Pass-Through in a Concentrated Industry: Empirical Evidence and Regulatory Implications*

Nathan H. Miller† Georgetown University

Matthew Osborne‡ University of Toronto

Gloria Sheu§ Department of Justice

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Abstract

We estimate pass-through with thirty years of data from the portland cement industry. Robust econometric evidence supports that fuel cost changes are more than fully transmitted downstream in the form of price changes. This validates an implicit pass-through assumption made in recent academic research and regulatory analyses. We combine the econometric results with estimates of competitive conduct obtained from the Miller and Osborne (2014) structural model to evaluate the incidence of market-based CO_2 regulation. Producers bear roughly 11% of the regulatory burden and could be compensated with 16% of the revenues obtained.

Keywords: pass-through, cap-and-trade, environmental regulation, portland cement
JEL classification: K3, L1, L5, L6

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†Georgetown University, McDonough School of Business, 37th and O Streets NW, Washington DC 20057. Email: nhm27@georgetown.edu.

‡University of Toronto, Rotman School of Management, 105 St. George St., Toronto, ON, Canada M5S 3E6. Email: matthew.osborne@rotman.utoronto.ca

§Department of Justice, Antitrust Division, Economic Analysis Group, 450 5th St. NW, Washington DC 20530. Email: gloria.sheu@usdoj.gov.

1 Introduction

The distributional consequences of taxation in imperfectly competitive markets depend on pass-through and markups (Weyl and Fabinger (2013); Atkin and Donaldson (2015)). This theoretical result poses a substantial challenge for applied research on incidence: reduced-form estimates of pass-through are insufficient if firms exercise market power, whereas structural models that allow for the recovery of markups often rely on tractable functional forms that predetermine pass-through. This issue is particularly salient for the study of emissions-intensive industries because production in these sectors often requires investments and fixed costs that necessitate high markups in equilibrium.

In this paper, we estimate pass-through in the portland cement industry using reduced-form regression techniques. We combine the results with estimates of markups derived from an earlier study of the industry (Miller and Osborne (2014)) to evaluate the distributional consequences of market-based regulation that places a price on CO_2 emissions. The portland cement industry accounts for roughly five percent of global anthropogenic CO_2 emissions, and also is a source of local pollutants such as particulate matter and mercury (Van Oss and Padovani (2003)). Market power arises due to spatial differentiation: cement is transported by truck to ready-mix concrete plants and large construction sites, and the associated costs typically account for a sizable portion of purchasers' total expenditures.

Our regression equation derives from a general class of oligopoly models. We show how regressors can be constructed in a manner that preserves the oligopoly interactions, even if only aggregated prices are observed. In our application, we rely on variation in region-specific average prices over the period 1980-2010. We calculate the fuel costs of each plant based on fossil fuel prices and kiln technology, and estimate pass-through by regressing observed prices on fuel costs that are averaged to the region level. Unbiasedness is obtained under standard orthogonality assumptions that are defensible given the institutional details of the empirical setting. To provide one such detail, there are no viable substitutes for fossil fuel in the production process because inputs (e.g., limestone and heat) are used in fixed proportions. As such, fuel costs plausibly are uncorrelated with unobserved costs, especially once plant fixed effects absorb any plant-specific factors related to the kiln technology.

The primary econometric result is that market-wide costs changes are more than fully passed through to cement prices. The result is robust across a range of specifications and modeling choices, and the confidence intervals are sufficiently tight to reject that pass-through is substantially incomplete. Weyl and Fabinger (2013) demonstrate that, in a general symmetric model of oligopoly, for pass-through to exceed unity it is sufficient that marginal costs are constant, firms exercise market power, and demand is log-convex. The model provides the testable auxiliary prediction that competition reduces pass-through under the same conditions. We find support for this auxiliary prediction in the data, using measures of competition based on the number, proximity, and capacity of nearby plants. Given the presence of plant fixed effects, identification of this interactive effect rests on entry, exit, and fluctuations in the diesel price, the last of which affects transportation costs and the magnitude of localized market power.

