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Market Effects of Environmental Regulation: Coal, Railroads, and the 1990 Clean Air Act[*]

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Abstract

Title IV of the 1990 Clean Air Act Amendments introduced a cap-and-trade system for sulfur dioxide emissions from electric power plants in the United States. This paper analyzes the effects of that regulatory change on the prices charged by the two railroads that hauled low-sulfur coal east from Wyoming.

We estimate the effect of the tradeable permits regime by comparing prices at affected plants (called "Table A plants") before and after the allowance market took effect, and by comparing prices at those plants to prices at unaffected plants. We show that after Title IV took effect, the delivered price of low-sulfur coal – controlling for the minemouth price of coal and the variable cost of transportation – rose at Table A plants within approximately 1000 miles of the Powder River Basin, and fell at Table A plants located further away. This shift in the delivered price schedule of PRB coal is consistent with a theoretical model of the effects of emissions regulation on demand for low-sulfur coal, and the corresponding optimal pricing strategy by a carrier with market power. Our results suggest that the railroads were able to price discriminate among power plants on the basis of the environmental regulations governing the plants.

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1 Introduction

Title IV of the 1990 Clean Air Act Amendments created a novel market in pollution allowances to control sulfur dioxide emissions from large fossil-fired electric power plants in the United States. This paper analyzes the effects of that new regulatory regime on the market for low-sulfur coal – in particular, on the price schedules charged by the two railroads that haul low-sulfur coal from Wyoming to power plants in the Great Plains and Midwest. The interaction of the allowance market and the coal market sheds light on the degree of market power enjoyed by the railroads, and on the unanticipated effects of market-based environmental regulation.

Because burning low-sulfur coal saves utilities the expense of buying allowances or of installing and operating pollution control equipment, the tradeable permits regime made low-sulfur coal more desirable relative to high-sulfur coal than it was before the regulation. In particular, the allowance market increased the demand for coal from the Powder River Basin in Wyoming (henceforth the "PRB") – the largest deposit of low-sulfur coal in the United States. All coal from the PRB must be carried on one of two railroads: the Burlington Northern Santa Fe (BNSF) and the Union Pacific (UP). Moreover, several coal mines in the PRB are "captive shippers" to one railroad or the other, and some power plants are located on rail lines served by only one of these two railroads. Although railroad rates are overseen by regulators, this situation nonetheless creates the opportunity for market power. We use detailed data on shipments of PRB coal to look for evidence that the two railroads were able to take advantage of this opportunity, and to analyze how delivered coal prices changed as a result.

We start by developing a simple theoretical model to analyze optimal spatial pricing policies with market power. A key feature of the model is that the demand for low-sulfur coal is more elastic under a tradeable permits regime than under an emissions standard, giving rise to price discrimination by a profit-maximizing carrier. The optimal delivered price schedule pivots under the permits regime: prices at nearby plants rise by more than they do at distant plants, and indeed prices may even fall on the extensive margin.

With this model in mind, we estimate the response of delivered coal prices to the change in regulation. The suddenness of the policy shift, and the fact that its first phase covered only a subset of power plants, allow us to identify the effect of the new policy. We measure the effect of the tradeable permits regime in two ways: by comparing prices at affected plants before and after the allowance market took effect, and by comparing prices at affected plants to contemporaneous prices at plants that were not covered by the new regulatory regime. Both comparisons yield similar results. Among plants that were subject to the new regime, delivered prices – controlling for transportation costs and the minemouth price of coal – increased at plants relatively near to the PRB (within approximately 1000 miles), and fell at more distant plants. As a result, the price schedule for plants subject to the new regime shifted, relative to prices at those same plants prior to the allowance market *and* relative to prices at plants that were not subject to the new regime. These empirical findings suggest that the two railroads were able to exercise some degree of market power, practicing price discrimination among power plants on the basis of regulatory regime. Our results are robust to unobserved contract-level heterogeneity and nonlinear price schedules. We also provide evidence in support of our contention that the emissions regulation affected demand for low-sulfur coal. Finally, we show that no similar shift in prices occurred for low-sulfur coal from Central Appalachia, where barge traffic makes coal transportation more competitive.

Although we lack the necessary data to estimate railroads' profits directly, we are able to perform a few "back-of-the-envelope" calculations to gauge the magnitude of their gains under the new regulation. Those estimates suggest that the annual producer surplus enjoyed by the railroads on deliveries to Table A plants increased by about 50% under the new regulation. These gains were on the order of ten percent of the total value of the "regulatory rents" that were captured by the regulated utilities as a whole, where those "rents" are defined as the difference between the market value of the pollution allowances and the variable costs of emissions reductions.

In the next section, we describe the regulatory regimes governing sulfur dioxide emissions and railroad transportation. Section 3 presents our theoretical model. We describe the data in Section 4, and in Section 5 present a series of maps to illustrate the geographic reach of PRB coal over the course of the 1990s. We present our empirical results in Section 6. Section 7 concludes.

2 The regulatory context

2.1 Regulation of sulfur dioxide emissions

Burning coal to produce electricity produces sulfur dioxide (SO_2) as a byproduct, because coal contains sulfur. Propelled into the atmosphere by tall stacks, SO_2 returns to earth as sulfuric acid in precipitation, and thus is a primary component of acid rain. In downwind urban areas, SO_2 contributes to respiratory ailments and morbidity.

Federal regulation of SO_2 emissions by coal-fired electric power plants has undergone three phases. Under the Clean Air Act Amendments (CAAA) of 1970, new generating units (those built after August 17, 1971) were subject to New Source Performance Standards which imposed a maximum allowable rate of SO_2 emissions of 1.2 pounds of SO_2 per million Btus. These "NSPS" units were free to meet the emissions standard in whatever way they chose. Some managers chose to install a flue gas desulfurization device, or "scrubber" – a building-sized piece of equipment that removes sulfur dioxide from the flue gases, usually by reaction with a limestone solution. The main alternative to scrubbing is to use low-sulfur coal.

In the second phase of federal regulation, under the Clean Air Act Amendments of 1977, new sources were required to remove a certain percentage of SO_2 from flue gases – tantamount to requiring scrubbers. Because this technology-based regulation provided no incentives to burn low-sulfur coal, this group of generating units will not figure in our analysis.

Finally, Title IV of the 1990 Clean Air Act Amendments introduced a novel market-based policy to control SO_2 emissions from existing fossil-fueled electric generating units.[1] (Throughout this paper, the terms "allowance market" and "tradeable permits regime" both refer to the Title IV program.) Each generating unit in the program is given permits, or "allowances," which allow it to emit a certain amount of sulfur dioxide in a given year. A unit that emits more sulfur dioxide than is covered by its allowance allocation can buy permits from other generating units. A generator that emits less sulfur dioxide than its allocation, either by using low-sulfur coal or operating a scrubber, may sell its surplus allowances or bank them for future use or sale.

Phase I of the allowance trading program started in 1995 and lasted through 1999. It applied directly to the 263 largest, dirtiest existing generating units, located at 110 power plants – those units that had been "grandfathered" out of prior federal standards on new sources. These units are known as "Table A" units, after the table of the legislation that listed them. Phase II of the program started in 2000 and extended the market to essentially every fossil-fired power plant of reasonable size. Compliance with the program has been perfect, largely due to the presence of a "truing-up" period in the first few months of each year (in which utilities had time to buy allowances needed to cover the previous year's emissions) and the threat of a $2000-per-ton fine for violations.

Coexisting with this federal regulatory structure is a patchwork of emissions standards imposed by state governments, who must ensure that separately mandated ambient air quality standards are met. Since power plants are a prominent source of air pollution, they are natural targets of state regulation. In most cases, state regulations are less stringent than the NSPS standard. On

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[1] Ellerman et al. (2000) provide a comprehensive analysis of Phase I of the tradeable permits program.

the other hand, they are often binding for generating units built before the 1970 CAAA took effect.

Emissions regulations apply at the level of the generating unit – *i.e.*, a individual steam-powered turbine, usually associated with a particular boiler that burns coal or other fuels to produce the steam. A single power plant typically encompasses multiple generating units, subject to regulations of different form and stringency. Coal deliveries, however, are reported for plants, not individual units. Since our observations in the empirical analysis are at the plant level, we refer to plants that house at least one Table A unit as "Table A plants." Throughout our analysis, we will focus on these plants as the group that was targeted and particularly affected by the new regulatory regime.[2] Because each plant comprises multiple units, however, Title IV did *not* represent a simple shift from no regulation to regulation for Table A plants. Rather, the regulatory regime changed from a prescriptive emissions standard to a tradeable permits system. A Table A plant might well have consumed low-sulfur coal to comply with emissions regulations, even before the allowance market began.

2.2 Regulation of railroad transport

The current regulatory framework under which railroads operate was established by the Staggers Rail Act of 1980. The Staggers Act allowed railroads without "market dominance" to set whatever rates they chose, and established guidelines that allowed rates to be 170-190 percent of variable costs without being evidence of market dominance. The Act also permitted railroads to establish contract rates with their shippers to a greater extent than was previously allowed.

While railroad regulation constrains the railroads' ability to exercise market power, evidence from rate cases suggests that they are still able to do so. At least one formal complaint has been brought against railroads over the transportation rates for PRB coal: the public utility of San Antonio initiated a rate case, objecting to an increase in transportation rates charged by Burlington Northern. The case was found in favor of the railroad. That the utility found it worthwhile to lodge a formal complaint, and that the regulatory body allowed the railroad ample scope for rate-setting, both provide evidence that railroads are able to exercise some degree of market power.

The threat of entry (itself subject to regulatory approval) also constrains the degree of market

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[2] We deliberately omit from this "treated group" the plants that lacked Table A units but included units that voluntarily participated in Phase I through the so-called "substitution and compensation" program. As Montero (1999) has shown, the plants that participated voluntarily were those that would likely have reduced emissions in any case. Because of this adverse selection problem, we group those voluntary participants in with the other non-Table A plants.

power the railroads may wield. In 1998 the Dakota, Minnesota & Eastern Railroad petitioned the Surface Transportation Board for approval to construct a 280-mile spur connecting the PRB with the existing DM&E line in Wasta, South Dakota. Their application was initially approved in 2001, but as of the spring of 2004 remained held up by legal roadblocks thrown up by its opponents, who include ranchers and Native Americans living along the proposed route (and less visibly, one may suppose, the UP and BNSF railroads) (Gallagher 2004).

3 Regulation, market power, and the price of low-sulfur coal

In this section, we start by developing a model of the demand among power plants for low-sulfur coal. We focus on the effects of two forms of emissions regulation. Relative to an emissions standard, a tradeable permits regime has two effects on demand for low-sulfur coal: it raises willingness to pay, and makes demand more elastic. We then use that demand model to derive delivered price schedules as a function of the distance from the source of low-sulfur coal. As a benchmark, we examine the perfectly competitive case. If low-sulfur coal is abundant and competitively supplied, its delivered price will be based entirely on marginal costs of production and transportation and therefore will not change as a result of environmental regulation *per se*. In contrast, a carrier with market power would charge a markup over marginal cost, creating a wedge between delivered price and delivered cost. In our model, the profit-maximizing delivered price schedule can be characterized as a two-part tariff, with the railroad charging a positive "fixed fee" plus a (constant) rate per unit distance. The railroad's optimal response to the introduction of an allowance market is to raise its "fixed fee" and reduce the transportation rate.

3.1 A model of low-sulfur coal demand

How much fuel a plant wishes to buy depends on its output of electricity. In turn, a plant's electricity output depends directly on its marginal costs relative to those of other plants supplying to the electricity grid. A chief component of marginal cost is fuel costs. Thus demand for fuel is downward-sloping, at least over some range. In the absence of regulation, demand for low-sulfur coal would be a segment of this derived demand for fuel. Since multiple sources of coal exist and since many plants can also burn other fuels, such as petroleum, an unregulated plant would not buy low-sulfur coal if it is more costly than alternative fuels. By limiting emissions or rewarding abatement, regulatory restrictions on sulfur dioxide make low-sulfur coal a more attractive fuel, relative to high-sulfur coal.

We adopt a constant-elasticity specification for demand of the form $p(q) = \alpha \left(\frac{q}{\beta}\right)^{-\frac{1}{\theta}}$ for $q \geq \beta$. Here α represents the reservation price, above which the plant would not buy any low-sulfur coal. In the absence of regulation, this choke price would simply be the price of the least-cost alternative fuel. Because the cost of alternative fuels varies with location, the reservation price for low-sulfur coal will also vary among plants by their locations. To keep the model simple, we assume that the alternative fuel for every plant is high-sulfur coal. Under regulation, the choke price also depends on the stringency of regulation and the costs of alternative means of compliance, as discussed below. For prices above α, consumption of low-sulfur coal is zero. At the choke price, consumption jumps to some minimum level β. (In the no-regulation case, this would represent the total amount of fuel the plant would burn if the price of fuel were α.) Below the choke price, quantity increases as price falls, along a demand curve with constant elasticity $-\theta$.[3] The choke price, minimum consumption level, and elasticity all vary with the type of regulation, as discussed in the next section.

The constant-elasticity functional form yields a delivered price schedule that is linear in distance, which is convenient for the empirical analysis (Greenhut and Greenhut 1977). Moreover, it accords with the observed regularity from the data that delivered price rises more rapidly than transportation cost.[4] In a sense, we are calibrating the choice of functional form to the initial conditions we observe in the data. We then let the theory tell us what should be the consequences of emissions regulation.

3.1.1 Emissions standard

Consider first a prescriptive emissions standard, specifying a maximum allowable emissions for each individual generating unit. An emissions standard increases demand for low-sulfur coal at each plant, relative to what it would be in the absence of regulation; the magnitude of this increase depends on the stringency of the regulation and on the costs of alternative means of abatement, such as scrubbers.[5] In particular, a plant's willingness to pay for each unit of low-sulfur coal increases

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[3] A downward-sloping demand curve at the plant level is necessary to ensure an upward-sloping delivered price schedule. In an earlier version of this paper, we assumed that plants made a binary choice whether or not to buy coal from 0. In that case, the profit-maximizing carrier from 0 sets delivered price equal to the delivered price of coal from the other origin – yielding prices that are lower for plants further away. Additional constraints on the firms' behavior are needed to yield an upward-sloping price schedule.

[4] Constant elasticity of demand is a sufficient (although not a necessary) condition for delivered prices to rise faster than the transportation cost. See Greenhut, Hwang, and Ohta (1974) and Greenhut and Greenhut (1977).

[5] We assume that scrubbing costs are distributed randomly among plants at different locations. Although any particular plant may find it advantageous to install a scrubber, other nearby plants will prefer to buy low-sulfur coal

by the marginal cost of the avoided abatement.

We can represent this in our simple model by writing the inverse demand function as follows

$$p_s^i(q) = \begin{cases} \alpha_s^i \left(\frac{q}{\beta_s^i}\right)^{-\frac{1}{\theta_s}}, & q \geq \beta_s^i \\ 0 \text{ otherwise.} \end{cases} . \tag{1}$$

The choke price α_s^i equals the cost of high-sulfur coal, *plus* the marginal cost of abatement if the plant were to just meet its emissions standard without buying any low-sulfur coal. The minimum consumption level β_s^i represents the amount of low-sulfur coal the plant would buy at the choke price. The more stringent is the emissions standard facing the plant, the higher will be α_s^i and the lower will be β_s^i, all else equal.[6]

3.1.2 Allowance market

Now consider the effects of a tradeable permits regime. We assume that the regulation is binding, meaning that the total number of pollution allowances is less than emissions would have been in the absence of regulation. Because allowances are scarce, they will have a positive price. We assume that the allowance market is competitive, so that regulated plants take the permit price as given. Thus an allowance market raises willingness-to-pay for low-sulfur coal, by an amount equal to the price of a permit times the difference in sulfur content between low-sulfur coal and the best alternative fuel. Moreover, this increase in demand is constant across a large range of quantities, for any given plant. For simplicity, we normalize the difference in emissions between high- and low-sulfur coal to be 1. Thus the compliance cost savings from substituting a unit of low-sulfur

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(or, if possible, buy tradeable permits). Moreover, once a plant has installed a scrubber at a given unit, it will never be economical for it to burn low-sulfur coal at that unit. Hence we may ignore plants with scrubbers in constructing delivered price schedules for low-sulfur coal. Keohane (2003) examines scrubbing costs and choices among power plants subject to various regulatory regimes in the U.S.

