Lack of analysis of transition/ implementation[b]	MBr critical use exemptions, light-duty vehicle surface coating NESHAP		RFS2		
Ex post rule changes	Locomotive emission standards		CFC phaseout, RFS2	Enhanced vehicle emissions I/M programs	
Unspecified reason	NO_x Budget Trading Program, light-duty vehicle surface coating NESHAP	Lead phasedown in gasoline	CFC phaseout	Arsenic Rule, Cluster Rule, enhanced vehicle emissions I/M programs, locomotive emission standards, MBr critical use exemptions	

Note: Identified sources of difference are based on primary studies in our sample.
[a]Supplementary studies suggest that this source of differences is also relevant for the CFC regulation.
[b]Supplementary studies suggest that this source of differences is also relevant for the lead phasedown in gasoline regulations.

In the case of the Cluster Rule, the EPA ex ante analysis focused on control technologies used to comply and therefore missed how behavioral change could also reduce emissions. Some mills substantially altered their product mixes away from bleached paper products in response to the regulatory requirements (Elrod and Malik 2017). This shift in production reduced the need to install abatement technologies to comply with the rule.

The rule establishing locomotive emission standards is another example where behavioral response 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: overhaul of line-haul locomotives every eight years and rebuilding engines at least once over the lifetime of the engine. However, only 6 percent of line-haul engines were rebuilt, suggesting that firms may have delayed costly rebuilds and instead absorbed additional operational costs (Kopits 2014).

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 level. However, where regulated entities exercise market power, face existing regulations that restrict behavior, or share the same ownership structure, market structure can influence the response to regulatory requirements.

For four regulations we studied, an inadequate accounting for industry structure likely contributed to differences in compliance strategies or costs relative to ex ante estimates. In the case of the light-duty vehicle surface coating NESHAP, corporate-wide compliance strategies led to greater uniformity across plants within a firm than anticipated, which also reduced compliance costs as a result of substantial economies of scale (Wolverton, Ferris, and Simon 2019). In the case of fuel content requirements, geographic differentiation may have increased the ability of refiners to exercise market power in isolated markets with a limited number of competitors. This resulted in larger increases in wholesale gasoline prices in some regulated markets relative to unregulated markets (Brown et al. 2008; Chakravorty, Nauges, and Thomas 2008). In the case of the NO_x Budget Trading Program, rate-regulated utilities were more likely to shift toward capital-intensive controls compared to those in competitive electricity markets (Fowlie 2010). This behavior is consistent with the so-called Averch-Johnson effect, where rate-regulated utilities can ensure recovery of capital costs by including them in the rate base (Fowlie 2010). EPA did not adequately account for how rate-based state regulation of electricity would affect capital investment decisions.

Inadequate consideration of technological innovation

EPA frequently bases its ex ante cost estimates on commercially available control technologies even when more cost-effective alternatives are under development or the regulation is expected to spur innovation. However, incorporating nascent technologies into ex ante assessments risks underestimating compliance costs. EPA's ex ante analysis did not adequately consider the role of technological innovation in six regulations in our sample.[2]

[2]Note that while the instances identified in our sample pertain to abatement sector innovations, technological advances completely exogenous to the regulation can also affect compliance strategies and costs.

For example, in the case of the Arsenic Rule, while iron-based adsorptive media was frequently used to comply with requirements, it was not analyzed ex ante, because it was in the pilot phase of development at the time (Morgan, Pasurka, and Shadbegian 2014). Likewise, EPA underestimated the extent of technological innovation already underway and the pace at which it could affect compliance choices for the light-duty vehicle surface coating NESHAP. Several manufacturers (and paint suppliers) were cooperatively exploring low-HAP coating formulations prior to promulgation, partially in response to increased competition and the formidable technical challenges anticipated to develop low-emission technologies (Wolverton, Ferris, and Simon 2019). For RFS2, however, EPA substantially overestimated the extent to which cellulosic ethanol production would come online (Gies 2014; Lade, Lawell, and Smith 2018a). In the absence of expected ethanol production, compliance has required significant additional volumes of diesel biofuel and imported sugarcane ethanol (Lade, Lawell, and Smith 2018b).

Inadequate consideration of flexibility provisions

For many EPA regulations, averaging, banking, or trading is available to reduce compliance costs. How and when firms use these flexibilities can have important implications for the 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.