We evaluate the incidence of market-based CO_2 regulation using the Weyl and Fabinger (2013) model of symmetric oligopoly. The effect of regulation on consumer surplus is determined by pass-through, while the effect on producer surplus depends on pass-through and a conduct parameter that equals the multiplicative product of firm margins and the elasticity of market demand. Our econometric estimates inform pass-through but not the conduct parameter. By contrast, recently estimated structural models of the industry have bearing on the conduct parameter, but are insufficiently flexible to inform pass-through. Thus, we calculate distributional effects for a range of pass-through that reflects the confidence intervals obtained in this paper, and a range of conduct parameters that reflects confidence intervals obtained from a bootstrap of the Miller and Osborne (2014) structural model. At the middle of these distributions, the pass-through that we estimate implies that cement producers bear 11% of the regulatory burden and could be fully compensated with 16% of the revenues obtained from regulation.

This counterfactual analysis has limitations, and we highlight three here. First, our approach does not enable us to put a confidence bound on the harm to producers because there is no straightforward way to compute the statistical covariance between pass-through and conduct. Both theory and our reduced-form results suggest this covariance is positive for pass-through in excess of unity, and we discuss the implications of such a relationship qualitatively. Second, our approach does not inform the extent of heterogeneity that arises among producers and consumers. We rely on the symmetric model because it comports with our econometric estimates, which capture the average effect of fuel costs on prices. Finally, the results may not convey to other sectors. A new working paper finds that portland cement is one of the few U.S. manufacturing sectors in which pass-through exceeds unity; more commonly pass-through is incomplete (Ganapati, Shapiro, and Walker (2016)).

In an extension, we evaluate recent regulations promulgated by the EPA to reduce emissions of hazardous air pollutants, including particulate matter, mercury, hydrocarbons, and hydrogen chloride. The EPA indicates that the monetized health benefits of regulation outweigh economic costs (EPA (2009); EPA (2010)), the latter of which can be first order if firms exercise market power (e.g., Buchanon (1969)). Our analysis corroborates the simulation results developed by the EPA. The pass-through estimates imply average price increases of \$4.78 across 20 local markets, relative to a simulation average of \$4.66. Further, there is a high degree of correlation in the predictions across markets. We believe this is attributable to a fortuitous selection of functional forms in the EPA simulation model.

Our analysis complements the research of Fowlie, Reguant, and Ryan (2016) on the long run effects of market-based CO_2 regulation. That study relies on a dynamic structural model in which payoffs are based on undifferentiated Nash-Cournot competition among cement plants facing a constant-elasticity market demand curve. Pass-through in this context is fully determined by the number of plants and the demand elasticity. We derive the pass-through rates implied by the model, over the range of elasticities by the authors, and show that they comport with our econometric estimates. Thus, our results support a previously untested modeling assumption that has first order implications for welfare effects.

A small literature focuses more directly on the distributional impacts of market-based CO_2 regulation. Bovenberg, Goulder, and Gurney (2001) and Smith, Ross, and Montgomery (2002) analyze calibrated general equilibrium models and of the U.S. economy, and determine that the free allocation of tradable emissions permits would substantially overcompensate firms. Burtraw and Palmer (2008) examine electricity generation specifically using a detailed industry model, and find that electricity generators can be fully compensated with small fraction of the total allowance value. Bovenberg, Goulder, and Jacobsen (2008) examine a number of related mechanism design issues using a calibrated general equilibrium model. Hepburn, Quah, and Ritz (2013) develop the theoretical result that market-based regulation is profit neutral if incumbents are freely allocated permits that cover a fraction of emissions not exceeding the Herfindahl index. Goulder (2013) provides a useful review. We contribute to the methodological diversity of this literature, even as our results reinforce that most of the regulatory burden is likely to fall downstream.[1]