[6] Note that a plant whose cheapest fuel was low-sulfur coal would buy it exclusively, regardless of regulation; its behavior would be unaltered by an emissions standard or an allowance market. We could represent this case in the model by specifying the segment of the demand curve corresponding to prices for which low-sulfur coal is the cheapest fuel. Doing so would complicate the model, but would not affect the basic conclusions that stem from a comparison of the two regulatory regimes considered here.

The main new prediction from such a model would be that the effects of both types of emissions regulation (relative to the no-regulation case) should be greater for plants far enough away from the low-sulfur coal source that they would not buy coal in the absence of regulation. Indeed, in the region closest to the low-sulfur coal source the delivered price schedules would be completely unaffected by regulation. By the same token, the *difference* in demand under the two regulations should also be greatest relatively far away from the coal source. Our data provide some evidence confirming this prediction. We focus, however, on the simple comparison between emissions standards and a tradeable-permits regime.

coal for a unit of high-sulfur coal is simply equal to the allowance price, which we denote by z.[7]

Let ρ be the difference in price between low- and high-sulfur coal at a particular plant; this price difference varies with location, because of differences in transportation costs, and need not be positive. If $\rho > z$, the plant would not buy any low-sulfur coal, since buying permits is a perfect substitute for abating emissions through fuel switching. On the other hand, if $\rho < z$, the plant would substitute low-sulfur coal for high-sulfur coal to the greatest extent possible, since it can sell the excess permits for more than the cost of abatement.[8] Hence demand for low-sulfur coal is highly elastic. In our model, we assume that it is less than infinitely elastic, however, since burning low-sulfur coal in boilers designed for high-sulfur coal is costly. Because PRB coal has a lower heat content, coal blending typically also reduces the "heat rate" or operating efficiency of a boiler – suggesting that there are marginal costs to blending.

Thus the inverse demand curve for plant i under an allowance market can be written as follows:[9]

$$p_m^i(q) = \begin{cases} \alpha_m^i \left(\frac{q}{\beta_m^i}\right)^{-\frac{1}{\theta_m}} + z, \quad q \geq \beta_m^i \\ \text{0 otherwise.} \end{cases} \tag{2}$$

The crucial feature of this model, which we explain in more detail below, is that $\theta_m > \theta_s$. The cost of blending low-sulfur coals is reflected in the parameter α_m^i. Note that the premium z is additive: the reservation price (maximum willingness-to-pay) is now $\alpha_m^i + z$. Figure 1 illustrates a representative demand curve for a given plant governed by tradeable permits, along with the demand curve for the same plant under an emissions standard.

This model embodies two crucial differences between the demand for low-sulfur coal under an allowance market and that under an emissions standard. First, the permit price z enters additively

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[7] In reality, of course, the emissions from alternative fuels will vary with the fuel. The effective premium a plant will be willing to pay per ton of low-sulfur coal depends on the relative sulfur contents per ton (or more accurately per unit of heat content). For our purposes, however, the key feature of an allowance market is that it produces elastic demand for low-sulfur coal at the plant level. That would be true even if the premium varied among plants.

[8] If the plant has abatement options with marginal costs below the price premium ρ, the plant will avail itself of them before replacing all of its high-sulfur coal with low-sulfur coal.

[9] Note that the demand function no longer has constant elasticity. Instead, elasticity as a function of price is now

$$e = \frac{\theta p}{p - z},$$

and hence is greater at higher price levels (lower quantities).

Our results hinge on what happens to θ in particular rather than to elasticity. However, in the spirit of the pure constant-elasticity case and for the sake of consistency in exposition, we shall continue to refer to θ as if it were the elasticity; in particular, we shall refer to an increase in θ as an increase in elasticity. In focusing on θ, we have in mind the effect of the emissions market on demand, *aside* from the introduction of an emissions price.

into the inverse demand function, raising willingness-to-pay. Second, demand is more elastic under an allowance market than under an emissions standard. A plant regulated by a standard lacks the option to buy permits, and must meet its standard regardless of cost. If its other abatement options (*e.g.*, scrubbing) are very costly, and thus offer poor substitutes for low-sulfur coal, such a plant may have a very high willingness to pay for small amounts of low-sulfur coal. Once a plant consumes enough coal to meet its standard, however, it has no further incentive to buy low-sulfur coal.

A tradeable permits system, in contrast, rewards any marginal reduction in emissions: every unit of pollution abated saves the plant the price of a permit. Yet the marginal cost savings from emissions reductions are capped by the permit price. Hence the willingness-to-pay for low-sulfur coal is nearly constant over a large range of quantities. Moreover, because any reduction in emissions is rewarded, the menu of abatement options expands. A plant used to burning high-sulfur coal may buy coal with intermediate sulfur content, reducing emissions at fairly low cost; this is not an option for plants subject to a more stringent standard. More abatement options means more substitutes for low-sulfur coal, and hence more elastic demand.

3.2 The delivered price of low-sulfur coal

To analyze the delivered prices a carrier would charge for low-sulfur coal, we employ a straightforward model of spatial pricing in the spirit of Hoover (1937) and Greenhut and Greenhut (1972).[10] We imagine a population of coal consumers (power plants) distributed at various distances from a single source of low-sulfur coal. Because we are interested here in market power in transportation, we assume that coal extraction is competitive. The price of a ton of coal at the minemouth equals the marginal cost of extraction, which we assume to be constant and equal to c.[11] The average cost of transportation is also assumed to be constant, and given by t. Thus the cost of delivering one unit of coal to a distance x from the origin is $c(x) = c + tx$.

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[10] The literature on spatial pricing typically refers to it as "spatial price discrimination" (e.g., Greenhut and Greenhut 1972). Strictly speaking, however, the variation in price across locations in these models is driven by differences in transportation cost rather than demand. We reserve the term "price discrimination" for the case where the railroad charges different markups over marginal cost in response to differences in demand elasticity among plants.

[11] Note that we set aside issues of scarcity and an increasing "user cost" (Hotelling 1931). Low-sulfur coal in the PRB is in abundant supply, and it seems implausible that scarcity could have increased significantly over the time period studied here. In particular, several mines in the PRB fell dormant during the 1990s, as earlier long-term contracts expired and prevailing minemouth prices fell to roughly \$5/ton. Were prices to rise by even a few dollars per ton, those mines would resume operation.

3.2.1 Perfect competition

As a benchmark, suppose that transportation were perfectly competitive. In this case, the delivered price of coal, as a function of distance from the origin, just equals marginal cost: $P(x) = c + tx$. Thus perfect competition results in f.o.b. pricing, as in the model of Greenhut and Greenhut (1972). Emissions regulation in this case leads some plants that were burning only high-sulfur coal to switch fuels, extending the geographic range of low-sulfur coal eastward. Since coal transportation remains competitive, however, its price must equal delivered cost. Average delivered price will rise because coal is being delivered greater distances than it used to be, but at any given location, delivered price at that location is no different from what it was, or would have been, before the regulation.

3.2.2 Market power in transportation

Now suppose that transportation of low-sulfur coal is controlled by a carrier with monopoly power. Given the market position held by the two railroads in the Powder River Basin, and the fact that they are likely to observe the same information about demand and supply shocks in the low-sulfur coal market, we might expect cooperation (at least implicit) to be fairly easy to sustain. The qualitative effects of regulation on the delivered price schedule would be identical under an assumption of Cournot competition. In the current context – two firms with predetermined capacities competing on price – the Cournot assumption would seem to be the natural alternative model of producer behavior (Kreps and Scheinkman, 1983).

Emissions standard The monopoly carrier chooses price and quantity at each location to equate marginal revenue and marginal cost. Thus its price-cost margin at each location is inversely proportional to the absolute value of the elasticity. Solving for price yields price as a function of distance – *i.e.,* the "delivered price schedule" (DPS) – for plants subject to the emissions standard:

$$P_s^* (x) = \frac{\theta_s}{\theta_s - 1} (c + tx) , \tag{3}$$

where s denotes the standard regime. Note that θ_s must be greater than 1 for the monopoly solution to be given by equation (3); we shall assume that this condition is met.[12] Hence the price

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[12] In general, a monopolist faced with an *inelastic* constant-elasticity demand curve would charge an infinite price and sell an infinitesimal quantity. In this model, that outcome is precluded by the assumption of a choke price. Instead, for $\theta_s \leq 1$ the monopolist would choose the corner solution, setting the low-sulfur coal price equal to the choke price at every location. In other words, the monopolist would practice perfect price discrimination. The outcome in this case would be identical to the case of perfectly inelastic (*i.e.*, unit) demand. See footnote 3.

at the origin ($x = 0$) is greater than the minemouth price, and the delivered price rises more rapidly with distance than does the delivered cost. Note that price and quantity at one location are in principle independent from price and quantity everywhere else. If marginal cost rises smoothly with distance, however, the price schedule can be written as a function of x, as in equation (3). Indeed, the DPS is equivalent to a two-part tariff in which every plant is charged a fixed fee $\frac{\theta_s}{\theta_s - 1}c$ per unit of coal regardless of distance, plus a variable rate per unit of distance equal to $\frac{\theta_s}{\theta_s - 1}t > t$. Figure 2 illustrates the delivered price schedule for particular cost and demand functions.[13]

In other settings, this form of spatial pricing – in which price rises more quickly with distance than does cost – would raise the possibility of arbitrage: plants nearby would have an incentive to buy coal and then ship it to more distant plants. In this case, however, resale is effectively barred by the nature of the product and the market position of the carriers. The railroads that set prices also provide the transportation; a power plant could not simply redirect the shipment to a more distant plant and pocket the difference in price. Coal is delivered on specialized coal hopper cars and unloaded into vast piles adjacent to the plant. Arbitrage would require a power plant to load the coal onto trucks, a costly means of transporting coal over long distances. Hence resale seems prohibitively expensive.

Allowance market An allowance market induces a shift in demand for low-sulfur coal that is endogenous to the output decision of the railroad. An increase in the supply of low-sulfur coal would decrease demand for allowances, lowering their price. Hence increasing output at an individual location lowers willingness-to-pay not only at that location, but at every plant subject to the allowance market. We assume that power plants take allowance prices as given. The carrier, on the other hand, takes this effect into account, since its decisions affect the whole market. In particular, a change in the permit price z due to an increase in output at a given plant affects revenues from every plant. Marginal revenue is now $MR = p + \alpha_m^i \beta_m^{\frac{1}{\theta}} \left(\frac{\partial q^{-\frac{1}{\theta}}}{\partial q} \right) q + \frac{\partial z}{\partial q} Q$,where Q is the total low-sulfur coal delivered to all locations.

Define $\eta \equiv -\frac{\partial z}{\partial Q} \frac{Q}{z} > 0$, a measure of the sensitivity of the price of pollution permits to a change in low-sulfur coal consumption. Note that $\frac{\partial z}{\partial q} = \frac{\partial z}{\partial Q}$ and that $\frac{\partial z}{\partial Q} < 0$: greater low-sulfur coal consumption diminishes demand for permits, driving their price down. The parameter η is

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[13] A peculiarity of the constant-elasticity functional form in this setting is that the choke price (denoted α in our model) plays no role in determining the profit-maximizing price. The reason is that α produces the same proportional increase in marginal revenue as in demand, at every quantity. Thus the marginal willingness-to-pay associated with any given marginal revenue is independent of the choke price. Of course, it is still true that the choke price will affect demand. The greater the cost of alternative fuels, the more low-sulfur coal a plant will buy at any given price.

akin to an elasticity: a 1% increase in low-sulfur coal consumption corresponds to an η% increase in the permit price. We show in a footnote that η will depend on the marginal cost of alternative abatement methods aside from low-sulfur coal – *e.g.*, scrubbing – and the amount of abatement achieved through plants switching to low-sulfur coal.[14] The steeper is the marginal abatement cost curve of alternative abatement, and the larger the share of total abatement due to low-sulfur coal, the larger is η. Since η depends on total low-sulfur coal consumption Q, it is approximately constant with respect to the output choice at any given location, and we treat it as constant.

The allowance market leads to the following delivered price schedule:

$$P_m^*(x) = \left(\frac{\theta_m}{\theta_m - 1}\right)(c + tx) + \left(\frac{\eta^*\theta_m - 1}{\theta_m - 1}\right) z^* \,, \tag{4}$$

where η^* and z^* denote the values of η and z in the profit-maximizing solution. Two differences stand out, relative to the delivered price schedule (3) corresponding to the emissions standard. First, because demand is more elastic under the allowance market than under a standard, $\frac{\theta_m}{\theta_m - 1} < \frac{\theta_s}{\theta_s - 1}$. The increase in elasticity among plants governed by the tradeable permits regime lowers the railroad's optimal price-cost margin to those plants. Hence the delivered price schedule is flatter: it rises more slowly with distance.

Second, the permit price induces a vertical shift in the demand curve – *i.e.*, a change in the "fixed fee" charged by the railroad. From equation (4), a necessary condition for the fixed fee to be higher under the allowance market is evidently that $\eta^* > \frac{1}{\theta_m}$. If the allowance price is sufficiently responsive to low-sulfur coal consumption at this point, then profits are increasing in the price of allowances. Hence the railroad has an incentive to restrict output in order to drive up the permit price.

In the appendix, we characterize more precisely the conditions under which the fixed fee increases. The argument considers the railroad's incentives in the situation in which the fixed fee is the same as that under the emissions standard. We show that the fixed fee increases under the

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[14] Let A denote abatement achieved through means other than low-sulfur coal from the PRB –*e.g.*,, scrubbing or other sources of low-sulfur coal. Define a marginal cost function $MC(A) = kA^\gamma$, with $\gamma > 1$. In equilibrium $MC(A) = z$. Note that this functional form implies a constant elasticity of abatement w.r.t. the permit price:

$$-\frac{dz}{dA}\frac{A}{z} = \gamma.$$

Moreover, given that overall abatement is fixed under a cap-and-trade system, a one-unit increase in low-sulfur coal consumption yields a one-unit reduction in the amount of other abatement required. Hence $\eta = -\frac{\partial z}{\partial Q}\frac{Q}{z} = \gamma\frac{Q}{A}$. The size of η relative to γ depends on the relative shares of abatement done by low-sulfur coal and by other means. For example, if low-sulfur coal accounts for a third of total abatement, then $Q = \frac{1}{2}A$: a 1% change in Q represents a $\frac{1}{2}$% change in A and hence leads to an $\frac{1}{2}\gamma$ % change in z.

allowance market for a wide range of η. In particular, a sufficient condition is that η lies between $\frac{1}{\theta_m}$ and an upper bound that is strictly greater than one and grows with the size of the market.

Intuitively, the endogeneity of the permit price gives the railroad an added incentive to create "artificial scarcity" in the coal market in order to drive up the price. In the usual monopoly-pricing scenario, the monopolist weighs an increase in output against the reduction in price that will result. The allowance market magnifies the effect of output on price. Because total emissions are fixed by the number of allowances, any increase in low-sulfur coal consumption must lead to a corresponding decrease in demand for allowances, driving their price down. This decrease in the allowance price reduces the incentive to reduce emissions, and hence reduces willingness-to-pay even further. By the same token, a reduction in output leads to a greater increase in willingness-to-pay than it would if allowance prices were exogenous. This magnifying effect, however, requires that allowance prices are sufficiently sensitive to low-sulfur coal consumption. In the limit, as η vanishes, the permit price becomes exogenous, and the feedback effect disappears.[15]

Because the fixed fee increases while the slope of the price schedule falls, the delivered price schedule under an emissions market can pivot relative to the schedule under an emissions standard. In this case, price increases under the allowance market for plants relatively close to the low-sulfur coal origin, and falls further away. Figure 3 provides an illustration. Such a pivot will occur if $\eta\theta_m$ is not too much greater than one.

Hence the form of regulation matters for the shape of the delivered price function. Under an allowance market, delivered prices will be higher for relatively nearby plants, but will rise more slowly with distance than they would under an emissions standard. That is, the railroad will charge a higher fixed fee but a lower rate per unit distance.

4 Data

We use three types of data: records of coal deliveries to power plants, plant-level information about coal transportation, and industry surveys of minemouth prices. Data on coal deliveries are taken from Form 423 of the Federal Energy Regulatory Commission (FERC), the "Monthly Report of

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[15] Note that in this model, an *exogenous* increase in willingness-to-pay would drive delivered price down. This is a simple consequence of the form of spatial pricing. The delivered price of low-sulfur coal rises more rapidly than the transportation rate, because for a constant-elasticity demand function the marginal revenue curve is flatter than the demand function. Hence a given increase in marginal cost (*i.e.,* from a nearer plant to a more distant one) translates into a more-than-proportional increase in price. By the same reasoning, when marginal revenue shifts up by a given amount, as it would under an exogenous permit price, the new price of coal that results is *lower* than the original one, since the demand curve falls faster than does marginal revenue.

