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A retrospective assessment of the costs of EPA's 1998 Locomotive Emission Standards

Abstract: While the need to update EPA benefit-cost analysis to reflect the most recent science is broadly acknowledged, little work has been done examining how well ex ante BCAs estimate the actual benefits and costs of regulations. This paper adds to the existing literature on ex post cost analyses by examining EPA's analysis of the 1998 Locomotive Emission Standards. Due to data limitations and minimal ability to construct a reasonable counterfactual for each component of the cost analysis, the assessment relies mainly on industry expert opinion, augmented with ex post information from publicly available data sources when possible. The paper finds that the total cost of bringing line-haul locomotives into compliance with the 1998 Locomotive Emission Standards rule remains uncertain. Even though the initial per-unit locomotive compliance costs were higher than predicted by EPA, total costs also depend on the number of locomotives affected by the regulation. Over 2000–2009, the number of newly built line-haul locomotives was higher but the number of remanufactured line-haul locomotives was lower than EPA's estimate.

Keywords: benefit-cost analysis; locomotives; retrospective analysis.

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1 Introduction

This paper examines how the US Environmental Protection Agency's (EPA) ex ante cost analysis of the 1998 Locomotive Emission Standard Final Rule compares to an ex post assessment of costs. This is not an evaluation of how well EPA conducted the ex ante analysis at the time of the rulemaking. As Kopits et al. (2014) discuss, even the most credible ex ante analysis of compliance costs will vary from actual costs for a large number of reasons. For instance, it is possible that market conditions, energy prices, or available technology change in unanticipated ways. Applying the conceptual framework outlined in Kopits et al., this

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paper investigates the key drivers of compliance costs to see if informed judgments can be made on the general accuracy of the ex ante estimates and what underlying factors contributed to differences (or similarities) between ex ante and ex post estimates. An important challenge faced in conducting this assessment is that information to evaluate costs ex post is quite limited. Any insights offered herein should be viewed with this limitation in mind.

The paper is organized as follows. Section 2 describes the 1998 locomotive rulemaking and summarizes EPA's ex ante compliance cost methodology. Section 3 describes the information sources available to conduct an ex post cost assessment. Section 4 provides an assessment of how the assumptions and estimates used for each part of EPA's ex ante analysis compare to what occurred in the locomotive industry in the first decade of the program. Section 5 offers some preliminary conclusions and summarizes the data limitations and remaining methodological challenges faced on the parts of the cost analysis where the ex post assessment is inconclusive.

2 EPA ex ante cost estimates of the 1998 locomotive rule

2.1 Impetus and timeline for regulatory action

On April 16, 1998, EPA published a rule for a comprehensive emission control program that subjected locomotive manufacturers and railroads to emission standards, test procedures, and a full compliance program. The rule was applicable to all locomotives manufactured in 2000 and later, and any remanufactured locomotive originally built after 1973.[1] The focus of EPA's 1998 rulemaking was on reducing oxides of nitrogen (NOx) emissions. Since most US locomotives are powered by diesel engines, they have significant NOx emissions, as well as hydrocarbon (HC) and particulate matter (PM) emissions, all of which have significant health and environmental effects. At the time of the rulemaking, locomotives were responsible for about 5.5% of NOx emissions from all mobile and stationary sources in the US.

The rule established three separate sets of emission standards (Tiers), with applicability of the standards dependent on the locomotive's date of manufacture: Tier 0 applied to remanufactured locomotives originally manufactured from 1973 through 2001; Tier 1 applied to new and remanufactured locomotives

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[1] The rule exempted locomotives powered by an external source of electricity and steam-powered locomotives.

and locomotive engines originally manufactured from 2002 to 2004; and Tier 2 applied to new and remanufactured locomotives and locomotive engines originally manufactured in 2005 or later. EPA's ex ante analysis projected that the standards would achieve significant reductions in NOx emissions from the beginning of the program (30 to over 60% reductions from 1990 baseline levels), as well as significant reductions in HC and PM emissions beginning in 2005 (about a 50% reduction relative to 1990 baseline levels).[2] Companies were allowed to meet these performance standards using any technology available to them. The rule also included average, banking and trading provisions to allow companies the flexibility to meet overall emissions goals at lower cost.

In 2008, EPA adopted a new set of emission standards, Tier 3 and Tier 4, for locomotives newly manufactured or remanufactured after 2008. The revised standards for remanufacturing existing locomotives took effect by January 1, 2010 for some models, or as soon as certified remanufacture systems were available, and the requirements for newly-built locomotives were phased-in starting in 2011. Therefore, *the universe of locomotives that were subject to the 1998 rule is limited to locomotives originally built or remanufactured between 2000 and 2009, after which the 2008 revisions began taking effect*.

2.2 EPA ex ante cost estimates

EPA estimated the total costs and emission reductions of the 1998 rule over a 41 year program run to ensure complete fleet turnover, due to the extremely long service life of the typical locomotive. Over 2000–2040, the new standards were estimated to cost $1.33 billion (NPV, 7% discounting, 1997$), and reduce NOx emissions from locomotives by nearly two-thirds, and HC and PM emissions by half. EPA did not monetize the health and environmental benefits from these emission reductions. The lifetime cost per locomotive was estimated to be approximately $70,000 for the Tier 0 standards, $186,000 for the Tier 1 standards and $252,000 for the Tier 2 standards. The average annual cost of this program was estimated to be $80 million per year, or about 0.2% of the total freight revenue for railroads in 1995. The average cost-effectiveness of the standards was expected to be about $163 per ton of NOx, PM and HC (US EPA, 1998).

Because the 1998 rule no longer applies to all the locomotives for which EPA estimated costs due to the promulgation of the 2008 rule, the present assessment is limited to the compliance costs incurred over roughly the first decade of

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[2] See US EPA (1998), Table 4–9, for a full list of the standards for each pollutant by locomotive type and Tier.

the program (2000–2009). EPA's ex ante analysis projected that approximately $600 million (NPV, 7%), or 45% of the total program costs, would occur over this period. To calculate what EPA estimated the cost per locomotive to be over 2000–2009, operating costs are limited to 10 years, as a way to approximate the operating costs incurred until each locomotive is remanufactured to the revised (Tier 3 and 4) standards. Using this approach, EPA's ex ante analysis implies the cost per locomotive over 2000–2009 was approximately $50,000, $100,000, and $98,000 for the Tier 0, Tier 1, and Tier 2 standards, respectively.

2.2.1 Main components of the ex ante cost analysis

To estimate costs of the Locomotive rule, EPA developed model locomotive categories for each tier to represent different locomotive model types.[3] For each model locomotive, EPA estimated the incremental per locomotive compliance costs including initial compliance costs, remanufacture costs associated with keeping locomotives in compliance with the standards through subsequent remanufactures, and the cost of any fuel economy penalties associated with compliance. Each component of these ex ante cost estimates for each model type is presented in Table 1.

EPA assumed the initial compliance cost (i.e., fixed and variable costs), together with a manufacturer markup for overhead and profit, comprise the total manufacturing costs and thus represent the initial cost increase to the operator. The annual remanufacture and fuel costs calculated over the service life of the locomotive comprised the additional operating costs incurred by the operator due to the rule. The total per locomotive compliance cost (i.e., the per locomotive initial cost plus the per locomotive operating costs), together with the estimated number of locomotives subject to the rule, was used to calculate the total costs of the program.

2.2.2 Treatment of uncertainty and baseline

The ex ante compliance costs were based in part on materials supplied by locomotive manufacturers and the railroad industry, contractor studies of the most likely compliance technologies, and public comments on the proposed rule or other

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[3] All descriptions of EPA's ex-ante estimates come from the regulatory support document for the rulemaking (US EPA, 1998).