Our research is one of a growing number of contributions that apply the "pass-through as a tool" paradigm of Weyl and Fabinger (2013) to empirical settings. Atkin and Donaldson (2015) use pass-through to account for markups while estimating the magnitude of intra-

[1]Firms may lobby for a favorable allocation of tradable permits even if they experience little harm. Indeed, regulation can be a windfall for firms if enough permits are allocated freely. The Portland Cement Association did not take a formal stance on the 2009 Waxman-Markey cap-and-trade bill, but we cannot rule out private communications and negotiations. The bill was going to provide 85% of the permits for free through 2014 and then phase into a full auction by 2024. Many of the free permits were designated for energy-intensive industrial sectors such as cement, steel, iron, and paper, so the outcome could be interpreted as consistent with an effective lobbying effort.

national trade costs.[2] Cabral, Geruso, and Mahoney (2015) and Duggan, Starc, and Vabson (2014) find support for incomplete pass-through in the Medicare Advantage market, and the former article shows that pass-through tends to be somewhat higher in counties with more competitors. This interactive effect of competition is consistent with the general symmetric oligopoly model given that pass-through is incomplete, and does not conflict with our own results. Argarwal, Chomsisengphet, Mahoney, and Stroebel (2014) estimate the effect of jet fuel prices on airline ticket prices, and use this pass-through relationship to assess the consumer benefits of regulating hidden fees. Kremer and Snyder (2015) relate investments in preventative and treatment medicines to differences in the curvature of consumer values before and after diagnosis.

The broader empirical literature on pass-through is too large to summarize fully here. Research has exploited cost variation from a number of factors, including exchange rates (e.g., Campa and Goldberg (2005); Gopinath, Gourinchas, Hsieh, and Li (2011)), sales taxes (e.g., Barzel (1976); Poterba (1996); Besley and Rosen (1998); Marion and Muehlegger (2011); Conlon and Rao (2016); Campos-Vazquez and Medina-Cortina (2016)), and input prices (e.g., Borenstein, Cameron, and Gilbert (1997); Genesove and Mullin (1998); Besanko, Dube, and Gupta (2005); Nakamura and Zerom (2010)). Empirical support for pass-through in excess of unity is common, though far from ubiquitous, in this literature. Of particular relevance is Fabra and Reguant (2014), which finds that costs imposed by the emissions trading scheme of the European Union are almost fully passed-through to consumers in the form of higher electricity prices. Stolper (2016) adopts a version of our regression specification and finds that higher pass-through in wealthier areas makes diesel taxes progressive.

The paper proceeds as follows. Section 2 provides the relevant institutional details of the portland cement industry and describes the available data. Section 3 sketches the symmetric oligopoly model of Weyl and Fabinger (2013). We show that pass-through can exceed unity under certain economic conditions, and that competition reduces pass-through in that case. Section 4 develops the regression model and discusses identification. It also provides methodological details about how we obtain conduct from the Miller and Osborne (2014) model and why it is difficult to place a confidence bound on producer surplus effects. Sec-

[2] Atkin and Donaldson (2015) assume that competition (and markups) are purely local, unobserved, and specific to the origin-destination pair. To implement, the authors estimate pass-through with subsample regressions on individual origin-destination pairs in a first stage. Pass-through is then substituted into a second stage regression that recovers how distance affects trade costs. The dependent variable in the second stage is the pass-through adjusted price gap between the origin and destination, and the main independent variable is the log-distance between the origin and destination. By contrast, in our setting competition is non-local and we use the distance between plants as an observed measure that shifts the degree of competition. We use this observed "competition-shifter" to estimate how pass-through varies with competition.

tion 5 defines the variables used in the regressions. Section 6 presents the regression results and shows that the econometric estimates validate the implicit pass-through assumption of Fowlie, Reguant, and Ryan (2016). Section 7 develops implications for the market-based regulation of CO_2 and the EPA regulation of hazardous air pollutants. Section 8 concludes with a short discussion about possible directions for future research.