Cost and Quality of Fuels for Electric Power Plants." The form must be filed by electric generating units with capacity of at least 50 megawatts. The form records all fuel deliveries received by each plant in each month. For each delivery, we know the price of the coal (in cents per million Btus); the quantity delivered; selected characteristics of the coal, including its heat, sulfur, and ash contents; the coal mine of origin; and the nature of the coal contract. In this paper, we focus on what FERC categorizes as "spot market" deliveries: deliveries under short-term contracts less than one year in length. These deliveries are much more likely to be sensitive to changes in policy regimes than are deliveries under long-term contracts, and thus present a cleaner test of the effect of the allowance market. Approximately one-third of the deliveries of PRB coal are spot transactions.

Distances between the Powder River Basin and each power plant – actual distances traveled by rail, not "as the crow flies" – were compiled from state-level maps and railroad atlases, along with the Platt's Coal Map produced by Financial Times Energy (Keohane 2003). We also know each plant's transportation options: which railroads (if any) serve it, and whether it is served by barge and/or truck.

To account for changes in the variable costs of railroad transportation, we use the Railroad Cost Adjustment Factor computed quarterly by the Association of American Railroads. The measure we use, which is used by the Surface Transportation Board in assessing railroad rates, is essentially an index of input prices (fuel, labor, and so on) adjusted for a measure of productivity. We transform it so that the base period is January 1990, and deflate the index by the intermediate-goods producer price index so that it reflects changes in real costs. This real cost index falls smoothly over the decade considered here, from its normalized value of one in January 1990 to 0.65 in December 1999.

Although we have only an index rather than a direct measure of cost, we can recover an estimate of the cost in the base year, if we are willing to assume that the margin over variable cost is constant over time. Suppose that the "true" price schedule (at time τ) is given by

$$p_\tau = \bar{p} + t_\tau x + mx,$$

where p is the delivered price, $\bar{p}$ is a "fixed fee" in a two-part tariff, x is distance, t_τ is variable cost at time τ, and m is the margin over variable cost. We lack data on t, however, and instead run the following regression:

$$p_\tau = \beta_0 + \beta_1 \nu_\tau x + \beta_2 x + \varepsilon_\tau,$$

where $v_\tau = \left(\frac{t_\tau}{t_0}\right)$ is a cost index calculated relative to the base period 0. At $\tau = 0$, $v_\tau = 1$

by construction and hence $\hat{\beta}_1 + \hat{\beta}_2 = t_0 + m$ in expectation, with $E\left(\hat{\beta}_0\right) = \bar{p}$. At $\tau = s > 1$, in expectation $\hat{\beta}_1 v_s + \hat{\beta}_2 = t_s + m$. Substituting for $\hat{\beta}_2$ and solving yields $\hat{\beta}_1 = \frac{t_s - t_0}{v_s - 1} = t_0$ in expectation.

Finally, our minemouth coal prices come from *Coal Outlook*, an industry newsletter which conducts and publishes bimonthly surveys of coal company staff. Thus these data represent the average spot prices the coal mines report receiving over a given two-week period. The data, plotted in Figure 4, are revealing. Minemouth prices for PRB coal at the low range of heat content rose somewhat in early 1994, from roughly \$3.50 to \$4.00 per ton. They then fell gradually from mid-1995, reaching \$3 in mid-1997 before fluctuating around \$3.50 through the end of the decade. The advent of the allowance market, and the corresponding increase in the demand for low-sulfur coal, did not lead to any lasting increase in the minemouth price of PRB coal. If the coal mines were able to capture substantial gains from the allowance market, they did so through advances in extraction technology, not through increases in coal prices.

5 The geographic extent of low-sulfur coal

Coal-fired power plants are distributed throughout the country, but are concentrated in the Midwest and particularly along the major river systems of the Mississippi and Ohio Rivers and the shores of the Great Lakes. This historical pattern of distribution was determined by the abundant water to run in cooling systems, the bituminous coal deposits in the Illinois Basin and in Central Appalachia, and the growth of Midwestern population centers. Figure 5 shows the distribution of Table A plants and those governed by the federal NSPS standards. It also identifies the three major coal regions in the United States, showing the differences in coal characteristics among them. PRB coal is very low in sulfur, but also has a much lower heat content than coal from the other major coal regions.

As a qualitative means of assessing the impact of the tradeable permits regime on the market for low-sulfur coal, we present a series of maps to illustrate the changes over time in the geographic reach of coal from the PRB.[16] Our measure of geographic range is the cumulative percentage of PRB coal: the total amount of PRB coal delivered in that year to all plants west of that location, divided by the total amount of all coal delivered to the same set of plants in that year.

The panels in Figure 6 display the cumulative percentage of PRB coal consumed by Table

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[16] These maps echo an earlier effort, with necessarily less complete data, by Ellerman and Montero (1998).

A plants in 1990, 1995, and 1999.[17] (Recall that Title IV took effect in 1995.) Darker regions correspond to higher percentages. The change from 1990 to 1999 is dramatic. In 1990, the maximum cumulative percentage was less than 50%: that is, no single plant even received more than half of its coal from the PRB. East of the Mississippi River, the cumulative percentage falls below 30%; the 10% line does not even reach into Indiana. By 1995, the first year of the tradeable allowances program, PRB coal has expanded eastward considerably. Roughly 60% of all coal deliveries west of the Mississippi are now PRB coal. By 1999, the 50% line reaches into Indiana and Alabama. Even more notable is the increased intensity of PRB coal consumption. West of the Mississippi, roughly eighty percent of all coal is PRB coal by 1999, and the westernmost plants consume PRB coal almost exclusively.

A natural "control group" for comparison is the set of NSPS power plants, shown in Figure 7. Since the regulatory regime for these plants did not change during the 1990s, their consumption of PRB coal was driven by factors other than the allowance trading program. In 1990, NSPS plants consumed a much higher proportion of PRB coal than their Table A counterparts, with the westernmost plants buying over 80% of their coal from the PRB. Over the region where PRB coal consumption was only 10% for Table A plants (westward from Illinois and Mississippi), the cumulative percentage for NSPS plants was 60%.

While the initial extent of PRB coal was greater among NSPS plants, the subsequent increase during the 1990s was much less dramatic. In 1990, no Title IV plants were consuming more than 50% PRB coal; by 1995, the 70% line is almost as far east for Title IV plants as for NSPS-D plants. From 1995 to 1999, the eastward shift in the cumulative share of PRB coal at NSPS is overtaken by the changes among Table A plants, at least at the high end of PRB shares. Thus the introduction of the tradeable permits program coincided with a dramatic eastward expansion in the range of PRB coal. Moreover, the spread of low-sulfur coal appears to have been more rapid for plants that were subject to the new regulatory regime.

6 The effect of Title IV on delivered coal prices

We use a series of regressions to estimate the delivered price schedule for coal from the PRB, and to analyze how that price schedule changed in response to the allowance market. We employ two distinct tests. First, we compare prices at Table A plants before and after Title IV took effect, and

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[17] These maps use all delivery data, not just spot-market coal.

analyze how the observed price changes vary with distance from the PRB. Second, we control for coal prices at plants that were not regulated by the new regime, in order to compare prices after Title IV at newly regulated plants with contemporaneous prices at plants outside of the trading program.

Under Title IV, the implicit fixed fee charged by the railroads rose substantially for Table A plants, while the transportation rate per ton-mile fell. The net effect was that delivered coal prices rose for the plants closest to the PRB, while they fell for plants further away. This shift remains significant when we control for contemporaneous prices to non-Table A plants. We find the same effect as well when we allow for unobserved heterogeneity at the level of short-term contracts, and when we introduce more flexible functional forms. The results are consistent with the model of price discrimination we developed in Section 3, and suggest that BNSF and UP were able to exercise market power in hauling coal from the PRB.

6.1 Econometric framework

In the theoretical model of Section 3, we characterized the optimal price schedule as implicitly replicating a two-part tariff. Accordingly, in our empirical analysis we model the delivered price to a given power plant as an affine function of the distance by railroad from the plant to the Powder River Basin. The dependent variable in our regressions is the net real delivered price of coal: the price at the power plant, minus the contemporaneous minemouth price published in *Coal Outlook*, expressed in 1995 dollars per ton.[18]

Our basic regression equation is the following, where p_{ijt} denotes the net real delivered price at time t under contract i to plant j.

$$\begin{aligned} p_{ijt} \;=\; & \beta_{00} + \gamma_{00} \cdot DIST_j + \psi \cdot DIST_j \times COSTINDX_t + \\ & \beta_{01} \cdot TITLE\,IV_t + \gamma_{01} \cdot DIST_j \times TITLE\,IV_t + \\ & \beta_{02} \cdot TITLE\,IV_t \times TABLE\,A_j + \gamma_{02} \cdot DIST_j \times \; TITLE\,IV_t \times TABLE\,A_j + \\ & \boldsymbol{\beta} \cdot COAL\,CHARS_{ijt} \; + \boldsymbol{\gamma} \cdot PLANT\,CHARS_j \; + \text{month dummies} + \varepsilon_{ijt} \end{aligned} \tag{5}$$

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[18] Form 423 reports the data in nominal cents/mmBtus; we use the reported heat content of the coal to convert the price into dollars per ton, and then deflate it by the monthly intermediate-goods Producer Price Index.

We use the net rather than the gross delivered price to control for changes in the price of minemouth coal. By subtracting out the minemouth price from the gross delivered price, we also account for Wyoming state severance taxes (levied on coal mines), which fell from 8.5% to 7% during the sample period.

Note that while the delivered price schedules derived in Section 3 (*e.g.,* equation (3) give equations for the full price, the two-part tariff interpretation also holds if the minemouth price c_0 is subtracted from the delivered price.

Three variables (and their interactions) are of primary interest. $DIST_j$ is the rail distance (in miles) from the PRB to the power plant. Its coefficient is an estimate of the transportation rate per ton-mile. We control for variable cost by including the cost index discussed above times the rail distance. $TITLE\,IV_t$ is a dummy variable that equals 1 after Title IV took effect.[19] In the full sample, we include a dummy for $TABLE\,A_j$ indicating whether a plant has a unit listed on Table A and is thus required to participate in the allowance market.

The vector $COAL\ CHARS_{ijt}$ includes the sulfur, heat, and ash contents of the coal. These characteristics are interacted with the dummy variables $TITLE\,IV$ and $TABLE\ A$ to allow the implicit prices of coal characteristics to vary with the policy regime. Among these characteristics, sulfur content is of greatest interest here. We measure it as the amount of SO_2 (in tons) that would be emitted by burning one ton of coal; thus the estimated coefficients can be interpreted as implicit prices of SO_2, in dollars per ton. Under the tradeable permits regime, power plants incurred an additional marginal cost of burning a ton of coal, equal to the price of an allowance. From 1995 to 2000, allowance prices ranged between a low of \$70 and a high of \$210 per ton of SO_2, with an average of just under \$140.[20] The implicit price on sulfur content during Title IV should be of similar magnitude, and negative (since higher-sulfur coal corresponds to greater emissions of SO_2).

$PLANT\ CHARS_j$ includes time-invariant characteristics of power plant j: its generating (or "nameplate") capacity and its transportation options (whether it is served by multiple rail lines or by barge); the latter enter interacted with distance. We normalize the coal characteristics and nameplate capacity by subtracting their grand means. Doing so aids interpretation, as we discuss below. Finally, we include month dummies to allow for seasonal effects.

The full sample comprises all spot-market deliveries of coal from the Powder River Basin in Wyoming, to plants served by railroad, during the period January 1990 to December 1999.[21] Table 1 presents summary statistics.

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[19] We define the Title IV period as beginning in July 1994, because power plants typically maintain several months' worth of coal inventories, and presumably anticipated the regulation in their purchase decisions before the first day the regulation took effect. The empirical results change very little if the Title IV period is defined as beginning in October 1994 or January 1995 instead.

[20] This average allowance price is computed from price data compiled by Cantor Fitzgerald EBS and Fieldston Publications and made available by the EPA.

[21] The Powder River Basin itself extends into Montana. The vast majority of spot coal deliveries from the PRB come from the southern portion in Wyoming, however, and we confine our analysis to that region.

6.2 Results

We first present results from estimating equation (5) by OLS – first for the Table A plants only, and then for all plants. As a robustness check, we then estimate a random-effects model to allow for correlation among deliveries under the same contract. Finally, we relax the assumption of linear price schedules.

6.2.1 OLS estimation

Comparisons among Table A plants before and after Title IV Table 2 presents the OLS results for Table A plants. In the first column, the rail distance, cost index, coal characteristics, and plant characteristics appear without interactions with the policy regime. This regression is useful as a benchmark for later results. The total transportation rate (the sum of the coefficients in the first two rows) is estimated to be 9 mills, or nine-tenths of a cent, per ton-mile – in line with published surveys of rail rates (*e.g.*, General Accounting Office, 2002). The coefficients on coal and plant characteristics are largely in line with expectations. Coal with higher heat content sells for higher prices; coal with higher sulfur content is less valuable (since higher sulfur content means higher SO_2 emissions), although in this regression the latter coefficient is not statistically significant. "Captive" plants – those served by only one railroad and not by barge or truck – pay 2 mills (0.2 cents) per ton-mile more than plants that also enjoy barge or truck service. Somewhat surprisingly, large plants pay higher prices; we return to the latter point below.

The constant term is positive and significant at the 1% level. After subtracting the contemporaneous minemouth price and accounting for distance, cost, coal quality, plant characteristics, and seasonal effects, \$3.31 per ton remains. Since we measure coal characteristics and plant size as deviations from means, this constant term captures the portion of the delivered price of a ton of "average" coal that is not accounted for by distance. We term this the "net railhead price." In line with the theoretical model above, it can be thought of as the implicit "fixed fee" per ton of coal.

Note that this is an *implied* fixed fee. Our data are the delivered prices per ton of coal – not the tariffs in the actual delivery contracts, which are confidential. Indeed, anecdotal evidence suggests that quoted prices tend to be expressed as rates per ton-mile rather than as two-part tariffs. Such evidence is perfectly consistent with the theoretical model of section 3 and with our empirical approach here. It simply suggests that our "net railhead price" should be understood as the intercept of a predicted delivered price schedule that results from individual negotiations between railroads and plants.

The regression reported in column 2 introduces the dummy variable for the allowance market, $TITLE\,IV$, and interacts it with several of the other variables. Note that the interaction with sulfur content is treated differently than with the other variables. Because the null hypothesis of primary interest for SO_2 content is that the coefficient is zero even after the allowance market takes effect, we interact SO_2 content with $(1 - TITLE\,IV)$ and with $TITLE\,IV$, and label the variables "pre-Title IV" and "Title IV" respectively. The results in Table 2 imply that prior to the allowance market, no significant value attached to marginal reductions in sulfur content. Under the tradeable permits regime, however, each one-ton reduction in effective SO_2 content was worth \$265.

The effect of nameplate capacity on coal price also changed significantly under the new regime. In the first half of the decade, the results suggest that a 100 MW increase in generating capacity (8.5% of the average) would have increased the delivered price by 12.5 cents per ton-mile. Under Title IV, this "size premium" vanished. While the size premium in the early period is puzzling, its disappearance may be attributable to the threat that utilities might substitute (over the long run) away from low-sulfur coal and into scrubbing. Building scrubbers involves economies of scale: larger scrubbers tend to be less expensive per unit of capacity, and multiple units at the same plant can be connected to one scrubber. Hence larger plants, all else equal, are more likely to install scrubbers; perhaps the railroads offered lower prices for low-sulfur coal in a bid to reduce the incentives for such plants to consider scrubbing.[22]

Next, consider the coefficients on rail distance and its interactions. Once the effect of Title IV is taken into account, the coefficient on rail distance alone is estimated to be significant at the 5% level during the early part of the decade, while the coefficient on "Rail distance × real cost index" falls relative to column 1. These results suggest that the real cost of rail transportation in 1990 (the base year) was 7 mills per ton-mile. Before Title IV, the railroads earned a margin of another 5 mills per ton-mile above cost. The constant term, meanwhile, is now zero, implying that in the early period the delivered price schedule was essentially linear.