In the case of MACT II, pulp mills had the option of reducing particulate matter at any individual unit to meet a mill-specific bubble instead of a unit-specific limit. About 25 percent of regulated mills used this compliance strategy, obviating the need to update air controls (Morgan, Pasurka, and Shadbegian 2014). Because EPA did not evaluate the implications of the bubble strategy, it overestimated capital costs ex ante for these plants. For the Title IV SO_2 Trading Program, marginal abatement costs were not equalized across plants (Carlson et al. 2000; Swinton 2004), because firms relied less on interfirm trading than anticipated (Ellerman et al. 2000). However, the larger-than-anticipated role of banking and use of substitution and compensation units operated to reduce unit compliance costs and allowance prices (Swift 2001).

Lack of Analysis of Transition/Implementation

We find evidence of transition or implementation issues that EPA did not consider ex ante for three regulations in our sample. In the case of MBr critical use exemptions, new crop diseases after switching away from MBr may have slowed the transition to alternatives in California (Wolverton 2014). For RFS2, explicit consideration of implementation challenges related to the "blend wall"—the amount of ethanol that can be combined or blended into conventional gasoline, given existing restrictions on maximum ethanol content—would have greatly increased ex ante cost estimates (Lade, Lawell, and Smith 2018a). For the light-duty vehicle surface coating NESHAP, EPA may have overestimated hard-to-quantify indirect costs of reformulating coatings, such as loss of market share over time due to lower-quality coatings, thus anticipating that plants would use capital-intensive thermal oxidizers instead of reformulation to comply.

Ex post rule changes

If a future revision to a rule is announced shortly after promulgation, it may affect regulated entities' decisions of how to comply with and alter realized compliance costs. When this occurs, it is difficult to isolate the effects of the regulation as envisioned ex ante from other regulatory changes. We identify four cases where EPA altered requirements soon after a rule was finalized.

For example, failure rates in Arizona's enhanced vehicle emissions I/M program were much lower than anticipated, partly because EPA allowed changes after promulgating the initial rule (Harrington, McConnell, and Ando 2000). For the CFC phaseout, EPA's underestimation of ex ante costs is likely explained in part by subsequent passage of the 1990 and 1992 Montreal Protocol amendments, which accelerated hydrofluorocarbon reductions relative to the original rule (Hammitt 2000). Because of blend wall issues and failure to produce cellulosic ethanol at a commercial scale, EPA revised the mandated cap levels for several categories of renewable fuels in every year since 2011. The uncertainty associated with these changes to the mandated levels proved disruptive to the ethanol credit market (Lade, Lawell, and Smith 2018b). The locomotive emissions standards fully took effect in 2008. However, another rule was promulgated in 2008 (issuing tier 3 and 4 standards) for locomotives remanufactured or newly built in 2010. It is possible that the significantly higher-than-expected number of new locomotives over the 2000–2009 period was in part due to regulated entities moving forward purchases to avoid these more stringent standards, though Kopits (2014) is not able to determine whether this was the case.

Unknown reasons

While many studies in our sample find that ex ante and ex post costs differ, they do not always explore the underlying reasons for these differences or are only able to identify relevant factors for a subset of results. Even when identifying drivers of differences between ex ante and ex post costs is the express purpose of a study, a lack of data often limits the examination of all potential sources of differences.

For instance, to meet NO_x Budget Trading Program requirements, EPA projected that selective catalytic reduction would account for around 30 percent of installed control capacity, but it was actually the dominant control technology adopted (EPA 2008; Fowlie 2010; Fowlie and Muller 2019). In the case of the lead phasedown in gasoline, EPA projected that planning costs associated with adding capital equipment would preclude the adoption of isomerization for two to three years, yet it was adopted by refineries during this time. In neither case were reasons for these differences identified.

Implications for Ex Post Compliance Costs

Realized compliance costs may not align with ex ante projections for a variety of reasons. Because more studies examine ex post evidence of compliance strategies than examine ex post evidence of compliance costs, we first ask what can be learned about ex post compliance costs 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.

What do we learn from differences in compliance strategies?

For 10 of the rules in our sample, we find evidence of differences between anticipated and actual compliance strategies. We are able to identify possible sources of these differences for all but the lead phasedown in gasoline (table 5). However, we are able to identify a clear-cut directional influence of changes in compliance strategies on ex post compliance costs for only three rules: RFS2, MACT II, and the light-duty vehicle surface coating NESHAP.