2 The Portland Cement Industry

2.1 Institutional details

Portland cement is a finely ground dust that forms concrete when mixed with water and coarse aggregates such as sand and stone. Concrete, in turn, is an essential input to many construction and transportation projects. The production of cement involves feeding limestone and other raw materials into rotary kilns that reach peak temperatures of 1400-1450° Celsius. Plants burn fossil fuels – mostly coal and petroleum coke – to produce these extreme kiln temperatures. Emissions of CO_2 range from 0.86 to 1.05 metric tonnes per metric tonne of cement, depending on the kiln technology. Of this, roughly 0.51 metric tonnes arise from the chemical conversion of calcium carbonate into lime and carbon dioxide. The combustion of fossil fuels accounts for most of the remainder.[3]

Capital investments over the last forty years have increased the industry's capacity and productive efficiency. Table 1 provides snapshots of the industry over 1980-2010. During this period, a significant amount of plant exit coincides with a major technological shift, as older wet kilns and long dry kilns are replaced with more efficient modern dry kilns.[4] Total industry capacity increases even as the number of plant and kilns falls. This variation is

[3]The CO_2 emissions rates are 1.05, 0.98, 0.87, and 0.86 for wet, long dry, dry preheater and dry precalciner kilns, respectively. Our calculations are consistent with the Cement CO_2 Protocol, developed by leading cement firms for the Cement Sustainability Initiative of the World Business Council for Sustainable Development. We scale up the impact of converting calcium carbonate to 0.525, in order to account for CO_2 emitted during the calcination of cement kiln dust. We add to this the CO_2 emitted from the burning of coal, based on an emissions factor of 0.095 metric tonnes per mBtu and the kiln energy requirements reported in Appendix B. We then scale down total emissions by five percent to convert units of clinker to units of cement. Similar calculations underly the analysis in Fowlie, Reguant, and Ryan (2016).

[4]For wet kilns, the raw materials are wet-ground to form a slurry, but for dry kilns the raw materials are dry-ground to form a powder. More fuel is required in the wet process to evaporate the added water. Modern dry kilns use exhaust gases from the kiln to preheat the raw material used in cement production. This allows calcination, one of the major chemical reactions required in clinker production, to occur partially or fully outside the rotary kiln. The process is supplemented with an additional combustion chamber if a precalciner is present. There is no systematic relationship between the kiln technology and the primary fossil fuel that is used to fire the kiln. Adjustment costs limit the profitability of switching fuels in response to changing relative prices.

Table 1: Plants and Kilns in the Cement Industry

	Number of Plants	Number of Kilns	Total Capacity	Capacity Share: Wet Kilns	Long Dry Kilns	Dry with Preheater	Dry with Precalciner
1980	142	319	77,100	49%	27%	16%	8%
1985	126	250	77,046	36%	24%	16%	24%
1990	109	208	72,883	32%	23%	19%	27%
1995	107	203	74,655	28%	22%	19%	30%
2000	107	196	82,758	24%	20%	17%	39%
2005	105	181	93,968	15%	14%	17%	54%
2010	101	153	103,482	8%	9%	14%	70%

Notes: Total capacity is in thousands of metric tonnes. All data are for the contiguous United States and are obtained from the PCA Plant Information Survey.

important in our empirical analysis for two reasons: first, it helps to identify pass-through, because changes in industry technology affect kiln efficiency and as a consequence plant level fuel costs; second, it aids in the identification of the interaction between competition and pass-through, since plant exit creates variation in competitive conditions over time.

Cement manufacturers sell predominately to ready-mix concrete producers and large construction firms. Contracts are privately negotiated and relatively short term (often around one year in duration). They specify a free-on-board price at which cement can be obtained from the plant, along with discounts that reflect the ability of the customer to source cement from competing manufacturers. While some cement manufacturers are vertically integrated into ready-mix concrete markets, Syverson and Hortaçsu (2007) show that this has little impact on plant- and market-level outcomes.