The allowance market had a dramatic effect on the shape of the estimated delivered price schedule. The estimated net railhead price jumps from zero to \$6.14 after Title IV took effect. At the same time, the estimated transportation rate falls by 6 mills per ton-mile. The combined effect of these two changes is to pivot the price schedule, raising its intercept but flattening the slope. Figure 8 illustrates this shift in predicted prices, plotting the net price schedules predicted

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[22] We thank Spencer Banzhaf for suggesting this interpretation to us.

by the coefficients in column 2 of Table 2 before and after Title IV took effect. Note that these price schedules, like the regressions they are based on, control for minemouth price and variable transportation costs.[23] Thus the net prices depicted in Figure 8 are best thought of as "constant-cost" prices, or the prices that would have prevailed absent changes in transportation cost. (Because real transportation costs fell over this period, the fall in actual delivered prices under Title IV was greater than the change in constant-cost prices depicted in Figure 8.) The "breakeven distance" at which these predicted prices were equal before and after the allowance market was 1054 miles.[24] Closer in, price went up; further away, price went down. (For comparison, the mean delivery distance in the sample for Table A plants during Title IV was 1155 miles.) While the differences are only a few dollars per ton, they translate into substantial sums per trainload: the average delivery of PRB coal to these plants during the Title IV period was over 60,000 tons.

Comparisons between Table A plants and non-Table A plants The same conclusions emerge from a comparison of delivered prices at Table A plants with prices to plants that were not directly affected by the new regime. Table 3 presents the results from OLS estimation of equation (5) on the full sample, including both Table A and non-Table A plants. This is analogous to a difference-in-differences specification, and tests whether the regulatory regime itself explains the shift in the price schedule.

The benchmark results presented in the first column of Table 3 are similar to those in Table 2. (Because we introduce several more interaction terms, we have not shown the effects of heat and ash interacted with the regime dummies.) The second column of the table includes interactions with dummy variables for both the Title IV period and the Table A designation. Note that lower-sulfur coal is valuable on the margin only to Table A plants and only during Title IV, as expected; the corresponding coefficient is negative and of similar magnitude as the result in Table 2. The results from the entire sample also confirm the presence of a significant size premium for Table A plants that vanishes during the allowance market.

The effect of the allowance market is markedly more pronounced for Table A plants than for non-Table A plants. The net railhead price to non-Table A plants increased by $2.96 per ton, while the transportation rate to those plants decreased by three mills per ton-mile. For Table A plants,

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[23] Since the covariates for coal quality and generating capacity are deviations from their grand means, these schedules represent the prices for coal of average characteristics delivered to an average-sized plant. Because the dependent variable is net of minemouth prices, the actual delivered prices at these locations would be roughly $4 per ton higher than the plotted estimates.

[24] All estimated breakeven distances are computed using more significant digits than are displayed in the table.

per-ton prices rose after Title IV took effect by an *additional* \$3.34; transportation rates fell by an additional 4 mills per ton-mile. All told, these estimates imply a "breakeven distance" of 914 miles for Table A plants. Figure 9 plots the resulting net price schedules. As in Figure 8, these represent predicted prices, controlling for minemouth prices and variable transportation costs.

The close correspondence with the earlier regressions gives compelling confirmation of the results. That the railroads appear to have been able to charge different prices *at the same point in time* to plants under different policy regimes supports the contention that they were able to price discriminate, and hence respond to the emissions regulation by adjusting their delivered prices.

6.2.2 Random effects

Delivery contracts negotiated among power plants, coal mines, and railroads may vary in ways unobservable to the econometrician: a plant manager may be a strong negotiator, the timing of a particular contract may prove particularly advantageous to the buyer or the railroad, and so on. These effects will likely be constant across deliveries under a given contract. To account for such unobserved heterogeneity, while allowing estimation of the effects of time-invariant plant characteristics (*e.g.*, distance from the PRB), we employ a random-effects specification. In terms of the equation (5), we separate the error term ε_{ijt} into two terms: a contract-specific random effect η_{ij} common to all deliveries from the same mine to the same plant in the same year; and a delivery-specific disturbance u_{ijt}.[25] These random-effects results are reported in Table 4. The two columns now replicate the second columns from Tables 2 (Table A plants only) and 3 (all plants). The estimated coefficients on rail distance are generally consistent with the OLS results, as are those for the coal and plant characteristics (some of which are suppressed in the table to save space).[26]

The results in the first column echo the estimates for Table A plants in Table 2: the allowance market coincided with a pivot in the price schedule, with the net railhead price rising by \$4.19 per ton and the transportation rate falling by 4 mills per ton-mile. In the larger sample, the difference in net railhead price between the Table A plants and the non-Table A plants loses statistical

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[25] Recall that the "spot market" deliveries analyzed in this paper are defined as contracts of less than one year in length. Hence the random effects correspond to plant-source-year triples. Since we count July 1994 as the start of Title IV, we treat January-June 1994 and July-December 1994 as separate "years" in the random effect plant-source-year triples.

[26] The coefficients on "Rail distance × real cost index" are reasonably far apart in the two columns of Table 4, suggesting that these coefficients are at best rough estimates of variable cost in 1990. Nonetheless, the sum of the coefficients on rail distance and rail distance interacted with the cost index – that is, the total estimated transportation rate – remains similar across all the specifications and samples.

significance. However, for Table A plants the estimated effects of the allowance market on the intercept and slope of the price schedule remain significantly different from zero at the 5% and 1% levels respectively. The results in Table 4 imply an increase in the net railhead price for Table A plants of \$4.47 per ton, with a standard error of 2.00; the estimated fall in the transportation rate is 5 mills per ton-mile, with a standard error of 0.0016.[27] Again, these results suggest that after the allowance market took effect, delivered prices to Table A plants – controlling for minemouth prices and transportation costs – rose within 1000 miles or so of the PRB, and fell further away.

6.2.3 Nonlinearities in the delivered price schedule

The regressions reported so far estimate linear delivered price schedules. We employed three sets of flexible functional forms in relaxing this linearity assumption. First, we allowed for different linear price schedules for plants closer than and further away from a specified break point; the break points ranged from 900 to 1400 miles. Second, we used simple polynomials in distance, up to fourth-order terms, interacting these with indicator variables for Table A and Title IV. Finally, we used Hermite polynomials in distance, up to 6th order terms, and interacted them with regime dummies.

All three sets of alternative specifications produced qualitatively similar results. The allowance market had a markedly greater effect on delivered prices for Table A plants than on those for other plants. Controlling for costs, delivered prices rose somewhat at nearby plants and fell at more distant ones. We report the results of one of our alternative specifications, that with a second order simple polynomial, in Table 5 and plot the predicted values for the price schedule in Figure 10.

6.3 Supporting evidence

In this section, we subject our hypothesis of market power in the PRB to two tests. In our theoretical model, we argue that demand for low-sulfur coal ought to become more elastic for power plants governed by the cap-and-trade regime. Indeed, this posited change in elasticity provides the basis for price discrimination by a railroad with market power. We test this prediction by estimating demand for low-sulfur coal.

Second, we examine price data for low-sulfur coal delivered from Central Appalachia, the other main source of low-sulfur coal, where barge traffic is likely to make transportation more competitive.

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[27] These standard errors are derived from estimating the random-effects model with the regime dummies appropriately redefined.

If market power explains the observed shift in delivered prices of PRB coal, then the tradeable permits regime should not have produced any similar effect on prices of Central Appalachian coal.

6.3.1 The effects of regulation on price elasticity of demand

Our theoretical results in Section 3 rests on differences among plants in the elasticity of demand for low-sulfur coal, due to the emissions regulations they face. If the empirical results above are the result of price discrimination, such differences in elasticities should be evident in the data. We can characterize coal deliveries along two dimensions: those to Table A vs. those to non-Table A plants, and pre-Title IV deliveries vs. Title IV deliveries. The discussion in Section 3 implies that demand for low-sulfur coal should have been more elastic for Table A plants after Title IV took effect than before. Moreover, once the allowance market was under way, demand should have been more elastic at Table A plants than at non-Table A plants.

We use a log-linear functional form for demand to estimate elasticities:

$$\begin{aligned}\ln q_{jt} \; = \; & \alpha_{01} \cdot TITLE\,IV_t + \alpha_{02} \cdot TITLE\,IV_t \times \; TABLE\,A_j \\ & \alpha_{10} \cdot \ln p + \alpha_{11} \cdot \ln p \cdot TITLE\,IV_t + \; \alpha_{12} \cdot \ln p \cdot TABLE\,A_j + \\ & \alpha_{13} \cdot \ln p \cdot TITLE\,IV_t \times TABLE\,A_j + \; \text{month dummies} + \; \delta_j + \; \varepsilon_{jt},\end{aligned} \tag{6}$$

where q_{jt} is the quantity (in million Btus) delivered to plant j at time t and p_{jt} is the real price (in cents/mmBtus, expressed in constant 1995 dollars).[28] To allow for the effects of unobserved plant-level characteristics, we allow for fixed effects at the plant level (δ_j); we assume that the remaining disturbances $\{\varepsilon_{jt}\}$ are i.i.d. across observations. We instrument for ln(price) with the log of the productivity-adjusted cost index used above; the log of the minemouth price; logs of indices for wages, spot diesel prices, and other input prices; and coal characteristics. We allow for maximum flexibility in the relationship between the instruments by interacting all the independent variables in the first-stage equation with the regime dummies. We estimate the model on all spot-market deliveries of Western low-sulfur coal for the period 1990-1999. (We use Western low-sulfur coal, of which PRB coal is a subset, in order to increase the price variation and the size of our sample.) The results are shown in Table 6.

The estimate of price elasticity for non-Table A plants in the base period is -1.2 and is sta-

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[28] We estimated the same equation with coal characteristics (ash, heat, and sulfur contents) included in the quantity equation; the coefficients on the prices and regime dummies were similar, while the coal characteristics had insignificant effects. The primary effect of coal characteristics on quantity demanded at the plant level is likely to be via the price of coal – especially since we control for fixed effects at the plant level.

tistically different from zero at the 1% level. More importantly for our purposes, the regression results suggest that after the introduction of the allowance market, demand becomes significantly more elastic at Table A plants than at non-Table A plants. The estimated demand elasticity for Table A plants also increases in magnitude (becomes more negative) under the cap-and-trade regime, although the difference between the two point estimates is statistically significant only at the 10% level (*p-value* $= 0.07$). Table 7 summarizes the estimation results, presenting the estimated elasticities by regime and time period.

6.3.2 Evidence from Central Appalachia

The Powder River Basin is not the only important deposit of low-sulfur coal. Another major source is Central Appalachia, comprising the mountainous counties of southwestern West Virginia, western Virginia, and eastern Kentucky drained by the Big Sandy River. In this section, we examine data on coal deliveries from that region, as a check on the results presented above.

The comparison allows us to take advantage of a critical regional difference in transportation. As with the PRB, only two railroads (Norfolk-Southern and CSX) serve Central Appalachian mines. But coal from Central Appalachia also travels by barge down the Big Sandy to the Ohio River, fueling the power plants that line the Ohio, Green, and Cumberland Rivers. Because barge transportation does not require the heavy capital investment in track and other fixed structures, it is much more competitive. Moreover, many plants are served by both barge and rail. As a result, the opportunities for price discrimination should be much attenuated. Table 8 presents summary data for coal from Central Appalachia.

Table 9 presents the results from estimating equation (5) by OLS for spot coal deliveries to rail-served plants from Central Appalachia. The dependent variable is once again the delivered price of coal, net of the contemporaneous minemouth price.[29] The sole difference from earlier regressions is that the "Rail distance × real cost index" is dropped from the regression.[30] The regression reported in column 1 includes data from Table A plants only, while the results from the full sample are presented in column 2.

The pivot in the price schedule that was evident for PRB coal is absent in the data from Central

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[29] We use the minemouth price series from *Coal Outlook* for Central Appalachian coal at Big Sandy with 11,500 Btus/lb heat content and less than 1.2 lbs SO_2/mmBtus sulfur content.

[30] Although we also have a cost index for Central Appalachia, we exclude it from the regressions reported in the table. When the rail distance * real cost index term is included in the regression, the estimated coefficient is negative, and the straight rail distance term increases accordingly. However, the standard errors on *both* terms balloon so that neither is statistically significant even at the 10% level. The other results in the regression are unaffected.

Appalachia. Over the entire period, delivered prices for Table A plants differ somewhat from those for non-Table A plants. But the allowance market does not have any significant effect for those plants. Indeed, the only apparent difference under Title IV is a *fall* of about three dollars per ton in the estimated net railhead price for non-Table A plants.

6.4 Estimating the gains to the railroads from Title IV

Our central argument is that Title IV increased demand among Midwestern power plants for low-sulfur coal from the PRB, and that the BNSF and UP railroads were able to exercise market power to take advantage of this demand. At first blush, then, it may seem surprising that the effect of Title IV was to lower prices over a greater geographic range than prices rise, and generally to lower prices by more where they decrease than the amount by which they rise where they increase. Recall, however, that the model in Section 3 exhibits exactly this effect: a tradeable permits regime would indeed flatten the delivered price schedule for low-sulfur coal, and perhaps even lead to lower prices on the extensive margin.

Since we control for transportation costs and the price of minemouth coal, these falling prices do not reflect falling costs. Nor did competition increase: the market structure for transportation out of the PRB remains constant over this period. Rather, the lower prices suggest price discrimination among plants with different demands for low-sulfur coal – where the differences in demand are induced by emissions regulation. This argument is bolstered by the results of the full-sample regressions, which show that the shift in coal prices was markedly greater for deliveries Table A plants than for contemporaneous deliveries to nearby plants that were governed by a different regulatory regime. Moreover, evidence from Central Appalachia suggests that the change in the delivered price schedule was limited to coal deliveries from the Powder River Basin, where the railroads faced no other competition in transportation.

If the shifts in prices do reflect market power, the railroads must have gained from them. We lack direct cost data, so we cannot to calculate profits directly. Moreover, since we have not estimated a full demand model, we are unable to model counterfactual demand under a different pricing regime. Nonetheless, we can derive "back-of-the-envelope" estimates for changes in revenues and even in producer surplus. Revenues can be computed directly from the reported price and quantity data. Although delivered prices to Table A plants fall over much of the delivery region after the advent of the allowance market, quantity increases dramatically. The net effect is that annual revenues from deliveries to Table A plants after Title IV took effect were 140% of what they were before the allowance market. (See Table 10).

At the same time, the cost index falls by more than a third between 1990 and 1999, which suggests that railroad profits are indeed increasing under Title IV. If we use the coefficient on "Rail distance × real cost index" as an estimate of the variable cost per ton-mile in 1990, we can compute a rough estimate of producer surplus. Using the estimates from the second column of Table 2, we can estimate net real price per ton for each delivery, subtract off variable cost (using the coefficient estimate of 0.007 on "Rail distance × real cost index" from the same regression), and multiply by quantity.

The results of this exercise are shown in Table 10. Estimated annual producer surplus from spot-market deliveries to Table A plants rose from \$37 million to \$56 million per year under the allowance regime – an increase of \$19 million, or just over 50%. Of course, these are only rough approximations of producer surplus, and by definition they ignore fixed costs entirely. On the other hand, they also represent only a portion of total revenues – that accounted for by spot-market deliveries to Table A plants.

To put these rough estimates of producer surplus in context, the market value of allowances during Phase I was roughly \$770 million per year (\$135/ton average price times 5.7 million allowances allocated each year). Annual variable abatement cost among Table A plants in each year of Phase I was on the order of \$560 million, leaving a surplus (over variable cost) of \$210 million.[31] In this light, our estimates suggest that the increase in producer surplus to the BNSF and UP railroads alone was on the order of ten percent of the size of the entire surplus captured by the electric utilities. This strikes us as substantial but still of plausible magnitude.

7 Conclusion

The aim of this paper is to understand how the tradeable permits system for SO_2 emissions created by the Clean Air Act Amendments of 1990 affected the market for low-sulfur coal. We have shown that the allowance trading program coincided with a shift in the delivered prices of low-sulfur coal from the Powder River Basin to power plants subject to the new regime. The implicit zero-distance or "railhead" price, net of the minemouth price of coal, rose by roughly six dollars per ton – a dramatic increase over the prior railhead price. At the same time, estimated transportation

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[31] This estimate of total variable abatement costs is derived by the authors from data on abatement and abatement costs described in Keohane (2003).

rates fell by about six mills per ton-mile, controlling for variable transportation costs. The net effect was to increase the "constant-cost" delivered price of PRB coal for western plants (within approximately 1000 miles), while lowering it on the extensive margin.

These findings are consistent with a theoretical model of the effects of emissions regulation on the demand for low-sulfur coal, and the implied optimal pricing behavior of a carrier with market power. They suggest that the two railroads that carry low-sulfur coal east from the PRB were able to price discriminate among power plants, according to the emissions regulations they faced.