Table 1 Calculation of per locomotive compliance costs (1997 US dollars) (EPA ex ante analysis).

Cost component	Tier 0					Tier 1				Tier 2 (2005–2010)		Tier 2 (After 2010)	
	Model A	Model B	Model C	Model D	Model E	Model A	Model B	Model C	Model D	Model A	Model B	Model A	Model B
Number of locomotives	3000	4900	2930	2035	2965	360	360	360	360	1700	1700	300	300
Initial costs													
Variable costs													
Hardware costs													
2 deg timing retard	$0	$0	$0	$0	$0	$0	$0	$0	$0	–	–	–	–
4 deg timing retard	$0	$0	–	–	–	–	–	–	–	$0	$0	$0	$0
4 pass aftercooler	–	$5000	$5000	$5000	–	–	–	–	–	–	–	–	–
Improved mechanical injectors	–	$800	–	–	–	–	–	–	–	–	–	–	–
Add electronic fuel injection	–	–	–	$35,000	–	–	–	–	–	–	–	–	–
Improved electronic injectors	–	–	$2000	–	$2000	$2000	$2000	$2000	$2000	$2000	$2000	$2000	$2000
Increased compression ratio	–	–	–	–	$800	$800	$800	–	–	–	–	–	–
Improved turbocharger	–	–	–	$25,000	$25,000	–	$25,000	–	–	–	–	–	–
Split cooling	–	–	–	–	–	$25,000		$25,000	$25,000	$25,000	$25,000	$25,000	$25,000
High pressure injection	–	–	–	–	–	$2000	$2000	$2000	$2000	$2000	$2000	$2000	$2000
Combustion chamber design	–	–	–	–	–	$800	$800	$800	$800	$800	$800	$800	$800
Assembly costs	$0	$4480	$6720	$4480	$6720	$6720	$6720	$560	$560	$560	$560	$560	$560
Subtotal variable cost per locomotive	$0	$10,280	$13,720	$69,480	$34,520	$37,320	$37,320	$30,360	$30,360	$30,360	$30,360	$30,360	$30,360
Fixed costs													
Engineering costs	$800,000	$1,700,000	$2,800,000	$1,700,000	$2,800,000	$3,600,000	$3,600,000	$3,600,000	$3,600,000	$4,000,000	$4,000,000	–	–
Testing costs	$422,783	$422,783	$845,566	$422,783	$845,566	$4,227,829	$4,227,829	$4,227,829	$4,227,829	$8,455,659	$8,455,659	$582,900	$582,900
Tooling	–	–	–	–	–	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	$1,000,000	–	–
Technical support	$200,000	$350,000	$500,000	$350,000	$500,000	$500,000	$500,000	$350,000	$350,000	$350,000	$350,000	–	–
Total fixed costs per supplier	$1,422,783	$2,472,783	$4,145,566	$2,472,783	$4,145,566	$9,327,829	$9,327,829	$9,177,829	$9,177,829	$13,805,659	$13,805,659	$582,900	$582,900
Total fixed costs[1]	$4,268,409	$7,418,409	$12,436,818	$2,472,803	$4,145,606	$9,328,029	$9,328,029	$9,178,029	$9,178,029	$13,806,059	$13,806,059	$582,915	$582,915
Subtotal fixed cost per locomotive[2]	$1423	$1514	$4245	$1215	$1398	$25,911	$25,911	$25,495	$25,495	$8121	$8121	$1943	$1943

(**Table 1** Continued)

Cost component	Tier 0					Tier 1				Tier 2 (2005–2010)		Tier 2 (After 2010)	
	Model A	Model B	Model C	Model D	Model E	Model A	Model B	Model C	Model D	Model A	Model B	Model A	Model B
Initial cost per locomotive[3]	$1707	$14,153	$21,558	$84,834	$43,102	$75,877	$75,877	$67,025	$67,025	$46,177	$46,177	$38,764	$38,764
Fuel costs													
Average fuel consumption	104,000	104,000	297,000	104,000	297,000	297,000	297,000	350,000	350,000	350,000	350,000	350,000	350,000
FE penalty	2%	1%	1%	1%	2%	1%	1%	1%	1%	2%	2%	2%	2%
Gallons of fuel/year[4]	2080	1040	2970	1040	5940	2970	2970	3500	3500	7000	7000	7000	7000
Cost per year (@ $0.70/Gal.)	$1456	$728	$2079	$728	$4158	$2079	$2079	$2450	$2450	$4900	$4900	$4900	$4900
Fuel costs per locomotive	$21,840	$10,920	$43,659	$10,920	$87,318	$83,160	$83,160	$98,000	$98,000	$196,000	$196,000	$196,000	$196,000
Remanufacture costs													
Cost per year	$0	$400	$846	$400	$846	$1000	$1000	$240	$240	$240	$240	$240	$240
Service life	15	15	21	15	21	40	40	40	40	40	40	40	40
Remanufacture cost per locomotive	$0	$6000	$17,766	$6000	$17,766	$40,000	$40,000	$9600	$9600	$9600	$9600	$9600	$9600
Total cost per locomotive	$23,547	$31,073	$82,983	$101,754	$148,186	$199,037	$199,037	$174,625	$174,625	$251,777	$251,777	$244,364	$244,364

[1] Represents the fixed cost per supplier multiplied by the number of suppliers for each model type (e.g., 3 suppliers for Tier 0 Models A, B and C, and 1 supplier for the remaining model types).

[2] Total fixed costs for all suppliers divided by the number of locomotives in each model category.

[3] Sum of total hardware (variable) cost per locomotive and total fixed cost per locomotive plus 20% manufacturer markup.

[4] Represents average fuel consumption multiplied by the fuel economy penalty.

Source: US EPA (1998).

information available to EPA. The EPA contractors and subcontractors included ICF, Incorporated, Acurex Environmental Corporation, and Engine, Fuel, and Emissions Engineering, Incorporated (EF&EE). The regulatory support document does not include a separate formal uncertainty analysis of the various inputs to the cost estimates, but it does state that the final cost estimates "tend to be somewhat conservative; that is, for those costs with significant uncertainty, EPA used the higher end of the estimated range" (US EPA, 1998). In some areas, the EPA presented a range of costs, especially when contractor estimates or public comments differed from EPA's initial estimates. A high cost case is included as a sensitivity analysis to show the effects of modifying base case assumptions regarding some components of the fixed costs (engineering costs, testing costs, number of suppliers) and the fuel economy penalty (which determines the additional fuel cost incurred from the added control equipment). These are discussed in greater detail below.

It should also be noted that for the most part, the regulatory support document did not include a detailed discussion of the counterfactual – e.g., to what extent that more efficient line-haul locomotives would have been developed and adopted over time in the absence of the rule. Baseline assumptions about technology (availability, cost, fuel economy), fuel costs, and other inputs (e.g., annual fuel consumption) used in EPA's ex ante analysis reflected current conditions rather than a forecast of future conditions in absence of the regulation. EPA estimated the number of newly manufactured and remanufactured locomotives of each model type based on information on the number of locomotives currently in service and existing production, remanufacture, and retirement rates. For projections of newly manufactured locomotives, the ex ante estimates reflected an expectation that the two largest western railroads would purchase large numbers of Tier 2 locomotives during 2005–2010 in order to accelerate their introduction into Southern California, but no explanation was offered for this expectation (US EPA, 1998). The EPA ex ante analysis did not discuss other potential exogenous factors that could influence the size of the regulated universe – e.g., demand side factors that could shift railroad market share relative to trucking and hence the number of new locomotives purchased.