Figure 1 provides a map of the cement industry in 2010. Most cement is trucked directly from the plant to the customer, although some cement is transported by barge or rail first to distribution terminals and only then trucked to customers. Transportation accounts for a substantial portion of purchasers' total acquisition costs, because portland cement is inexpensive relative to its weight. Miller and Osborne (2014) estimate transportation costs to be \$0.46 per tonne-mile, and determine that these costs create market power for spatially differentiated plants. Accordingly, the academic literature commonly models the industry using a number of geographically distinct local markets (e.g., Ryan (2012); Fowlie, Reguant, and Ryan (2016)). Aside from these spatial considerations, cement is viewed as a commodity. Foreign cement enters the domestic market through a number of customs districts that we

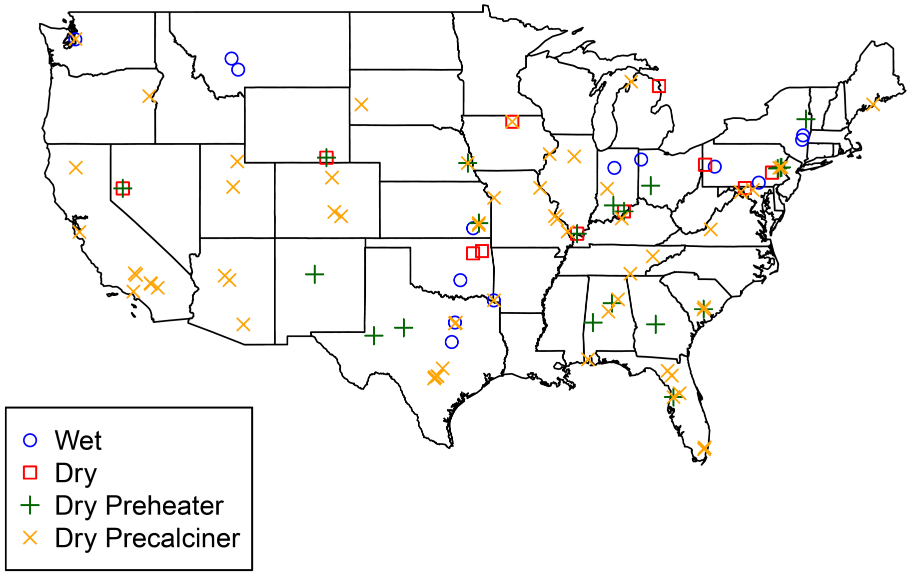

Figure 1: The Portland Cement Industry in 2010

refer to in this paper as ports, while exports are negligible.[5]

2.2 Data sources

We draw data from numerous sources. Chief among these is the *Minerals Yearbook*, an annual publication of the Unites States Geological Survey (USGS), which summarizes a census of portland cement plants.[6] The price data are aggregated to protect the confidentiality of census respondents, and reflect the average free-on-board price obtained by plants located in distinct geographic regions. The USGS frequently redraws boundaries to ensure that each region includes at least three independently owned plants. This "rule of three" prevents any one firm from backward engineering the business data of its competitors. Thus, the regions are not intended to approximate local markets in any economic sense. The *Minerals Yearbook* also contains aggregated production and consumption data, as well as the location of the customs districts through which foreign imports enter the domestic market. Our regression sample uses USGS data over 1980-2010, which yields 773 region-year observations.

Our second source of data is the *Plant Information Survey*, an annual publication of the Portland Cement Association (PCA), which provides information on the plants and kilns

[5]Due to technological advances in the late 1970s, cement now can be shipped economically from Asia and Europe via ocean freighters, and then trucked to customers. Imports are highly procyclical and appear to fill the gap between demand and domestic capacity (e.g., Miller and Osborne (2014)).