Our results also suggest a novel explanation for the relatively low delivered price of PRB coal during the late 1990s, particularly to utilities in the Midwest. Indeed, PRB coal was considerably cheaper during that period than many analysts had expected, contributing to the lower-than-expected allowance prices and the strong performance of the tradeable permits program as a whole (Ellerman and Montero 1998). Ellerman and Montero note that PRB coal prices began to fall before Title IV took effect, and attribute the change to the railroad deregulation at the start of the previous decade – in particular, the Staggers Act of 1980. That regulatory change, however, is a less plausible explanation for the continued drop in PRB coal prices throughout Phase I, over fifteen years after railroad deregulation and just when demand for low-sulfur coal increased as a result of the allowance market.

In contrast, our analysis points to price discrimination as a key factor in explaining the low prices of low-sulfur coal. By raising the delivered price of PRB coal at some power plants and lowering it at others, the railroads were able to benefit from the allowance market, taking advantage of its effects on the demand for low-sulfur coal. In this light, the low prices at many power plants after Title IV took effect are evidence *in favor* of market power, rather than against it.

In this as in other instances, market power reduces welfare relative to a perfectly competitive situation. But that may be the wrong comparison for practical purposes. A more realistic alternative might be to take the market structure as given, and consider the welfare consequences of regulatory design. The results presented here suggest an unheralded benefit from a market-based environmental regulation, relative to a traditional standards-based approach. By making low-sulfur coal demand more elastic, the tradeable permits program appears to have provided railroads with an incentive to lower their prices over a wide range instead of raising them, making pollution abatement less expensive than it would otherwise have been.

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Model Appendix

In this appendix, we show that for a wide range of values of η the optimal fixed fee will be greater under the allowance market than under an emissions standard. The proof is based on the following thought experiment. Suppose that the permit price were fixed at the level just large enough to offset the fall in the fixed fee from the increased elasticity, so that the net change in the fixed fee was zero. Starting at this point, would the railroad have an incentive to vary output in order to drive the permit price up or down?

Let $\hat{z}$ be the permit price at which the optimal fixed fee charged by the railroad would be the same under an allowance market and an emissions standard: that is, $\hat{z} \equiv \frac{\theta_m - \theta_s}{(\eta\theta_m - 1)(\theta_s - 1)}c$. Let $\hat{Q}_m$ to be the total quantity of low-sulfur coal consumed under an allowance market when the railroad adjusted its price schedule to maximize profits given the permit price $\hat{z}$. As in the text, define $\eta \equiv -\frac{\partial z}{\partial Q}\frac{Q}{z}$, and let $\hat{\eta}$ be its value at $\hat{z}$ and $\hat{Q}$. Define $\hat{x}_m$ to be the extensive margin under the allowance market given $\hat{z}$ – that is, the distance to the furthest plant from the low-sulfur coal source.

Finally, let $\alpha'(x)$ represent the change in the reservation price α_m^i with distance from the coal origin. We assume that the reservation price is nonincreasing in distance. This will hold, for example, in a model in which plants that are further from the low-sulfur coal source are closer to high-sulfur coal deposits, the price of high-sulfur coal is increasing with distance from the high-sulfur origin, and the costs of other pollution control are randomly distributed among plants with respect to distance.

The following proposition gives a *sufficient* condition for the optimal fixed fee to be higher under the allowance market. We do this for expositional simplicity. The necessary condition involves the same lower bound but an upper bound that might be considerably higher, as is clear in the course of the proof.

The proposition shows that as long as $\hat{\eta}$ is greater than $\frac{1}{\theta_m}$ and is less than an upper bound, the profit-maximizing fixed fee is larger under a tradeable permits regime than under an emissions standard. The upper bound, moreover, is strictly greater than unity. It increases with the "market size" in that it is greater, the greater is total consumption of low-sulfur coal $\hat{Q}_m$ relative to consumption at the extensive margin $\hat{x}_m$.

Proposition 1 *Suppose that* $\frac{1}{\theta_m} < \hat{\eta} < 1 + \frac{\hat{Q}_m}{\hat{\beta}_m^i}\left(\frac{\theta_m t}{\hat{\alpha}_m}\right)$. *Then the optimal fixed fee charged by the railroad is greater for plants regulated by an allowance market than for those subject to an emissions* *standard.*

Proof. Using the delivered price schedule given by equation (4), profit as a function of the output schedule $\{q(x)\}$ and the permit price z as $\pi(\{q(x)\}, z(Q)) = \int_0^{\hat{x}_m} [P(x) - c(x)]\, q(x) dx$.

The effect of a marginal change in quantity on profit, given $z = \hat{z}$, is

$$\frac{d\pi\left(\hat{Q}_m, \hat{z}\right)}{dQ_m} = \frac{\partial\pi\left(\hat{Q}_m, \hat{z}\right)}{\partial Q_m} + \frac{\partial\pi\left(\hat{Q}_m, \hat{z}\right)}{\partial z}\frac{\partial z}{\partial Q_m}.$$

If $\frac{d\pi\left(\hat{Q}_m, \hat{z}\right)}{dQ_m} < 0$, then the optimal quantity is less than $\hat{Q}_m$, implying that in equilibrium the permit price will be greater than $\hat{z}$ and thus the optimal fixed fee will increase under the emissions market. The first term on the right-hand side is zero by the envelope theorem. The last term, $\frac{\partial z}{\partial Q}$, is negative, as discussed in the text. This leaves the middle term $\frac{\partial \pi}{\partial z}$: the partial derivative of profit with respect to the permit price. We wish to show that this term is positive.

Differentiating π with respect to z and substituting for $\hat{P}(x)$ (the profit-maximizing delivered price schedule given $\hat{z}$) yields

$$\begin{aligned} \frac{\partial \pi}{\partial z} &= \underbrace{\left(\frac{\hat{\eta}\theta_m - 1}{\theta_m - 1}\right)\hat{Q}_m}_{\text{direct gain from permit price increasing WTP}} + \underbrace{\int_0^{\hat{x}_m}\left[\hat{P}(x) - c(x)\right]\frac{\partial \hat{q}(x)}{\partial z}dx}_{\text{effect of change in quantity at inframarginal units}} \qquad \text{(A.1)} \\ &+ \underbrace{\left[\hat{P}\left(\hat{x}_m\right) - c\left(\hat{x}_m\right)\right]\hat{q}\left(\hat{x}_m\right)\frac{d\hat{x}_m}{dz}}_{\text{change in profit at the external margin}}. \end{aligned}$$

The first term in equation (7) represents the direct increase in revenue from an increase in the permit price, and is positive as long as $\hat{\eta} > \frac{1}{\theta_m}$. The second term captures the effect on profits of the change in quantity at inframarginal plants. The third term is the change in profit at the external margin.

Note that $\hat{q}(x) = \beta^i_m \left(\frac{\hat{P}_m(x) - \hat{z}}{\alpha^i_m}\right)^{-\theta_m}$; thus

$$\frac{\partial \hat{q}(x)}{\partial z} = -\frac{\partial}{\partial z}\left(\hat{P}_m(x) - \hat{z}\right) \cdot \frac{\theta_m \hat{q}\left(x\right)}{\hat{P}_m(x) - \hat{z}}. \qquad \text{(A.2)}$$

In general, $P_m(x) - z = \left(\frac{\theta_m}{\theta_m - 1}\right)(c + tx) + \left(\frac{(\eta-1)\theta_m}{\theta_m - 1}\right)z$, so $\frac{\partial}{\partial z}\left(\hat{P}_m(x) - \hat{z}\right) = \frac{(\hat{\eta}-1)\theta_m}{\theta_m - 1}$. Thus if the allowance price z is not too sensitive to low-sulfur coal consumption – in particular, if $\hat{\eta} < 1$ – an increase in the permit price increases quantity at each location. When $\eta < 1$, a one-unit change in z yields a smaller change in delivered price: $\frac{\partial P}{\partial z} = \frac{\eta\theta_m - 1}{\theta_m - 1} < 1$. That is, some of the permit price increase is “absorbed” by the carrier. On the other hand, the permit price increased is transmitted directly into the inverse demand function. As a result, a rise in z yields an increase in quantity demanded. The reverse is true when $\hat{\eta} > 1$: in that case, an increase in the permit price is magnified by the price schedule, and dampens demand.

Note that

$$\begin{aligned}
\hat{P}(x) - c(x) &= \left(\frac{1}{\theta_m - 1}\right)(c + tx) + \left(\frac{\hat{\eta}\theta_m - 1}{\theta_m - 1}\right) z \\
&= \left(\frac{1}{\theta_m - 1}\right)\left[(c + tx) + (\hat{\eta}\theta_m - 1) z\right] \\
&> \left(\frac{1}{\theta_m - 1}\right)\left[(c + tx) + (\hat{\eta} - 1) z\right] \\
&= \frac{1}{\theta_m}\left(\hat{P}(x) - z\right)
\end{aligned}$$

Thus

$$\begin{aligned}
\left[\hat{P}(x) - c(x)\right]\frac{\partial \hat{q}(x)}{\partial z} &= -\left[\hat{P}(x) - c(x)\right]\frac{(\hat{\eta} - 1)\,\theta_m}{\theta_m - 1}\cdot\frac{\theta_m \hat{q}\,(x)}{\hat{P}_m(x) - \hat{z}} \\
&> \left[\hat{P}(x) - c(x)\right]\frac{(1 - \hat{\eta})\,\theta_m}{\theta_m - 1}\frac{\hat{q}\,(x)}{\hat{P}(x) - c(x)} \\
&= \frac{(1 - \hat{\eta})\,\theta_m}{\theta_m - 1}\hat{q}\,(x)\,.
\end{aligned}$$

Substituting into (A.2) yields

$$\begin{aligned}
\frac{\partial \pi}{\partial z} &> \left(\frac{\hat{\eta}\theta_m - 1}{\theta_m - 1}\right)\hat{Q}_m + \frac{(1 - \hat{\eta})\,\theta_m}{\theta_m - 1}\int_{\bar{x}_0}^{\hat{x}_m}\hat{q}\,(x)\,dx + \left[\hat{P}\,(\hat{x}_m) - c\,(\hat{x}_m)\right]\hat{q}\,(\hat{x}_m)\,\frac{d\hat{x}_m}{dz} \\
&= \left(\frac{\hat{\eta}\theta_m - 1}{\theta_m - 1}\right)\hat{Q}_m + \left(\frac{(1 - \hat{\eta})\,\theta_m}{\theta_m - 1}\right)\hat{Q}_m + \left[\hat{P}\,(\hat{x}_m) - c\,(\hat{x}_m)\right]\hat{q}\,(\hat{x}_m)\,\frac{d\hat{x}_m}{dz} \\
&= \hat{Q}_m + \left[\hat{P}\,(\hat{x}_m) - c\,(\hat{x}_m)\right]\hat{q}\,(\hat{x}_m)\,\frac{d\hat{x}_m}{dz}. \qquad \text{(A.3)}
\end{aligned}$$

We can use the boundary conditions to analyze $\frac{d\hat{x}_m}{dz}$. At the boundary $\hat{x}_m$, the delivered price of low-sulfur coal (given $\hat{z}$) must equal the reservation price: $\hat{P}\,(\hat{x}_m) = \alpha\,(\hat{x}_m) + \hat{z}$, where

$\alpha(\hat{x}_m) = \alpha_0^i + \alpha_m^i$ for i at the boundary $\hat{x}_m$. This implies that

$$\begin{aligned}
\frac{d\hat{x}_m}{dz} &= -\frac{\partial \hat{P}(\hat{x}_m)/\partial z - 1}{\partial \hat{P}(\hat{x}_m)/\partial \hat{x}_m - \alpha'(\hat{x}_m)} \\
&= -\frac{\left(\frac{\eta\theta_m - 1}{\theta_m - 1}\right) - 1}{\left(\frac{\theta_m}{\theta_m - 1}\right) t - \alpha'(\hat{x}_m)} \\
&= \frac{(1-\hat{\eta})\,\theta_m}{\theta_m t - (\theta_m - 1)\,\alpha'(\hat{x}_m)}. \qquad \text{(A.4)}
\end{aligned}$$

The denominator is positive by our assumption on α'. Thus $\frac{d\hat{x}_m}{dz} \geq 0$ iff $\hat{\eta}$ is less than or equal to 1.

Moreover, applying $\hat{P}(x) - c(x) > \frac{1}{\theta_m}\left(\hat{P}(x) - z\right)$ again at the boundary $\hat{x}_m$:

$$\hat{P}(x) - c(x) > \frac{1}{\theta_m}\left(\hat{P}(x) - z\right) = \frac{\hat{\alpha}_m}{\theta_m}.$$

Furthermore, at the boundary $\hat{q}_m(\hat{x}_m) = \hat{\beta}_m^i$.

Substituting into equation (7) yields

$$\frac{\partial \pi}{\partial z} > \hat{Q}_m + \hat{\alpha}_m \hat{q}(\hat{x}_m)\frac{(1-\hat{\eta})}{\theta_m t - (\theta_m - 1)\,\alpha'(\hat{x}_m)}.$$

A sufficient condition for the fixed fee to rise under the tradeable permits regime is that the RHS of this inequality be positive, *i.e.*:

$$\begin{aligned}
\hat{\alpha}_m \hat{\beta}_m^i \frac{\hat{\eta} - 1}{\theta_m t - (\theta_m - 1)\,\alpha'(\hat{x}_m)} &< \hat{Q}_m \\
\hat{\eta} &< 1 + \frac{\hat{Q}_m}{\hat{\beta}_m^i}\left(\frac{\theta_m t - (\theta_m - 1)\,\alpha'(\hat{x}_m)}{\hat{\alpha}_m}\right).
\end{aligned}$$

Note that the second term on the right-hand side is strictly positive.

We can simplify this further by assuming that the reservation price is constant (note that this is the "hardest" case). This yields

$$\hat{\eta} < 1 + \frac{\hat{Q}_m}{\hat{\beta}_m^i}\left(\frac{\theta_m t}{\hat{\alpha}_m}\right).$$

Note that $\hat{Q}_m \geq \hat{\beta}_m^i = \hat{q}_m$ by construction, and that we might in general expect $\hat{Q}_m \ggg \hat{\beta}_m^i$ when the market is "large." Thus this upper bound is an increasing function of the size of the market. ■

Table 1: Summary statistics

Variable	Mean	Standard deviation	Minimum	Maximum
TABLE A PLANTS				
Pre-Title IV	$N = 518$			
Net delivered coal price (1995 $/ton)	15.499	4.806	7.254	30.520
Rail distance to PRB (miles)	1201.844	296.086	716	1711
Plant served by multiple RRs	0.212	0.409	0	1
Plant captive to one RR	0.667	0.471	0	1
Nameplate capacity (GWe)	1.187	0.708	0.212	3.339
SO_2 content (tons per ton coal)	0.005	0.001	0.002	0.009
Heat content (Btus/lb)	8631.062	168.195	8249	8954
Ash content (% by weight)	5.099	1.067	4.1	25.58
Title IV	$N = 765$			
Net delivered coal price (1995 $/ton)	12.362	2.579	7.033	24.386
Rail distance to PRB (miles)	1154.708	256.841	716	1699
Plant served by multiple RRs	0.236	0.425	0	1
Plant captive to one RR	0.535	0.499	0	1
Nameplate capacity (GWe)	1.154	0.745	0.140	3.339
SO_2 content (tons per ton coal)	0.005	0.001	0.002	0.009
Heat content (Btus/lb)	8610.525	211.714	7969	9003
Ash content (% by weight)	5.197	0.595	3.6	7.08
OTHER PLANTS				
Pre-Title IV	$N = 1602$			
Net delivered coal price (1995 $/ton)	13.315	5.986	3.119	76.144
Rail distance to PRB (miles)	1099.712	424.005	348	1881
Plant served by multiple RRs	0.380	0.485	0	1
Plant captive to one RR	0.455	0.498	0	1
Nameplate capacity (GWe)	1.073	0.835	0.087	3.564
SO_2 content (tons per ton coal)	0.005	0.001	0.002	0.010
Heat content (Btus/lb)	8579.105	215.905	7382	9406
Ash content (% by weight)	5.060	0.697	3.6	12.7
Title IV	$N = 2935$			
Net delivered coal price (1995 $/ton)	13.760	5.123	2.784	39.661
Rail distance to PRB (miles)	1208.356	375.182	320	2248
Plant served by multiple RRs	0.214	0.410	0	1
Plant captive to one RR	0.632	0.482	0	1
Nameplate capacity (GWe)	1.245	0.959	0.116	3.564
SO_2 content (tons per ton coal)	0.005	0.001	0.002	0.010
Heat content (Btus/lb)	8605.408	190.395	7987	9374
Ash content (% by weight)	5.187	0.568	0.56	10.67

Table 2: Results from OLS estimation: Table A plants only

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	(1)	(2)
Rail distance	-0.001	0.005 *
	(0.001)	(0.002)
Rail distance × real cost index	0.010 **	0.007 **
	(0.001)	(0.002)
Title IV		6.141 **
		(1.326)
Title IV × rail distance		-0.006 **
		(0.001)
SO_2 content	-142.387	
	(98.165)	
SO_2 content (pre-Title IV)		-58.108
		(162.191)
SO_2 content (Title IV)		-265.126 *
		(102.249)
Heat content	0.001	-0.000
	(0.001)	(0.002)
Title IV × heat content		0.003
		(0.002)
Ash content	0.214	0.175
	(0.154)	(0.121)
Title IV × ash content		0.266
		(0.308)
Nameplate capacity	0.620 *	1.251 **
	(0.277)	(0.370)
Title IV × nameplate capacity		-1.420 **
		(0.455)
Plant served by multiple RRs × rail distance	0.001	0.001
	(0.001)	(0.000)
Plant captive of RR × rail distance	0.002 **	0.002 **
	(0.000)	(0.000)
Constant	3.306 **	-0.102
	(0.859)	(1.056)
Monthly dummies?	Yes	Yes
Observations	1283	1283
R-squared	0.69	0.73

Notes: * significant at 5 % level ** at 1 % level.
Standard errors are clustered by plant-source-year triples.