For 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 as compared to ex ante estimates for the program (e.g., Lade, Lawell, and Smith 2018a, 2018b). In the case of MACT II, failure to consider how the bubble strategy reduced capital costs likely resulted in an overestimate of compliance costs for mills embracing the strategy (Morgan, Pasurka, and Shadbegian 2014).[3] Finally, while several factors likely contributed to differences in compliance strategies for the light-duty vehicle surface coating NESHAP, they all lowered realized compliance costs relative to ex ante expectations.

For the remaining rules, it is not possible to draw conclusions about ex post unit costs based on shifts in compliance strategy alone. For the Arsenic Rule, the Cluster Rule, and the NO_x Budget Trading Program, we know that some entities reduced compliance costs through behavioral and process changes, but studies do not shed light on how the costs of these changes compare with ex ante estimates. In the cases of MBr critical use exemptions, locomotive emission standards, and the Title IV SO_2 Trading Program, multiple competing factors affected compliance strategy, which makes assessing their net directional influence challenging. For instance, in the case of the Title IV SO_2 Trading Program, less interfirm trading than anticipated led to higher marginal compliance costs than anticipated. However, greater use of banking and substitution and compensation units lowered compliance costs. In addition, while railroad deregulation and investment by utilities in mining and transportation infrastructure made low-sulfur coal cheaper, some state-level regulations increased reliance on scrubbers. Technological innovation also improved both scrubber efficiency and fuel blending options.

Are ex post costs lower or higher than ex ante estimates?

Table 6 shows the combined directional influence of identified sources of differences between ex ante and ex post cost estimates for each regulation (see appendix C for details). A blank cell indicates that no primary study informs the ex post estimates for a specific rule and cost type.

We can identify the direction of difference between ex ante and ex post aggregate compliance cost estimates for three rules: the light-duty vehicle surface coating NESHAP, phase I of the Title IV SO_2 Trading Program, and the Cluster Rule. For the light-duty vehicle surface coating NESHAP, compliance costs were likely overestimated ex ante. For phase I of the SO_2 Trading Program, ex ante estimates were consistent with ex post evidence on costs. However, these conclusions are based on partial coverage (i.e., a subset of cost categories, regulated entities, or years). For the Cluster Rule, our conclusions are also more limited, pointing to an overestimate of aggregate capital costs.

We draw conclusions for a larger set of rules on the likely direction of difference between ex ante and ex post *unit* compliance costs. In the cases of the light-duty vehicle surface coating NESHAP, the Title IV SO_2 Trading Program, MBr critical use exemptions, and MACT II, EPA likely overestimated unit compliance costs for a subset of regulated entities. In the cases

[3]Morgan et al. (2014) note that this conclusion is valid only if EPA ex ante control cost estimates are reasonably accurate for the end-of-pipe controls installed at these mills.

Table 6 Direction of difference between ex ante and ex post compliance cost estimates

EPA rule	Aggregate cost	Unit cost	Costs as reflected in permit or market prices
Lead phasedown in gasoline			
CFC phaseout			Relatively accurate initially, unclear after 1990
Boutique fuel regulations			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 programs		Likely underestimated, Arizona only	
NO_x Budget Trading Program			
Locomotive emission standards		Likely underestimated for some locomotive types	
Cluster Rule	Likely overestimated, at least for capital costs	Indeterminate	
MACT II		Likely overestimated for capital cost of plants using bubble	
Arsenic Rule		Indeterminate	
Light-duty vehicle surface coating NESHAP	Likely overestimated	Likely overestimated	
MBr 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.

of enhanced vehicle emissions I/M programs and locomotive emissions standards, it likely underestimated costs. Of the retrospective studies that examine the market price effects of regulation but lack other compliance cost information, evidence suggests that EPA may have underestimated compliance costs in two cases (boutique fuel regulations and RFS2) and likely overestimated costs in one case (MBr critical use exemptions).

Conclusions and Lessons Learned

In this paper, we review 28 published studies that offer insights into the ex post compliance strategies and costs of 13 EPA regulations. The relatively small number of studies that evaluate ex post compliance costs is itself a telling indicator of the difficulty of conducting these studies. Our review indicates that retrospective analyses tend to occur opportunistically where data happen to be available, and the regulatory design enables a credible empirical evaluation strategy (see also Cropper, Morgenstern, and Rivers 2018; Aldy et al. 2022). Our sample includes only five studies that use a quasi-experimental approach.