3 Information available to conduct ex post evaluation

As noted at the outset, it was challenging to find ex post compliance information pertaining to the 1998 Locomotive Emission Standards. Publicly-accessible data sources, such as the Census of Manufactures (CMF), Annual Survey of Manufactures (ASM), American Association of Railroad (AAR) publications, EPA's AirControlNet database, and Railinc Equipment Registration and Information System (Umler), contain some information that is helpful in determining the number of locomotives affected by the regulation, but generally lack information on the realized cost of particular control mechanisms.

It was also difficult to identify appropriate industry experts with sufficient information about the ex post regulatory compliance costs. Numerous independent associations, including the Manufacturers of Emission Controls Association, the Association of American Railroads (AAR), the American Shortline and Regional Railroad Association (ASLRRA), and the Engine Manufacturers Association, were unresponsive to our information requests. We then contacted two engineering consulting firms: Power Systems Research and Engine, Fuel, and Emissions Engineering, Incorporated (EF&EE). One database produced by Power Systems Research was found to be a potentially useful source for obtaining information on the historical locomotive fleet, but a subscription to this database was not possible due to funding constraints. EF&EE is a research, development, and consulting firm specializing in motor vehicle emissions and emissions control. The president and founder of EF&EE, Mr. Chris Weaver, was responsive to our requests and willing to respond to all parts of a questionnaire we prepared based on our review of EPA's ex ante cost estimation methodology.[4]

Ultimately, the analysis below is based on information provided by EF&EE, the sole respondent to the questionnaire, augmented by publicly available data where possible. Since Mr. Weaver's firm helped develop EPA's 1997 ex ante cost estimates for this regulation, following the advice received from EPA's Science Advisory Board (US EPA, 2013), significant efforts were made to provide as much documentation and supporting evidence for his input as possible and any assessment and statements based on his professional experience and expert opinion are referenced as such throughout the paper.

4 Ex post assessment of compliance cost

4.1 Locomotive model types

Railroads can be separated into three classes based on size: Class I, Class II, and Class III. Class I railroads represent the largest railroad systems in the country,

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[4] A copy of the questionnaire is provided in US EPA (2014).

carry most of the interstate freight and passenger service, and buy almost all of the new locomotives. Class II and III railroads represent the remainder of the rail transportation system and generally operate within smaller, localized areas, and their fleet of locomotives tends to be older. Locomotives in each class can perform two different types of operations: line-haul and yard (or switch). Line-haul locomotives, which perform the line-haul operations, generally travel between distant locations, such as from one city to another. Switch locomotives, which perform yard operations, are primarily responsible for moving railcars within a particular railway yard. Switchers make up a relatively small share of the locomotive market, accounting for approximately 7–8% of total Class I fuel consumption in recent years.[5]

To develop the ex ante cost analysis for the 1998 rulemaking, EPA assumed the locomotives subject to each tier of standards could be grouped into different model categories (or engine families) and then developed a cost estimate for each model type (as shown by the individual columns in Table 1). The Tier 0 standards would apply to five model types: switch locomotives from Electro-Motive Diesel (EMD) (Model A), older and newer line-haul locomotives from Electro-Motive Diesel (Model B and C), and older and newer line-haul locomotives from General Electric (GE) Transportation Systems (Model D and E).[6] For Tier 1 locomotives, EPA believed that early versions of the new engine designs used to meet the Tier 2 standards would make their appearance during the Tier 1 period. Thus, as shown in Table 1, EPA assumed there would be two Tier 1 models for each of the two manufacturers. Models A and B are Tier 1 line-hauls from EMD and GE respectively, and Models C and D are early version Tier 2 design line-hauls from EMD and GE, respectively. EPA assumed that for Tier 2, each manufacturer would have a single model (Model A – EMD, Model B – GE).

After the rule was in place, each manufacturer ended up deploying more versions or types of their locomotive models than estimated by EPA ex ante. However, for the most part the model categories used by EPA were sufficient for purposes of estimating compliance costs (EF&EE expert opinion). EMD and GE both deployed direct current (DC) and alternating current (AC) versions of their basic line-haul locomotives at each Tier level, but the engines and emission control systems in the DC and AC engines were essentially the same, so it is not clear that these should count as separate models. EMD also deployed passenger locomotive models for each Tier, generally with twelve-cylinder engines rather than 16 cylinders. GE also deployed a 6000 hp, 16-cylinder version of its Evolution Series (GEVO) engine.

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[5] Source: STB Schedule 750 of Annual Report Form R-1, ERTAC (2012).

[6] GE did not make switch locomotives at that time, or since.

4.2 Number of locomotives affected by the regulation

EPA estimated the number of newly manufactured and remanufactured locomotives affected by the regulation based on information on the number of locomotives currently in service and existing production, remanufacture, and retirement rates for Class I, II, and III and passenger rail locomotives. Since Class I railroads buy almost all of the new locomotives in the US, and in the timeframe addressed in the 1998 rule, the bulk of the non-Class I railroad locomotives were not covered by the rule, we focus here on Class I.

New Locomotives. EPA obtained information on Class I locomotives from the AAR Annual Railroad Facts publication. At the time of the rulemaking, about 17,500 of Class I locomotives were manufactured post 1972, most of which were used in line-haul service (Tier 0, Models B through E). The 3500 older locomotives that were manufactured prior to 1972 are used as switchers. EPA assumed that by 2008, almost all 1973 through 1999 line-haul locomotives (13,200) would be remanufactured to meet EPA's standards. EPA also assumed there would be 400 newly manufactured line-haul locomotives for years 2000–2004, 600 for years 2005–2010, and 300 new units for all subsequent years. Table 1 breaks down EPA's ex ante estimate of the total number of locomotives affected by each Tier of standards for each model type.

As shown in Table 2, actual sales of new Class I locomotives were higher than EPA's estimate. Over 3800 newly manufactured locomotives were in the fleet from 2000 through 2004, or an average of 760 per year. Nearly 4000 were added from 2005 through 2009, or about 790 per year. This increase was likely driven at least in part by demand side factors. As fuel prices increased, railroads gained market share compared to trucks, so railroads purchased more new locomotives as a result. In addition, improvements in fuel efficiency of new locomotives (compared to existing ones) may have played a role. That is, if higher fuel prices and increased new engine fuel efficiency provided an incentive to companies to retire old locomotives earlier instead of remanufacturing them to comply with Tier 0 requirements during a rebuild, this could have contributed to an increase in new locomotives in compliance with Tier 1 standards. Similarly, improvements in fuel efficiency and lower maintenance costs could have led to a rebound effect for locomotive travel, thus contributing to the robust sales of Tier 2 locomotives.

Remanufactured Locomotives. As shown in Table 2, a total of 839 Class I locomotives were rebuilt during the first decade of the program (2000–2009), and far fewer rebuilds occurred over 2000–2004 than during the previous or following 5 year periods. There were only 40 rebuilds per year on average over 2000–2004, but about 130 per year on average over 1995–1999 and 2005–2009. The slowdown in rebuilds may reflect a strategic decision on the part of the railroads in response

Table 2 Class I rail statistics, 1995–2010.