Table 3: Results from OLS estimation: All plants

Dependent variable: Delivered coal price net of minemouth price (1995 \$/ton)	(1)	(2)
Rail distance	0.003 ** (0.001)	0.007 ** (0.001)
Rail distance × real cost index	0.005 ** (0.001)	0.003 (0.001)
Title IV		2.964 ** (0.649)
Title IV × rail distance		-0.003 ** (0.001)
Table A plant		-2.279 * (1.117)
Table A × rail distance		0.003 ** (0.001)
Table A × Title IV		3.342 * (1.521)
Table A × Title IV × rail distance		-0.004 ** (0.001)
SO_2 content	104.238 (71.181)	
SO_2 content (non-Table A; pre-Title IV)		223.597 (137.443)
SO_2 content (non-Table A; Title IV)		162.853 (102.427)
SO_2 content (Table A; pre-Title IV)		-72.941 (162.332)
SO_2 content (Table A; Title IV)		-290.301 ** (107.597)
Heat content	0.005 ** (0.001)	0.004 ** (0.001)
Ash content	-0.122 (0.199)	0.161 (0.354)
Nameplate capacity	0.544 ** (0.101)	0.225 (0.158)
Table A × Nameplate capacity		1.146 ** (0.403)
Title IV × Nameplate capacity		0.587 ** (0.211)
Table A × Title IV × Nameplate capacity		-2.030 ** (0.512)
Plant served by multiple RRs × rail distance	0.000 (0.000)	0.000 (0.000)
Plant captive of RR × rail distance	0.002 ** (0.000)	0.002 ** (0.000)
Constant	3.727 ** (0.356)	2.291 ** (0.437)
Monthly dummies?	Yes	Yes
Observations	5820	5820
R-squared	0.57	0.60

Notes: * significant at 5 % level ** at 1 % level.
Standard errors are clustered by plant-source-year triples.
Not presented: Heat and ash contents interacted with Title IV and Table A dummies.

Table 4: Results from random-effects estimation

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	Table A (1)	All plants (2)
Rail distance	0.002 (0.002)	0.004 ** (0.001)
Rail distance × real cost index	0.010 ** (0.002)	0.005 ** (0.001)
Title IV	4.194 ** (1.304)	1.822 * (0.835)
Title IV × rail distance	-0.004 ** (0.001)	-0.002 * (0.001)
Table A plant		-2.464 (1.620)
Table A × rail distance		0.003 * (0.001)
Table A × Title IV		2.651 (2.165)
Table A × Title IV × rail distance		-0.003 * (0.002)
SO_2 content (pre-Title IV)	88.061 (93.489)	
SO_2 content (Title IV)	65.335 (81.073)	
SO_2 content (non-Table A; pre-Title IV)		93.466 (89.535)
SO_2 content (non-Table A; Title IV)		-76.613 (53.262)
SO_2 content (Table A; pre-Title IV)		54.600 (143.208)
SO_2 content (Table A; Title IV)		32.613 (123.632)
Heat content	0.002 * (0.001)	0.002 ** (0.001)
Ash content	-0.042 (0.049)	0.229 (0.155)
Nameplate capacity	1.139 ** (0.312)	0.613 ** (0.219)
Title IV × Nameplate capacity	-1.238 ** (0.401)	0.011 (0.282)
Table A × Nameplate capacity		0.784 (0.521)
Table A × Title IV × Nameplate capacity		-1.257 (0.682)
Plant served by multiple RRs × rail distance	0.001 ** (0.000)	0.000 (0.000)
Plant captive of RR × rail distance	0.002 ** (0.000)	0.002 ** (0.000)
Constant	0.213 (0.975)	3.106 ** (0.677)
Monthly dummies?	Yes	Yes
Observations	1283	5820
Number of contracts	285	1348

Notes: * significant at 5 % level ** at 1 % level

Not presented: Heat and ash contents interacted with Title IV and Table A dummies.

Table 5: OLS regression with 2nd order simple polynomial

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	
Rail distance × real cost index	0.003 (0.001)
Rail distance	0.009 ** (0.002)
(Rail distance)^2	-1.05×10^{-6} (1.09×10^{-6})
Table A plant	8.518 (4.697)
Table A × rail distance	-0.017 * (0.008)
Table A × (rail distance)^2	8.45×10^{-6} * (3.24×10^{-6})
Title IV	4.350 ** (1.023)
Title IV × rail distance	-0.006 ** (0.003)
Title IV × (rail distance)^2	1.69×10^{-6} (1.32×10^{-6})
Table A × Title IV	-17.014 ** (5.620)
Table A × Title IV × rail distance	0.034 ** (0.010)
Table A × Title IV × (rail distance)^2	1.68×10^{-5} ** (4.16×10^{-6})
Constant	1.583 * (0.728)
Monthly dummies?	Yes
Observations	5820

Notes: * significant at 5 % level   ** at 1 % level
Standard errors are clustered by plant-source-year triples.
Unreported covariates: SO_2 content, heat content, ash,
nameplate capacity, multiple railroad and captive indicators.

Table 6: Results from fixed-effects IV estimation of price elasticities for Western low-sulfur coal

Dependent variable: ln(quantity)	
ln(real price)	-1.200 ** (0.194)
ln(real price) × Table A	0.237 (0.391)
ln(real price) × Title IV	1.260 ** (0.252)
ln(real price) × Table A × Title IV	-2.019 ** (0.493)
Title IV	-5.843 ** (1.169)
Table A plant × Title IV	9.379 ** (2.303)
Constant	18.543 ** (0.804)
Monthly dummies?	Yes
Observations	10012
Number of plants	187

Notes: * significant at 5 % level ** at 1 % level.

Table 7: Summary of elasticity estimates

	Non-Table A	*Table A*
Pre-CAAA90	-1.20	-0.99
CAAA90	0.07	-1.75

Table 8: Summary statistics for Central Appalachian coal

Variable	Mean	Standard deviation	Minimum	Maximum
TABLE A PLANTS				
Pre-Title IV	$N = 751$			
Net delivered coal price (1995 $/ton)	8.007	7.554	-19.197	47.224
Rail distance to PRB (miles)	306.543	234.162	88	808
Plant served by multiple RRs	0.167	0.373	0	1
Plant captive to one RR	0.657	0.474	0	1
Nameplate capacity (GWe)	1.214	1.018	0.305	3.339
SO_2 content (tons per	0.012	0.001	0.009	0.016
Heat content (Btus/lb)	12424.82	605.603	9325	14383
Ash content (% by weight)	10.244	2.899	3.6	28.2
Title IV	$N = 817$			
Net delivered coal price (1995 $/ton)	7.302	11.418	-6.887	247.781
Rail distance to PRB (miles)	268.007	212.210	88	1059
Plant served by multiple RRs	0.018	0.134	0	1
Plant captive to one RR	0.581	0.493	0	1
Nameplate capacity (GWe)	1.040	0.783	0.305	3.498
SO_2 content (tons per	0.013	0.001	0.003	0.015
Heat content (Btus/lb)	12424.02	522.015	8789	13910
Ash content (% by weight)	10.435	2.871	3.8	27.14
OTHER PLANTS				
Pre-Title IV	$N = 2206$			
Net delivered coal price (1995 $/ton)	13.030	6.923	-5.111	33.157
Rail distance to PRB (miles)	394.224	234.267	12	1216
Plant served by multiple RRs	0.143	0.350	0	1
Plant captive to one RR	0.850	0.356	0	1
Nameplate capacity (GWe)	1.233	1.183	0.116	3.564
SO_2 content (tons per	0.013	0.001	0.008	0.016
Heat content (Btus/lb)	12762.03	418.391	10943	14296
Ash content (% by weight)	9.035	2.158	3.48	17.4
Title IV	$N = 1678$			
Net delivered coal price (1995 $/ton)	9.075	6.451	-14.852	32.584
Rail distance to PRB (miles)	368.937	235.991	12	1216
Plant served by multiple RRs	0.122	0.328	0	1
Plant captive to one RR	0.837	0.368	0	1
Nameplate capacity (GWe)	1.431	1.247	0.116	3.564
SO_2 content (tons per	0.013	0.001	0.006	0.016
Heat content (Btus/lb)	12688.24	481.000	9909	15373
Ash content (% by weight)	9.628	2.629	3.47	24.6

Table 9: Results from OLS estimation: Low-sulfur coal from Central Appalachia

Dependent variable: Delivered coal price net of minemouth price (1995 $/ton)	Table A (1)	All plants (2)
Rail distance	0.012 **	0.015 **
	(0.002)	(0.001)
Title IV	0.073	-3.006 **
	(0.834)	(0.800)
Title IV × rail distance	-0.001	-0.000
	(0.002)	(0.002)
Table A plant		1.089
		(1.841)
Table A × rail distance		-0.008 *
		(0.004)
Table A × Title IV		2.530
		(2.773)
Table A × Title IV × rail distance		-0.001
		(0.005)
SO_2 content (pre-Title IV)	-457.364	
	(308.713)	
SO_2 content (Title IV)	606.774 *	
	(284.697)	
SO_2 content (non-Table A; pre-Title IV)		11.649
		(120.240)
SO_2 content (non-Table A; Title IV)		-65.013
		(124.190)
SO_2 content (Table A; pre-Title IV)		-432.352
		(491.504)
SO_2 content (Table A; Title IV)		577.822
		(424.369)
Heat content	0.006 **	0.003 **
	(0.001)	(0.001)
Ash content	0.271	-0.655 **
	(0.199)	(0.182)
Nameplate capacity	1.266 **	-0.328
	(0.358)	(0.254)
Table A × nameplate capacity		2.362 *
		(1.080)
Title IV × nameplate capacity	0.125	0.592
	(0.651)	(0.305)
Table A × Title IV × nameplate capacity		-1.160
		(1.595)
Plant served by multiple RRs × RR distance		-0.006 **
		(0.001)
Plant captive of RR × RR distance (no barge)		0.004 **
		(0.001)
Constant	3.693 **	5.349 **
	(0.958)	(0.733)
Monthly dummies?	Yes	Yes
Observations	1568	5452
R-squared	0.25	0.54

Notes: * significant at 5 % level ** at 1 % level.
Standard errors are clustered by plant-source-year triples.
Not presented: Heat and ash contents interacted with Title IV and Table A dummies.

Table 10: Quantities, revenues, and estimated producer surplus

	Quantity (million tons/year)	Revenues ($million/year)	Producer surplus ($million/year)
Pre-Title IV	5.6	78.0	37.0
Title IV	9.2	111	55.8

Notes: All figures represent annual averages, for spot deliveries to Table A plants only.

Quantities and revenues are based on reported prices and quantities.

Producer surplus is a back-of-the-envelope estimate using coefficients from OLS regressions; see discussion in text.

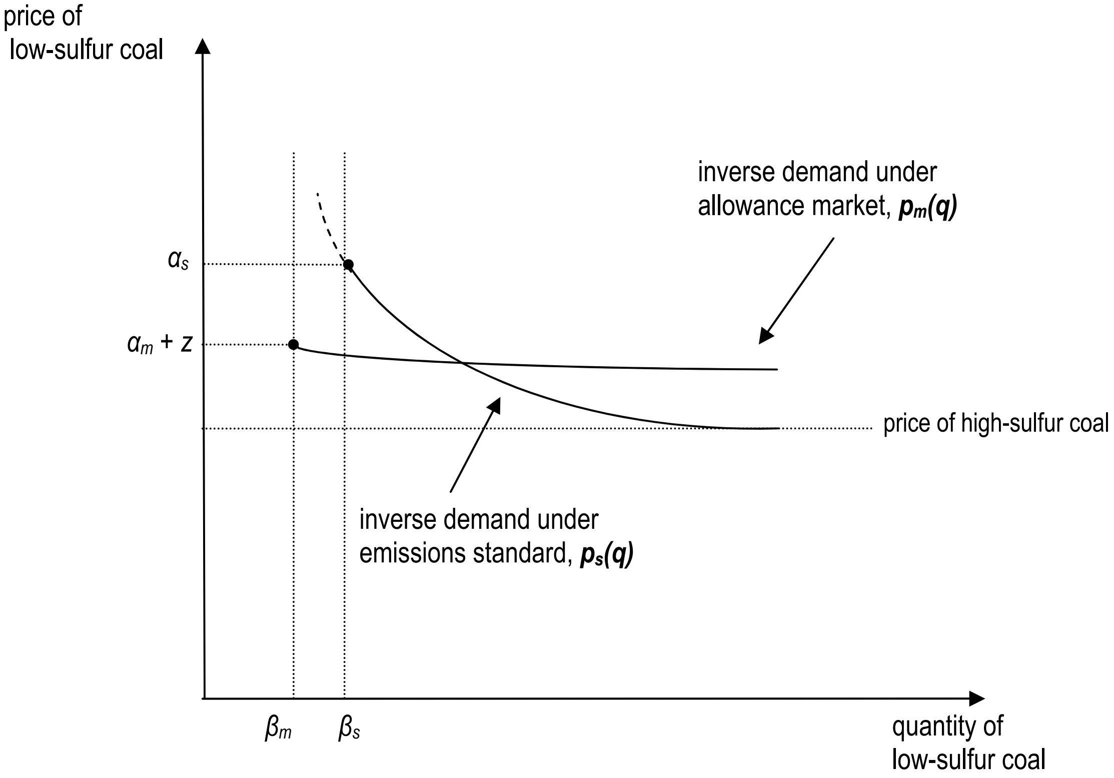


Figure 1 – Inverse demand functions under different emissions regulations.