Within this limited set of studies, we assess which elements of compliance costs are informed by each study, discuss possible sources of differences between ex ante and ex post cost estimates, and evaluate the extent to which our results indicate the direction of difference between ex post costs and ex ante estimates. We find that many of the studies provide insights on realized compliance strategies. While some studies offer insights on specific elements of unit compliance costs, only a few shed light on how they differ overall, and even fewer speak to the total cost of regulation.

In most cases, multiple factors contributed to identified differences. Although inaccurate accounting of baseline conditions and technological innovation are the most common factors contributing to ex post differences (for seven and six rules, respectively), failure to account for several types of behavioral responses also contributed to differences between ex post and ex ante cost estimates (for eight rules). These include adjustments to margins not accounted for in an engineering-based approach, responses to noncompetitive industry structure, and averaging, trading, and banking activities.

We are only able to identify whether realized costs are under- or overestimated relative to ex ante projections in a few cases. Even then, we can make these assessments for only a subset of regulated entities or years. Because of the small number of regulations and the limited scope of many of the studies, we therefore cannot reach a general conclusion as to whether ex post costs tend to be greater or less than ex ante estimates. In addition, to draw conclusions about whether a rule has been cost effective, one would also need to evaluate emissions, risk reductions, or benefits ex post, which brings its own separate set of challenges. Although beyond the scope of this review, only a small subset of the studies included in our sample also examine benefits. In addition, we do not explore the hypotheses in table 1 that are related to the motives of EPA decision makers and analysts. While this is an important area for future research, these hypotheses are untestable based on the information available from the studies in our sample. In spite of these limitations, we believe that this review offers several valuable lessons for improving the conduct of ex ante and ex post cost analyses going forward.

Lessons for Conducting Ex Ante Cost Analysis

Based on our assessment of the sources of differences between ex ante and ex post cost estimates, we recommend increased reliance on modeling frameworks that account for industry structure, flexible provisions, implementation issues, and compliance and enforcement difficulties. Improved forecasts or sensitivity analyses of key inputs and assumptions based on data that are typically available prior to promulgation could also yield better-informed ex ante cost projections. Moreover, better accounting for existing regulations, emerging technologies, and other factors could improve baseline forecasts for ex ante analysis.

That said, some sources of differences are essentially unforecastable and will likely remain difficult to account for ex ante—consider significant technological breakthroughs and major institutional changes. In some cases, such as when a rule phases in over a long time frame, it may be worth conducting a revised benefit–cost analysis to evaluate the extent to which unforeseeable changes affect a rule's costs (or benefits).

Lessons for Conducting Ex Post Cost Analysis

This review highlights that without adopting an evaluation plan ex ante, it is difficult to conduct a thorough and systematic retrospective evaluation of regulatory costs (see also Cropper, Morgenstern, and Rivers 2018; Aldy et al. 2022). Efforts to improve the ability to conduct more high-quality retrospective analyses should therefore focus on enhancing data collection efforts across a wider array of regulatory contexts and integrating defensible counterfactuals into the policy design process. Without increased attention to these issues, the ability to draw more general conclusions about the realized cost of regulation will continue to be limited.

EPA could help facilitate a greater level of retrospective review of its regulations—for example, by laying out plans for future ex post study in a final rule. To this end, Senators Sinema (D-AZ) and Lankford (R-OK) have introduced a bipartisan bill, the Setting Manageable Analysis Requirements in Text (SMART) Act (S. 2801), requiring agencies to set out in final rules a plan for retrospective review to assess their effectiveness. Plans for future study could specify measurable outcomes for retrospective analysis (with greater attention to the most uncertain elements of the ex ante analysis), time period for evaluation, quantitative methods to be used, identification of a control group and a baseline, and possible approaches to resolving key uncertainties. Making these data publicly available would also allow outside parties to conduct their own retrospective reviews. For rules where regulatory analysis occurs well before full implementation, laying out explicit plans for ex post evaluation at an appropriate interval after promulgation could be informative and allow for potential midcourse corrections in policy design or stringency.

Finally, EPA could take advantage of opportunities for quasi-experimental analysis, for instance, when a rule adopts differential phase-in schedules or regional requirements or establishes a critical threshold (e.g., for size), thus creating a potential counterfactual. In addition, pilot studies could shed light on the likely cost implications of a rulemaking.

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