Year	Average fuel cost (1997$) ($/gal)	Number of locomotives in service	Number of locomotives new	Number of locomotives rebuilt	Average fuel consumed per locomotive (thousand gallons)	Revenue ton-miles per gallon fuel consumed (millions)
1995	60.01	18,810	928	201	186	373
1996	67.66	19,267	761	60	187	377
1997	67.82	19,682	743	68	183	374
1998	57.00	20,259	889	172	179	380
1999	55.45	20,254	709	156	185	382
2000	87.46	20,026	640	81	186	394
2001	85.54	19,743	710	45	189	401
2002	73.33	20,503	745	33	183	402
2003	89.25	20,772	587	34	185	403
2004	106.98	22,015	1121	5	185	407
2005	151.42	22,779	827	84	181	412
2006	192.11	23,732	922	158	178	421
2007	218.24	24,143	902	167	169	433
2008	312.05	24,003	819	129	163	454
2009	177.12	24,045	460	103	134	476
2010	224.29	23,893	259	181	147	481
2000–2001 Average	87	19,885	675	63	187	397
2002–2004 Average	90	21,097	818	24	185	404
2005–2009 Average	210	23,740	786	128	165	439

to the 1998 standards. Typically, line-haul locomotives are overhauled about every 8 years and repowered at least once during their lifetime[7], but because the emission limits were mandated only at the time of remanufacture, railroads may have found it cheaper to deal with the inefficiencies/costs associated with delaying rebuilds or retiring locomotives earlier and buying more new ones than rebuilding older models to comply with Tier 0 requirements. Continuous improvements in engine durability, improved maintenance practices, and other factors may have also played a role in increasing the remanufacturing interval over time even absent emission standards. The increase in rebuilds in the second half of the decade could suggest that companies were no longer able to delay rebuilds, or it could reflect strategic behavior in anticipation of the revised locomotive standards. Operators may have opted to rebuild older locomotives ahead of schedule to Tier 0 standards before the more stringent emission standards took effect.

The number of switch locomotives that were affected by the 1998 rule is likely much less than the number EPA assumed. Any new switch locomotives sold will be of the “genset” type (discussed in the next section), but the large supply of old locomotives that can be kept running at low cost limits the potential sales of new switchers and old switchers can be run for a long time without remanufacturing.

In sum, the number of remanufactured locomotives complying with Tier 0 over the first decade of the program is likely lower than EPA anticipated, and the number of new locomotives complying with Tier 0, 1 and 2 standards is higher than EPA anticipated.

4.3 Methods of compliance

EPA expected numerous emission control technologies would be available at the time the locomotive emissions standards would take effect. For example, manufacturers could achieve significant NOx emission reductions at minimal cost by adopting technologies and practices that would improve the fuel injection timing, rate, and/or duration, or make engine modifications to achieve the desired power rating.[8] The effective use of some technologies can be optimized through the use of other technologies, and adverse effects of some technologies can be limited or eliminated through the application of other technologies. For

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[7] http://www.fhwa.dot.gov/environment/air_quality/conformity/research/mpe_benefits/mpe06.cfm.

[8] See US EPA (2014) for a technical discussion of all technologies considered in EPA’s ex-ante analysis.

this reason, in estimating compliance costs EPA considered use of multiple technologies together to form a larger emission reduction system.

Table 3 presents EPA's ex ante crosswalk between the expected compliance technologies, their usage, and the locomotive model types by Tier. To comply with Tier 0 standards, EPA expected manufacturers would use three main strategies. First, locomotives equipped with turbocharged engines would be able to employ: modified/improved fuel injectors, enhanced charge air cooling, injection timing retard, and in some cases, improved turbochargers, to reduce NOx emissions. Second, EPA expected that engine coolant would continue to be the cooling medium in most cases, rather than a separate cooling system, and that it would be cost-effective to replace two-pass aftercoolers with four-pass aftercoolers during the remanufacturing process. Finally, the key tools available to manufacturers to reduce emissions for naturally-aspirated and Roots-blown engines would be modifications to the fuel system, modifications to the combustion chamber and injection timing.

In addition to the controls available for Tier 0 compliance, electronic controls and enhanced aftercooling could be used for Tier 1 compliance, and timing retard could be used to reduce NOx emissions without a negative impact on PM. Also, some models could use in-cylinder and turbocharger modifications. Finally, increased compression ratios could be used to reduce PM emissions and ignition delay, and smoke emissions would be reduced by adopting upgraded turbocharger designs.

Finally, for Tier 2, EPA expected that, with the change from DC to AC traction motors, manufacturers would be using new four-stroke engines, which would have lower PM emissions as they achieve better oil control. Additional NOx and PM emission reductions were expected through continued refinements in charge air cooling, fuel management, and combustion chamber configuration. Improved fuel management would include increased injection pressure, optimized nozzle hole configuration, and rate-shaping. Finally, potential combustion chamber redesigns would include the use of reentrant piston bowls and increased compression ratio.

EF&EE found that all of these strategies were used to comply with Tier 0, except for engine modifications to reduce power output, where the approach was instead to substitute smaller non-road engines. After the rule was enacted, the two major locomotive manufactures abandoned the switch locomotive market, and with it, the market for naturally aspirated and Roots-blown engines, leaving it to smaller companies. The preferred approaches of those smaller companies were the “Hybrid” and “Genset Switcher”. The hybrid substitutes one smaller non-road engine plus a large battery pack for the large locomotive engine, while the genset switcher substitutes (typically) two or more small non-road engines.

Table 3 Control options, expected usage and locomotive models (EPA ex ante analysis).

Tier	Expected technology usage and models developed for cost analysis	2 deg timing retard	4 deg timing retard	4 pass aftercooler	Improved mechanical injectors	Add electronic fuel injection	Improved electronic injectors	Increased compression ratio	Improved turbocharger	Split cooling	High pressure injection	Combustion chamber design
Tier 0 (1973–2001)	Percent locomotives using technology	50	50	60	30	13	27	20	30	–	–	–
	Models using technology											
	A	X	X									
	B	X	X	X	X							
	C	X		X			X					
	D	X		X		X			X			
	E	X					X	X	X			
Tier 1 (2002–2004)	Percent locomotives using technology	100	–	–	–	–	100	50	25	75	100	100
	Models using technology											
	A	X					X	X		X	X	X
	B	X					X	X	X		X	X
	C	X					X			X	X	X
	D	X					X			X	X	X
Tier 2 (2005–2010)	Percent locomotives using technology	–	100	–	–	–	100	–	–	100	100	100
	Models using technology											
	A		X				X			X	X	X
	B		X				X			X	X	X
Tier 2 (after 2010)	Percent locomotives using technology	–	100	–	–	–	100	–	–	100	100	100
	Models using technology											
	A		X				X			X	X	X
	B		X				X			X	X	X

Source: US EPA (1998).

EPA correctly predicted the potential to substitute non-road engines for locomotive engines in switchers, but did not foresee the use of batteries or two or three smaller non-road engines in place of a single larger one.

Two other technologies that were used to meet Tier 0 requirements were increasing the compression ratio and modifying the cylinder liner and piston rings to reduce lubricating oil consumption. EPA had expected compression ratio changes to be introduced for compliance with Tier 1, but GE did so for Tier 0 as well (Chen, Flynn, Gallagher, & Dillen, 2003).

Finally, the usage frequencies assumed by EPA for several technologies for Tier 0 were too low because they were used by more models than anticipated. For example, EF&EE reports that Model B used electronic fuel injectors (EFI) (Fritz, Hedrick, & Smith, 2005). Note these EFI systems may not have been absolutely necessary to meet the emission standards themselves. Rather, they were likely used to minimize the loss in fuel economy from retarding injection timing to meet the NOx standards. In addition, EF&EE reports that new Tier 0 locomotives (Models C and E) used split cooling (Uzkan & Lenz, 1999), increased compression ratios, and combustion chamber design, and Chen et al. (2003) comment in their conclusions that the same technology package can also be used to upgrade baseline engines to the same standards. As with EFI, EF&EE expects that it was not strictly necessary to add split cooling in order to meet the standards. Rather, it was used to minimize the need to retard injection timing, with the resulting adverse impact on fuel economy and mechanical reliability.