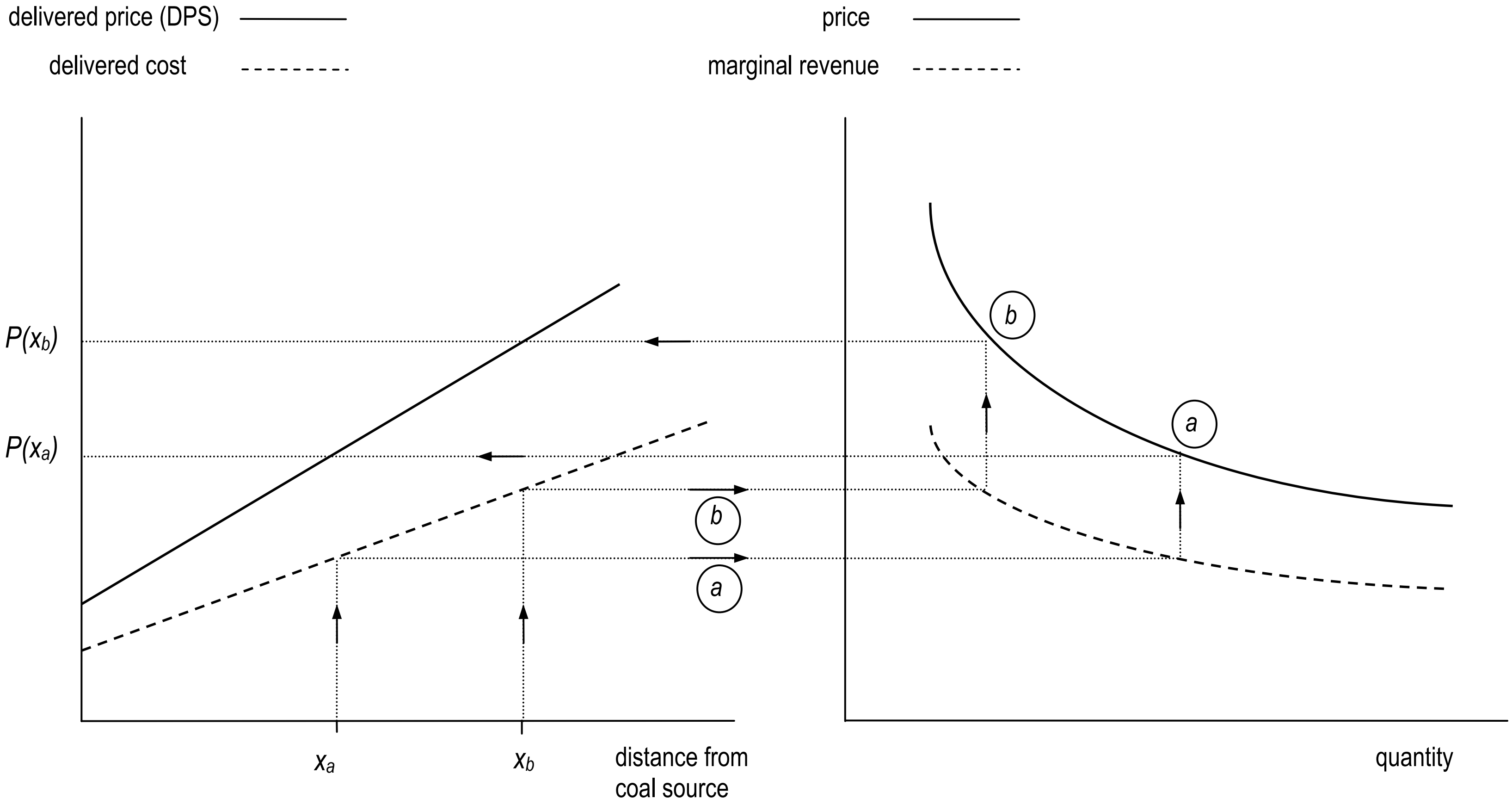


Figure 2 – Delivered cost, demand, and delivered price in the model with market power. The left-hand panel depicts delivered cost and delivered cost as a function of distance. The right-hand panel depicts inverse demand and marginal revenue as a function of quantity. Two plants are depicted, with plant *a* located closer to the low-sulfur coal origin than plant *b.* Note that the vertical axes are measured in the same units in both panels.

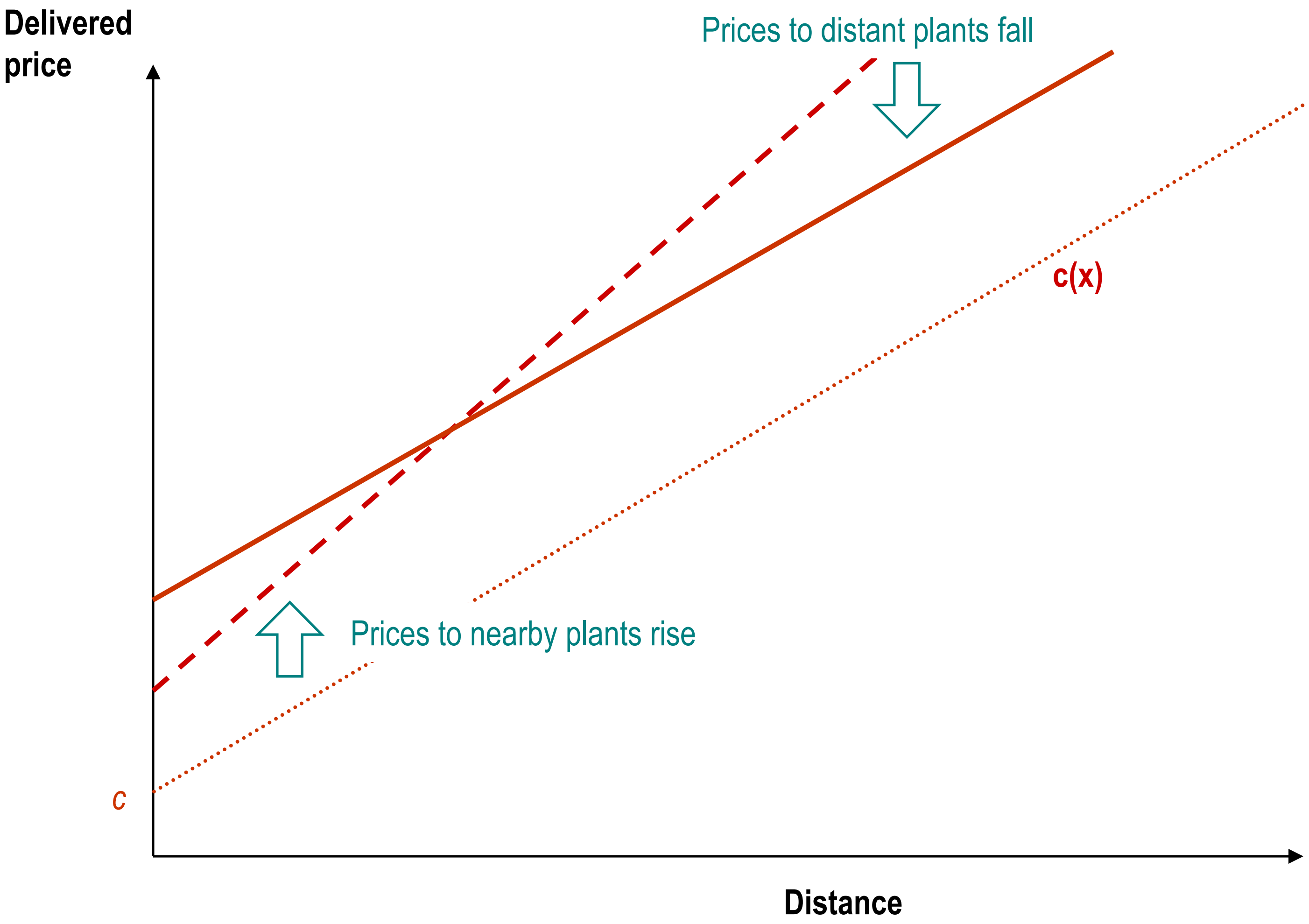


Figure 3 – A cap-and-trade regime can result in a pivot in the price schedule, relative to an emissions standard, with prices to nearby plants rising and those to more distant plants falling.

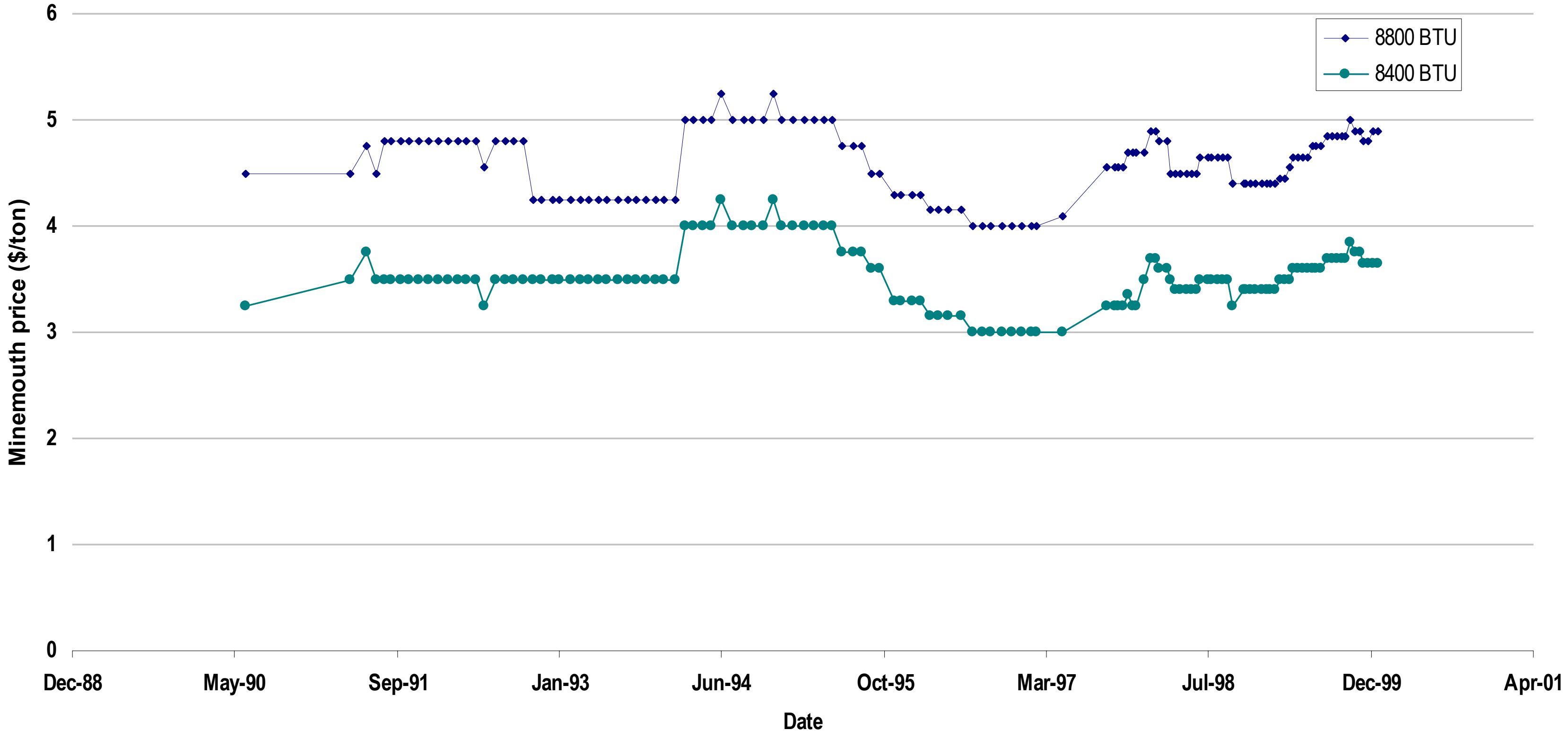


Figure 4 – Minemouth prices of PRB coal, 1990-1999.

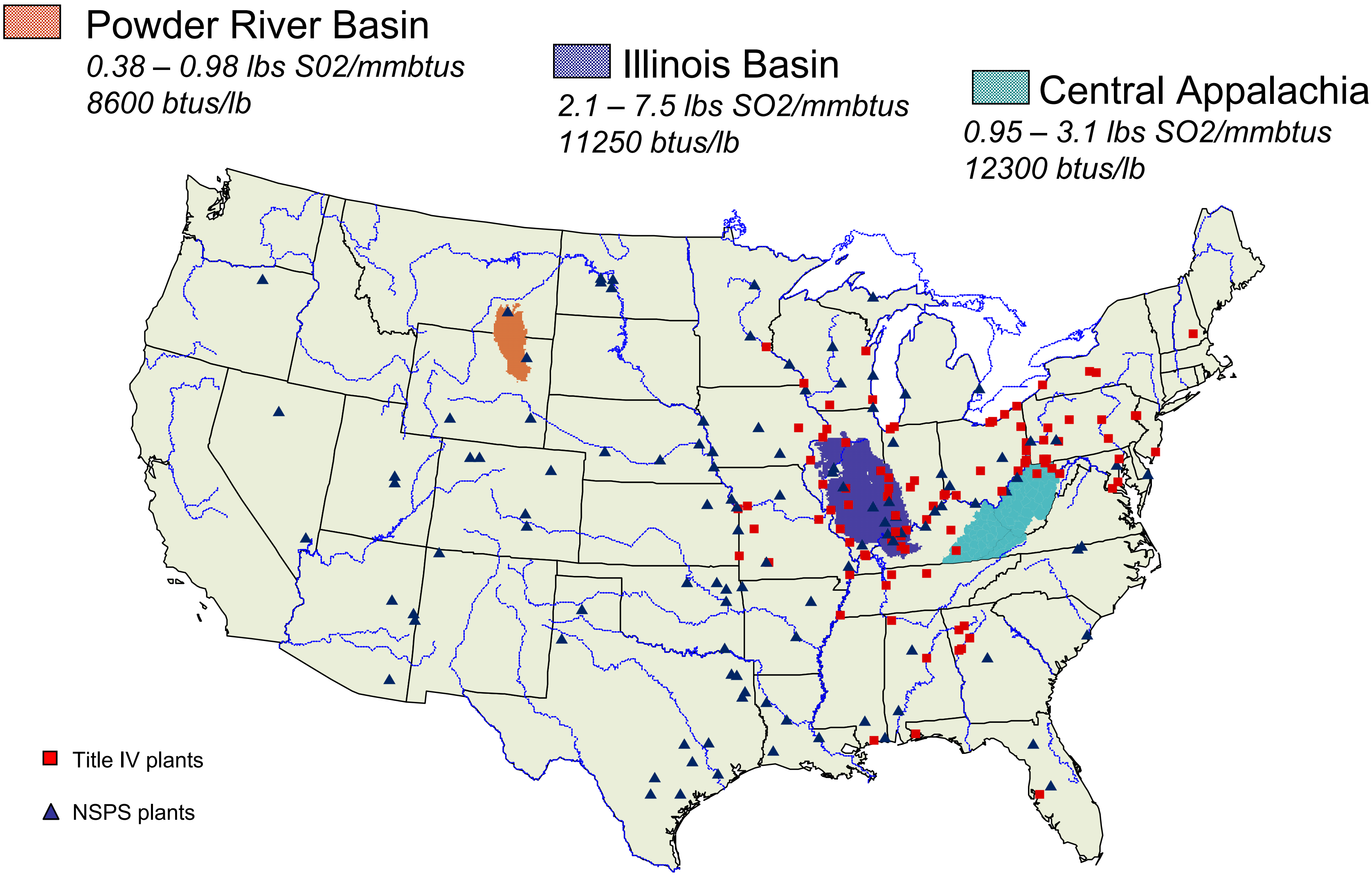
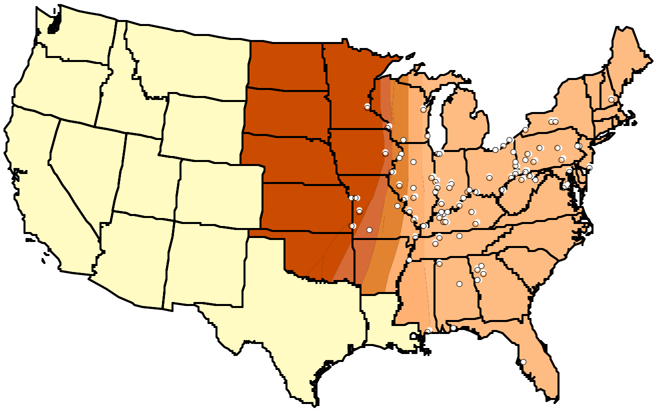


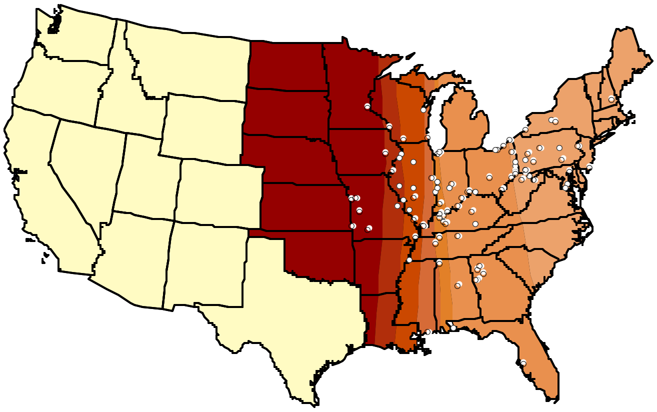
Figure 5 – Geographic distribution of regulated power plants and major coal deposits of the United States.

Figure 6 – Cumulative percentages of PRB coal to Table A plants, 1990-1999.