All of the strategies outlined above were, in fact, used on line-haul locomotives in order to comply with both Tier 1 and Tier 2 standards (Dillen and Gallagher, 2002; Flynn, Hupperich, Napierkowski, & Reichert, 2003). In addition, all Tier 1 units used 4-pass aftercooling and changes were made to the cylinder liner and piston rings to reduce lubricating oil consumption (EF&EE expert opinion). As for switch locomotives, the principal compliance mechanism was to employ non-road engines certified to Tier 1 or Tier 2 standards in genset switchers. For Tier 2, combustion chamber designs were extensively optimized, but this optimization did not include the use of re-entrant combustion chambers. For engines in the size and speed range, the optimal combustion chamber has been found to be wide and flat (the so-called Mexican hat shape) rather than re-entrant. The usage frequencies noted in Table 3 for each technology were reasonable, the one exception being that all Tier 2 units ended up using 4-pass aftercooling (EF&EE expert opinion).

There were some other changes in the locomotive market in the years following the rulemaking that were unanticipated by EPA, but for the most part these did not impact the cost of meeting Tier 2. For example, the anticipated migration from 2-stroke to 4-stroke engine designs for EMD did not occur, but this did not necessarily create a cost divergence because the rulemaking did not ascribe the switch to 4-strokes as being due to EPA's program in the first place. EMD wound up using the same technologies on its two-stroke engine, and they were equally effective in reducing emissions. Similarly, the widespread change from 4400 HP DC locomotives to 6000 HP AC locomotives that was anticipated in 1998 has largely failed to occur. Although a substantial number of AC locomotives are in service, line-haul locomotives with DC propulsion continue to make up a substantial fraction of new locomotive sales. Those AC locomotives that are sold are primarily in the 4300–4400 horsepower range. EMD locomotives in this power range have 16-cylinder two-stroke engines, while GE units have 12-cylinder four-stroke GEVO engines. Although DC and AC locomotives differed in their electrical systems, there was little or no difference in the engine and emission control systems. The same engine families were used in DC and AC locomotives, so this also should not have altered the direct compliance cost of meeting the Tier 2 standards (EF&EE expert opinion). It is not clear whether the lack of a widespread adoption of 4-stroke engine designs or 6000 HP AC locomotives was in part influenced by the new requirements. If so, then any unrealized performance improvements may be considered indirect costs attributable to the rule.

In sum, except for the use of Tier 2 and Tier 3 non-road engines in genset switchers, EF&EE could not identify any major emission control technologies not considered by EPA that were actually employed in a significant number of locomotives.[9]

4.4 Per locomotive compliance cost

4.4.1 Initial compliance cost

EPA estimated the initial cost increase to the operator as the sum of the fixed costs and variable costs of hardware needed for compliance, adjusted by a 20% manufacturer's markup for overhead and profit.

Fixed Costs. EPA's fixed costs of manufacturing locomotive models compliant with the emissions standards included costs of testing (development, certification, production, and in-use), engineering, tooling (for Tier 1 and 2 only),

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[9] In the public comments on the proposed rule, EMD stated that exhaust gas recirculation (EGR) would be the likely technology of choice for meeting Tier 2 standards. EMD also projected a 5–10% fuel economy penalty, rather than the 1 percent estimated by EPA, based on the experience of others in the use of EGR. EGR was not used to meet Tier 2 (EF&EE expert opinion).

and technical support.[10] EPA estimated these fixed costs for each locomotive supplier, multiplied by the number of suppliers for each model type, and divided by the total number of locomotives (assuming suppliers would recover costs from the locomotives) to derive the total per locomotive fixed cost by model type. EPA assumed that there were three suppliers each for Tier 0 Model A, B, and C locomotives, and one supplier each for Tier 0 Model D and E, Tier 1 Model A, B, C, and D, and Tier 2 Model A and B locomotives. EPA based this assumption on the numbers of independent part suppliers and remanufacturers for the various locomotive models at the time of the analysis. The number of suppliers EPA estimated for each model category was less than the total number of suppliers in existence at the time because EPA assumed that the manufacturers for which initial costs were cost prohibitive would pay other manufacturers with the ability to incur initial costs to perform the necessary services.

Because the fixed costs were for goods and services that are useful for more than 1 year of production, EPA amortized initial costs over 5 years (i.e., manufacturers would recover costs within the first 5 years of production). For Tier 2, because the standards were to be in effect for longer than 5 years, EPA developed two sets of unit costs (because initial fixed costs would be recovered by 2010). EPA did not calculate separate compliance costs reflecting fully-recovered fixed costs for Tier 0 and Tier 1 as it did for Tier 2, because the initial hardware costs occur only at original manufacture (for Tier 1) or the first remanufacture (for Tier 0), and thus are applicable only during the first few years of the program. Table 1 includes the fixed costs of manufacturing for each Tier and model type that were estimated by EPA.

Certification data published in 2005 shows that the number of suppliers, and especially the number of different Tier 0 remanufacturing systems developed, were higher than EPA estimated. EPA estimated that a total of 11 remanufacturing systems would be developed and certified for Tier 0 locomotive models, from a total of three suppliers. In 2005, there were 37 remanufacturing systems certified, from four suppliers (US EPA, 2005). EPA's estimates of the *cost per remanufacturing system certified* are probably too high, as they assume that the same level of effort went into certifying remanufacture systems as new engines which is probably not the case (EF&EE expert opinion). Even taking this into account, however, the large number of systems certified means that the total costs of certification of Tier 0 remanufacturing systems were probably about double EPA's estimate (EF&EE expert opinion). This suggests that the total realized fixed costs for the Tier 0 line-haul locomotives (Models B-E) were closer to $53 million (1997$) than

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[10] See US EPA (2014) for more detailed discussion of what is included in each of these categories.

EPA's original estimate of $26.5 million. What this implies about the realized per locomotive fixed cost depends on how EPA's estimate of the number of remanufactured locomotives compares to the number of locomotives actually affected by the rule in each model category. Since the total number of locomotives to be remanufactured was over-estimated, the fixed cost per locomotive for remanufactured locomotives was likely higher than EPA's estimate.

EF&EE's expert opinion indicates that EPA's assumptions regarding the total fixed costs of certification for newly built locomotives were fairly accurate. Since the total number of newly built locomotives over 2000–2009 was underestimated, the realized fixed cost per locomotive for new locomotives was likely lower than EPA's estimate.

Variable Costs. EPA's estimate of the initial incremental variable compliance costs included costs of hardware and assembly. The *hardware costs* represented the emission reduction technologies EPA projected that manufacturers would employ for compliance with the standards. Table 1 shows the hardware costs assumed for technology and specifies the combinations of these technologies that were expected to be used for each locomotive model type and Tier. *Assembly costs* included the labor and overhead costs for retrofitting (in the case of Tier 0) or for initial installation of the new or improved hardware. These also varied with the characteristics of individual locomotives and the type of hardware necessary for compliance with the applicable emission standards.

EF&EE's expert opinion indicates that EPA's estimate of the hardware cost of each emission control technology was reasonable. However, since the usage frequency of several technologies was higher than EPA anticipated (as discussed in Section C.2), per locomotive total hardware costs for line-haul locomotives were likely higher than EPA's ex ante estimate. For Tier 0, the use of electronic fuel injectors would have added $35,000 in hardware costs for an older line-haul EMD locomotive (Model B), and the use of split cooling, increased compression ratios, and combustion chamber design would have added about $26,000 in hardware costs for newer line-hauls (Model C and E locomotives).[11] For Tier 1 and 2, the use of 4-pass aftercooling may not have added to the hardware costs per locomotive since the aftercooling costs may have already been included in the assumption of split cooling being used in these locomotives (EF&EE expert opinion).

The industry move to genset switchers instead of remanufacturing old ones to comply with the new standards means the realized Tier 0 per locomotive compliance cost was likely different than what EPA estimated for the switch locomotives

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[11] Price increases reflect EPA assumed costs of these technologies for other Model types, as shown in Table 1.

(Model A). Presumably companies found gensets to be more cost-effective than remanufacturing to Tier 0 standards. However, it is unclear to what extent genset switchers were developed in reaction to the rule or other factors. The genset has major benefits in terms of availability/reliability and fuel consumption, so EF&EE's expert opinion indicates that this technological change would likely have been undertaken even in the absence of the emission standards. Better reliability means one unit can often replace two old conventional units, and fuel consumption is at least 50% less.[12] The genset switcher is significantly more expensive but costs have come down in recent years. EF&EE reported that the current price of a new genset switcher is around $700,000 whereas a standard switcher such as an SW1200 could be sold for about $236,000 (although that does not include the cost of remanufacturing the engine to Tier 0).

EF&EE's expert opinion indicates that the assembly costs were reasonable for new locomotive but were likely underestimated by a factor of two or three for remanufactured locomotives. EPA's assembly cost estimates for remanufactured locomotives in Tier 0 were similar to those for new ones in Tier 1. However, remanufacturing takes place in locomotive repair shops that perform a variety of activities, rather than in assembly areas that specialize in only one locomotive model. EF&EE observed that these operations are much less efficient. If assembly costs were double or triple what EPA estimated, this would add about $4500–9000 per locomotive for older line-hauls meeting Tier 0 (models B and D) and close to $7000–13,000 per locomotive for newer line-hauls subject to Tier 0 (models C and E) (since remanufactured locomotives make up most of the ones subject to Tier 0).

4.4.2 Remanufacture costs

EPA's ex ante cost estimate included the costs associated with keeping locomotives in compliance with the standards through subsequent remanufactures (e.g., cost of replacing electronic fuel injectors or wiring harnesses on a set schedule). Table 1 summarizes the remanufacture cost per locomotive for each Tier and model type that was estimated by EPA. For line-haul locomotives, expert opinion indicates that EPA's estimate of the annual remanufacture cost per locomotive and assumptions about remanufacture frequency were reasonable (EF&EE expert opinion). On the other hand, most switchers would not be remanufactured at all over the first decade of the program.

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[12] Estimates based on EF&EE discussion with a genset switcher company.

4.4.3 Fuel costs

EPA estimated increases in fuel consumption due to various emission control technologies and the corresponding incremental fuel costs. Based on past developments in the industry, EPA believed that manufacturers would make every effort to eliminate any initial fuel consumption penalties, and would have largely succeeded by 2010. However, EPA included fuel economy penalties for the full 41 years covered by the analysis.

As shown in Table 1, fuel costs made up a large share of EPA's total per locomotive cost estimates for all model types except older line-haul models (Models B and D, Tier 0). For Tier 0, for switchers (Model A), fuel cost makes up over 90% of cost of compliance. For older line-haul models (B, D), fuel cost make up smaller share of the per locomotive compliance cost (11–35%). For newer line-haul models (C, E), fuel cost make up about half (42–56%) of per locomotive cost. For Tier 1 and Tier 2, fuel costs account for 53–59% and 70−80% of EPA's total cost per locomotive, respectively.

EPA's estimates of per locomotive fuel costs were calculated as: average annual fuel consumption (gal/year) * fuel economy penalty (%) * price ($/gal) *service life (15–21 years for Tier 0, 40 years for Tier 1&2). Each component is discussed below.

Fuel price. EPA assumed a constant fuel price of $0.70 per gallon of diesel consumed (1997$). As shown in Table 2, actual prices over the first decade of compliance were substantially higher. Locomotive fuel averaged $1.49/gal (1997$) over 2000–2009[13], or more than double EPA's estimate (AAR, 2002, 2011).[14] Most of the increase in diesel price over this period was unanticipated. Around the time of the rulemaking, the Energy Information Administration (EIA) was forecasting a modest increase in fuel prices – e.g., about 0.4% annual growth in the end user price of distillate fuel between 1995 and 2015 (EIA, 1997) – but world oil prices, the main determining factor in the price of diesel, increased substantially more than EIA was projecting at the time. Over 2000–2009, oil prices were on average 76% higher than what EIA had projected in the 1997 Annual Energy Outlook (AEO) (EIA, 2011).

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[13] This estimate includes the impact of hedging, which railroads used to stabilize the impact of fuel price volatility. The source for the data is Annual Report Form R-1, Schedule 750.

[14] The other potential source of fuel price data is the AAR Monthly Railroad Fuel Price Indexes report, which is based on a survey of the largest Class I railroads, using a methodology decided by the Interstate Commerce Commission. A weighted average of fuel price (total dollars divided by total gallons) is used to construct the index. Note that estimates based on this index indicate fuel prices were even higher than the Railroad Facts data suggests – i.e., averaging more than $2/gal (1997$) over 2000–2009 (AAR, 2001, 2003, 2006, 2009).

Average annual fuel consumption per locomotive. Table 1 includes the constant fuel consumption assumptions used for calculating fuel costs. For Tier 0, EPA assumed average annual fuel consumption per locomotive of 104,000 gallons for switchers and remanufactured older line-hauls (Models A, B, and D), 297,000 for newer (mostly remanufactured) line-hauls (Models C and E). Average annual fuel consumption per locomotive was assumed to be 297,000 gallons for the Tier 1 line-hauls (Models A and B), and 350,000 gallons for the remaining Tier 1 line hauls (early versions of Tier 2 design) and all Tier 2 locomotives. EPA recognized that there was a short-term trend of increasing fuel consumption, but was not confident that the trend would continue. The long-term trend up to that time was for fuel consumption to remain fairly constant as a result of continual improvements in locomotive fuel economy, which offset the significant increase in ton-miles of freight hauled.

EF&EE's expert opinion is that EPA's estimates of average annual per locomotive fuel consumption were reasonable, but there is little data available against which to check this claim. The data in Table 2 shows that on a fleetwide basis per locomotive fuel consumption fluctuated in the early years of the program and declined more significantly after 2004. Annual per locomotive fuel consumption for all Class I locomotives in use averaged about 187,000 gallons over 2000–2001, 185,000 gallons over 2002–2004, and 165,000 gallons over 2005–2009. These fleetwide averages are lower (at least for 2002–2009) than the annual fuel consumed per locomotive assumed in EPA's analysis, but without more information on the share of fuel consumption coming from new locomotives, it is difficult to draw ex post conclusions about this element of EPA's analysis. The fleetwide averages could be consistent with the EPA assumptions if operators run the newest line-haul engines more per year than the older ones in their fleet (outweighing any fuel efficiency gains from newer models). It is also possible that annual per locomotive fuel consumption was lower than EPA estimated due to fuel efficiency improvements in the new engines. (Since fuel efficiency of newer models is likely better than that of older models, and since the newest engines are likely to handle more ton-miles per year than the fleetwide average[15], all we can reasonably conclude based on existing data is that annual fuel consumption of a new locomotive was more than 186,000 gallons over 2000–2004 and more than 165,000 gallons over 2005–2009).