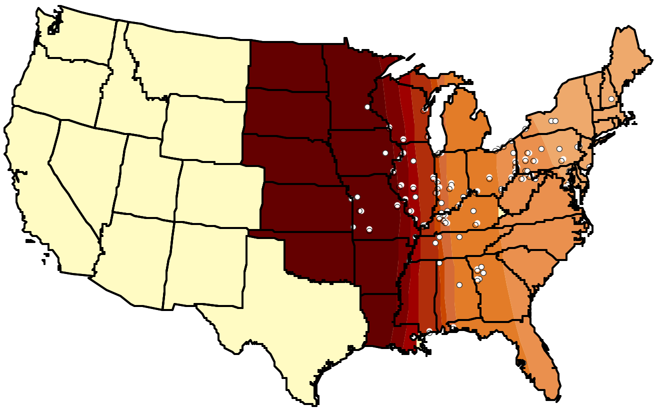
1990



1995

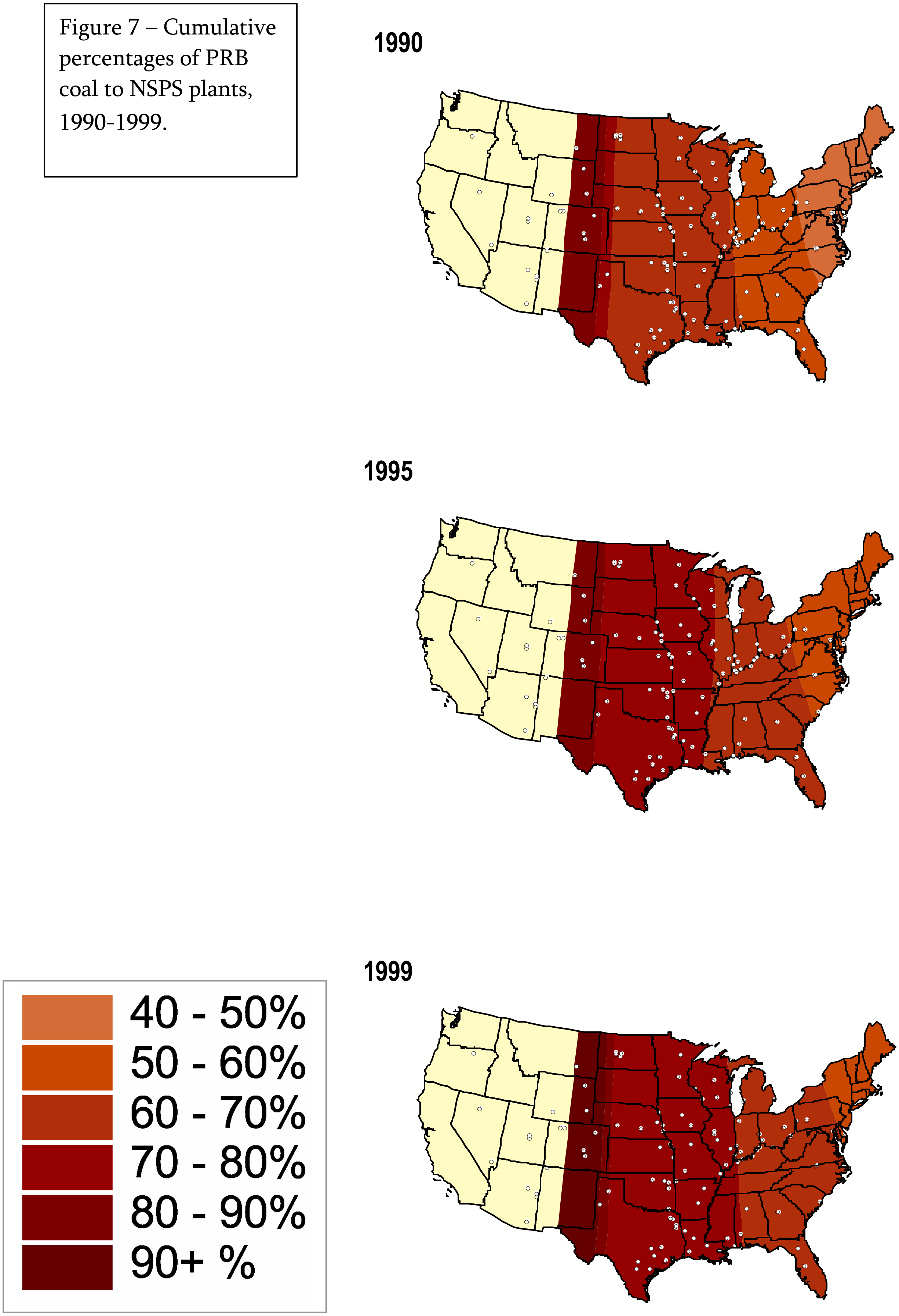


1999



- ■ 10 - 20%
- ■ 20 - 30%
- ■ 30 - 40%
- ■ 40 - 50%
- ■ 50 - 60%
- ■ 60 - 70%
- ■ 70 - 80%
- ■ 80 - 90%
- ■ 90+ %

Figure 7 – Cumulative percentages of PRB coal to NSPS plants, 1990-1999.



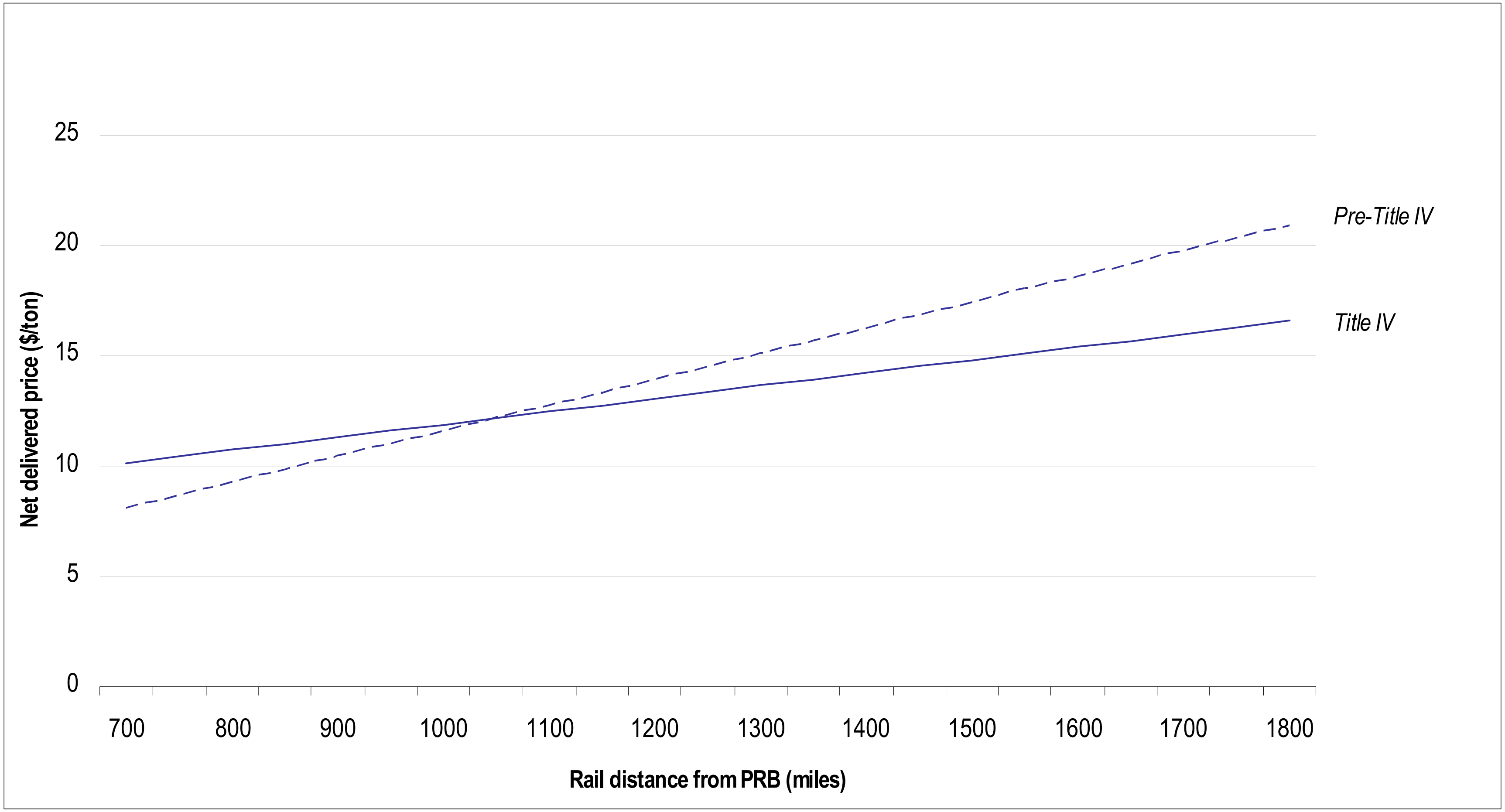


Figure 8 – Predicted price schedules for coal with average characteristics, to Table A plants, before and after the advent of the allowance market. Prices are "constant-cost" prices, net of the minemouth price and controlling for variable transportation costs.

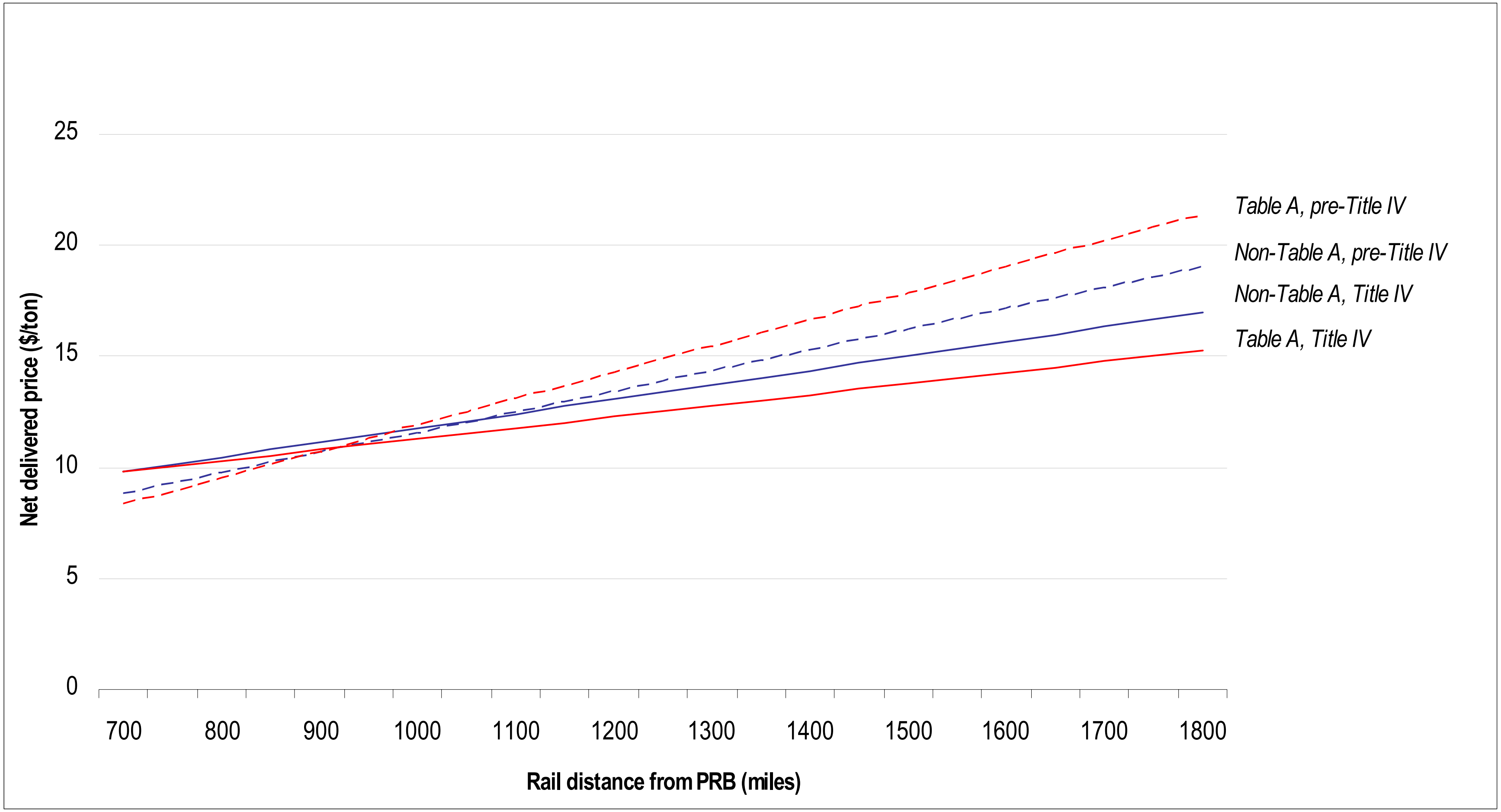


Figure 9 – Predicted "constant-cost" net delivered price schedules for both Table A and non-Table A plants, before and after the advent of the allowance market.

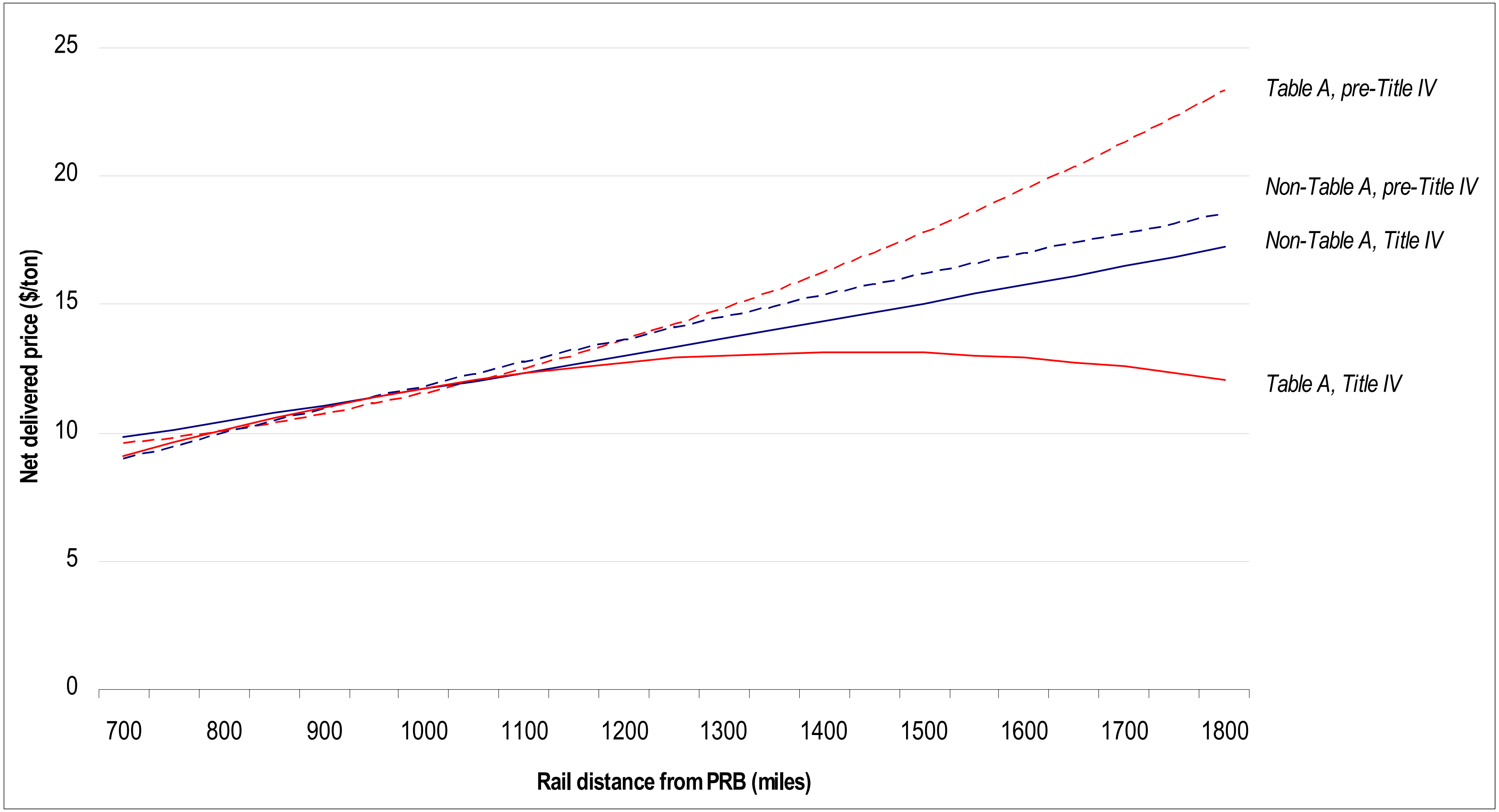


Figure 10 – Predicted “constant-cost” net price schedules, using estimates from simple second-order polynomial regressions.