For switch locomotives, it is likely that average annual fuel consumption of genset switchers was lower than EPA's assumed 104,000 gallons per year for

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[15] Over 2000–2006, new locomotives comprised approximately 25% of the fleet, but given the higher power and more intensive use of newer locomotives, they probably handled 35–40% of total gross ton-miles (FRA, 2009).

a switch locomotive (Tier 0, Model A). Gensets were introduced around 2005 (EF&EE expert opinion), and currently, switcher fuel consumption is about 40,000–70,000 gallons a year, or 30–60% lower than EPA's estimate.[16]

Fuel Economy Penalty. EPA used the existing engines as the fuel-economy baseline and then estimated increases in fuel consumption due to various emission control technologies and the corresponding incremental fuel costs. EPA assumed fuel penalties of: 2% for Tier 2 locomotives, 1% for Tier 1 locomotives, and 1–2% for Tier 0 locomotives.

Based on past developments in the industry, EPA believed that manufacturers would make every effort to eliminate any initial fuel consumption penalties, and would have largely succeeded by 2010. However, EPA included fuel economy penalties for the full 41 years covered by the analysis. EPA also conducted a high case sensitivity analysis with 2–4% fuel economy penalties (but did not adjust assumptions about fuel price or fuel consumption in the sensitivity analysis).

To determine the realized fuel economy penalty from compliance with the rule, one needs to compare the actual fuel economy of new and remanufactured locomotives over 2000–2009 with the fuel economy of new and remanufactured locomotives that would have been achieved in absence of the rule. Both of these are extremely difficult to estimate – the former because in use, model specific fuel economy information is not readily available from manufacturers, and the latter because locomotive manufacturers are constantly striving to reduce fuel consumption, as this is one of the principal decision for Class I railroads in selecting a locomotive.

For competitive reasons, locomotive manufacturers generally do not release fuel consumption data,[17] and the ability to glean anything about the realized fuel economy using existing aggregate data is extremely limited. For example, one common measure of the fuel efficiency of freight rail is revenue ton-miles per gallon of fuel consumed. By this measure, as shown in Table 2, the overall fuel efficiency of Class I rail has consistently improved over time, especially after 2005. As with the fuel consumption estimates discussed above, however, these measures likely provide an underestimate of the fuel economy of locomotives subject to the rule, since newer (and rebuilt) engines will generally have higher fuel efficiency than the fleetwide average. A slowdown in rebuild frequency would also be reflected in the observed fleetwide change in fuel efficiency.

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[16] Estimate based on EF&EE discussion with a genset switcher company.

[17] Figure 2 of Flynn et al. (2003), for example, shows the general relation between NOx and fuel economy, but omits the units from the fuel-economy axis.

Even if we could get rough estimates of how much fuel economy of new line-haul locomotives improved over 2000–2009, the challenge of constructing the counterfactual would remain. Given the long term trend of improved fleetwide rail efficiency observed before the rule,[18] and projections made in the year before the rule was promulgated,[19] the fuel economy of new locomotives may have increased even more than observed over 2000–2009 in absence of the emission standards. However, with other changes going on in the industry over this period (e.g., increasing share of unit train service, increasing congestion),[20] we are skeptical that it will be possible to identify a fuel economy change attributable to the rule based on aggregate data.

Model specific information from the trade press indicates that manufacturers were able to develop new locomotives and remanufacture kits to meet emission standards without sacrificing fuel economy. For example, in 2009 EMD Tier 0+ kits offered up to 2% fuel savings versus previous engine configurations.[21] It is unclear, however, to what extent fuel economy improvements would have been implemented in the absence of the rule. It is therefore also unclear to what extent fuel economy improvements actually achieved were motivated by the rule and associated actions to comply. Locomotive suppliers would have had incentive to continue to look for ways to offer improvements in fuel efficiency, especially in the face of rising fuel prices, so it is possible that they would have been able to tweak existing models or introduce even more fuel-efficient ones in the absence of pollution controls.

Compared to a counterfactual case in which the locomotive manufacturers were able to use the latest technical advances to optimize fuel consumption without regard to NOx or PM emissions, EF&EE expert opinion is that the fuel consumption penalty was higher than anticipated, probably about 2–4%. This is based on experience and professional judgment, and interpretation of optimization studies undertaken on an EMD 710-series locomotive engine (Dolak &

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[18] Based on data in Table 2, revenue ton-miles per gallon fuel consumed increased on average nearly 2% annually between 1990 and 2000 (AAR, 2002).

[19] EIA forecast in the year before the rule was promulgated projected a continued increase in overall rail efficiency – i.e., an average annual 1% improvement in ton miles per BTU between 1995 and 2015 (EIA, 1997).

[20] Unit trains, typically 100 cars or more, follow a direct route without passing through yards or terminals on the way, and are therefore more fuel efficient than carload service which requires switch engines in breaking up trains and making new ones in every terminal through which the shipment passes. In recent years, there has been a strong trend towards unit trains – partly due to the growth of intermodal traffic from West-coast ports and coal traffic from the Powder River Basin (FRA, 2009).

[21] See, for example, Progressive Railroading, August 2009, “Locomotive Manufacturers Offer Information on their Fuel-Saving Models”, http://www.progressiverailroading.com/mechanical/article/Locomotive-Manufacturers-Offer-Information-on-their-FuelSaving-Models--21139#.

Bandyopadhyay, 2011), however, and not on public-domain data. Dolak and Bandyopadhyay (2011) show that even for engines developed to meet Tier 2 standards, there remains a tradeoff between NOx and fuel-efficiency. The results shown in the paper suggest that, for the range of plausible injection timing settings, the difference between lowest NOx (subject to PM limitations) and lowest fuel consumption fuel efficiency is roughly 2–4% in fuel efficiency.

In addition, it is important to keep in mind that efforts to control emissions may lead to other improvements in production processes and/or equipment which would not have occurred in the absence of the regulation. Manufacturers could have added technologies to new locomotives and remanufacture kits that were not strictly needed to comply with the emission standards but helped to offset any fuel economy loss from the pollution controls. The Tier 0 discussion above and the locomotive manufacturer's own assessment[22] suggest that this occurred. In this case, the fuel penalty associated with operating costs would be offset to some unknown extent, though an additional hardware cost would be attributable to the regulation.

As for switch locomotives, EPA assumed this group could be brought into compliance with Tier 0 by retarding injection timing alone, with a fuel economy penalty of only 2%. EF&EE's expert opinion is that additional changes were also needed – i.e., improvements in fuel injectors at a minimum. In practice, however, very few if any, of these units were remanufactured. Some operators instead moved to genset switchers which, as already mentioned, had significant fuel savings – of at least 20–50%[23] – compared to conventional older switchers. However, most purchases of gensets or hybrids to date have been financed in part with air quality improvement grants, and in the absence of grants, it may have been more cost-effective to purchase a second-hand four-axle locomotive for yard operations rather than remanufacturing an existing switcher (FRA, 2009).

5 Overall implications and study limitations

As stated at the outset, the purpose of this paper is not to review the ex ante cost analysis of the 1998 Locomotive rule. Rather, the goal was to explore available

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[22] Lawson, Pete, GE Transportation Systems, Faster Freight Cleaner Air Conference, Long Beach, CA, February 27, 2007, www.fasterfreightcleanerair.com/presentations.html#California2007. Also see GE's promotional materials for the Evolution Series locomotive: http://www.getransportation.com/resources/doc_download/275-evoloution-series-engine.html.

[23] Industry sources obtained by EF&EE, and http://www.gwrr.com/about_us/community_and_environment/gwi_green/genset_locomotives.be.

data to gauge whether actual compliance costs may have diverged from ex ante cost estimates and, if so, what factors might have contributed to any divergence (e.g., changing market conditions, technological innovation).

Significant methodological challenges were encountered in conducting this ex post assessment. There is a paucity of data needed to calculate various components of the realized costs, especially information on the actual costs of individual control technologies, and data on fuel consumption and fuel economy of new and remanufactured locomotives. We are also extremely limited in our ability to construct a reasonable counterfactual for each component of the cost analysis. For example, to the extent that more efficient line-haul locomotives (through advancements in engine design, cooling systems, etc.) would have been developed and adopted over time in the absence of the rule, the costs of these technologies should not be attributed to the 1998 rule, and the costs of the Tier 1 and Tier 2 standards were less than EPA's ex ante estimate. Due to data limitations and our minimal ability to speculate about what would have occurred in the absence of the rule, most of our assessment is limited to comparing the opinion of one industry expert about how industry complied with the emission standards and some ex post information to what EPA assumed. Finally, examining whether EPA's method for building up the fixed costs of compliance provides an accurate reflection of the true initial cost is outside the scope of our preliminary analysis. We have not investigated the extent to which the 20% manufacturer markup on per locomotive initial compliance cost was appropriate. We are also not able to determine to what extent manufacturers and remanufacturers used average, banking and trading provisions of the rule to meet overall emissions goals at lower cost.

Keeping the above caveats in mind, Table 4 summarizes the findings and the information sources used for each part of the analysis. We found a number of EPA's ex ante estimated or assumed cost factors were fairly similar to the limited ex post empirical data and EF&EE opinion. These assumptions include: locomotive model types, the types of compliance technologies, fixed costs and assembly costs for newly manufactured locomotives, hardware costs of each emission control technology, and annual remanufacture costs per locomotive. However, the assessment identified other areas in which the ex ante estimates differed from the realized per-unit compliance costs over the first decade of the program (2000–2009). First, the initial per-unit costs for remanufactured line-haul locomotives (Tier 0) were likely higher than EPA estimated because the large number of remanufactured engine families certified and the smaller number of units remanufactured increased the fixed cost per locomotive. Second, increased usage rates for some technologies caused variable costs for remanufactured locomotives to be higher than the EPA estimates for most model types. Third, operating

Table 4 Summary of findings.

Components of cost estimate		Source of ex post information	Assessment (compared to ex ante)
Regulated universe			
Types of entities		EF&EE	Reasonable
Number of entities		AAR for all class I EF&EE for switch	New – Higher Remanufactured – Lower Switch – Lower
Methods of compliance			
Types		EF&EE+journal articles	Reasonable
Usage		EF&EE+journal articles	Higher than anticipated for some technologies on some model types
Per locomotive compliance costs			
Direct, one-time	Per locomotive fixed cost	EF&EE+EPA certification data	New- Reasonable Remanufactured – Higher than projected
	Per locomotive variable cost	Hardware Costs: EF&EE+journal articles	Hardware costs: Line Haul – Higher than projected Switch – Inconclusive
		Assembly Costs: EF&EE	Assembly costs: New- Reasonable Remanufactured – Higher than projected
Direct, On-Going	Operating (additional fuel costs)	Fuel price: AAR	Fuel price: higher than projected
		Annual Fuel Consumption: EF&EE for line haul, genset websites for switch	Annual fuel consumption: Line Haul – Reasonable Switch – Lower
		Fuel economy penalty: EF&EE+journal articles, AAR, FRA, manufacturer promotional materials	Fuel economy penalty: Line Haul – Likely higher Remanufactured Switch –Likely higher

(**Table 4** Continued)

Components of cost estimate		Source of ex post information	Assessment (compared to ex ante)
	Maintenance	EF&EE	Reasonable
Indirect			
Opportunity costs			
Total per locomotive cost			Line Haul – Likely higher Switch – Inconclusive (difficult to assess whether alternative technology would have been developed in absence of the rule)
Total costs			Line Haul – Inconclusive Switch – likely lower (very few remanufactured and new units adopted alternate technology)

costs per locomotive (new or remanufactured) imposed by the rule may have been higher than anticipated because actual fuel prices were much higher than EPA assumed. This implies the same percentage fuel consumption penalty could have contributed to higher dollar cost due to higher fuel prices; that is, over the first decade of the program, due to the higher fuel price alone the total per locomotive costs shown in Table 1 could have been 32–50% higher for Tier 0 (line-hauls built 2000–2001 or remanufactured), 22–29% higher for newly built line-haul locomotives over 2002–2004 (Tier 1), and 57% higher for newly built line-haul locomotives over 2005–2009 (first 5 years of Tier 2).[24]

The impact of the higher fuel price may have been offset to some extent by lower fuel consumption and/or lower fuel penalties than anticipated by EPA. The information available to us suggests that manufacturers were able to reduce fuel penalties from the pollution controls by designing more fuel efficient locomotives, but we are unable to quantitatively assess how the additional costs incurred to bring about these fuel efficiency improvements compare to the ex ante fuel economy penalty costs of the rule. In addition, the difficulty in constructing the counterfactual remains. Given the strong incentive for manufacturers to improve fuel efficiency, especially in the face of rising fuel prices as occurred in the 2000s, it is likely that fuel efficiency improvements would have occurred over time in the absence of the regulation. In fact, compared to the counterfactual case in which the locomotive manufacturers would have used the latest technical advances to optimize fuel consumption without regard to NOx and/or PM emissions, it is possible that the fuel economy penalties were higher than EPA's assumptions, which would further increase the fuel costs of compliance. Taken together, these issues suggest that, given the information currently available to us, it is extremely difficult to estimate the extent to which the impact of higher fuel price may have been offset by changes in other components of the fuel cost of the rule. However, even setting aside the operating cost impact of the rule, EF&EE expert opinion and accompanying information about the variable and fixed costs of compliance suggest that the total per locomotive cost was likely higher than EPA's ex ante analysis projected for most new line-haul and especially most remanufactured line-haul locomotives subject to the rule over 2000–2009.

Our ex post assessment of the total cost of bringing line-haul locomotives into compliance with the 1998 rule is inconclusive. This is because total compliance cost depends not only on the per locomotive compliance cost but also on the number of locomotives affected by the regulation. Over 2000–2009, the number

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[24] These percentages are calculated with only 10 years of the fuel and remanufacture costs. Attributing all operating costs over the remaining life of the locomotive to the 1998 rule would be inappropriate given the 2008 revisions to the standards.

of newly built line-haul locomotives was higher but the number of remanufactured line-haul locomotives was lower than EPA's estimate. It is difficult to tease out the extent to which this was driven by an industry reaction to the 1998 rule (or the 2008 rule) or by external factors. If operators found it to be more cost-effective to buy new rather than remanufacture the old units to Tier 0 standards, then it would be inappropriate to conclude that the higher-than-expected sales of new Tier 2 locomotives added to the cost of complying with the standards without accounting for the offsetting savings from lower maintenance and fewer remanufactures over this time period. It is possible that the lower costs due to far fewer remanufactures taking place than anticipated may have outweighed the higher compliance costs from new line-hauls.

The costs of bringing switch locomotives into compliance does not have a major impact on overall costs of the 1998 rule because switchers comprise a relatively minor part of the overall locomotive market. The large supply of old locomotives that can be kept running at low cost limited the sales of new switchers and the remanufacture of older engines over the 2000–2009 period.

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