[6]The census response rate is typically well over 90 percent (e.g., 95 percent in 2003), and USGS staff imputes missing values for the few non-respondents based on historical and cross-sectional information.

in the United States. We obtain the location, owner, and primary fuel of each plant, as well as the annual capacity of each rotary kiln and the type of technology employed. In total, there are 3,494 plant-year observations over 1980-2010, of which 3,445 are active and 49 are idle. We also make use of the PCA's *U.S. and Canadian Portland Cement Labor-Energy Input Survey*, which is published intermittently and contains information on the energy requirements of clinker production and the energy content of fossil fuels burned in kilns. We have data for 1974-1979, 1990, 2000, and 2010.

We obtain data on the national average delivered bituminous coal price in the industrial sector over 1985-2010 from the annual *Coal Reports* of the Energy Information Agency (EIA). We backcast these prices to the period 1980-1984 using historical data on national average free-on-board prices of bituminous coal published in the 2008 *Annual Energy Review* of the EIA. We obtain national data on the prices of petroleum coke, natural gas, and distillate fuel oil, again for the industrial sector, from the State Energy Database System (SEDS) of the EIA.[7] We obtain data on the national average price of unleaded gasoline over 1980-2010 from the Bureau of Labor Statistics, in order to better model the spatial configuration of the industry. We convert this series to an index that equals one in 2000. Lastly, to help control for demand, we obtain county-level data from the Census Bureau on construction employees and building permits. We provide details on data sources and related topics in Appendix B.

3 Pass-Through and Market-Based Regulation

We first develop pass-through in the symmetric oligopoly model of Weyl and Fabinger (2013) and then discuss the relevance for market-based regulation. Let the oligopoly consist of n firms, each of which produces quantity q at cost $c(q)$. Firms receive the price $p(q)$, assuming symmetric quantities. Let $Q = nq$ be the market quantity, $\epsilon_D = \frac{p}{p'q}$ be the market elasticity of demand, and $mc(q) \equiv c'(q)$ be the marginal cost. Market power is summarized by a conduct parameter, $\theta = \frac{p-mc}{p}\epsilon^D$, that equals the elasticity-adjusted Lerner index. This formulation remains quite general, nesting the homogeneous products Nash-Cournot model, the

[7]The SEDS also includes data on coal prices, but no distinction is made between bituminous coal, sub-bituminous coal, lignite, and anthracite, despite the wide price differences that arise between those fuels. We also obtain state-level data on fossil fuel prices. There are many missing values at that level of reporting, and we impute these as described in Appendix B. Using fuel costs variables based on state-level fossil fuel prices has virtually no effect on our results, so long as plant fixed effects are included in the specification. We use the national fuel prices in our baseline specifications because, when included together in regressions, fuel cost variables based on national fossil fuel prices dominate those based on state-level prices. This could due to noise introduced by the imputation of missing values in the state-level data.

differentiated products Nash-Bertrand model, and many others.[8] Lastly, let $\epsilon_S = \frac{S'p}{Q}$ be the elasticity of the inverse marginal cost curve ("the supply function"), and let $\epsilon_\theta = \frac{d\theta}{dq}\frac{q}{\theta}$ summarize how the conduct parameter changes with quantity. We focus on comparative statics around a single symmetric equilibrium, while acknowledging that market-based regulation possibly could shift the market to a different equilibrium.

Output satisfies the following first-order conditions in equilibrium:

$$p(q) = mc(q) + \theta ms(q) \tag{1}$$

where $ms = p'Q$ is the marginal surplus that consumers earn when quantity expands. Equation (1) is a generalized version of the markup equation that often appears in structural models of competition. An important point is that pass-through, which captures the response of price to a small increase in marginal cost, must be derived implicitly from equation (1), since price enters the right hand side of the equation through its relationship with quantity. Weyl and Fabinger (2013) show that in this general model of symmetric oligopoly, pass-through can be derived as a function of conduct, the elasticity of conduct with respect to quantity, the elasticity of marginal surplus with respect to quantity, $\epsilon_{ms} = \frac{ms}{ms'q}$, and the demand and supply elasticities. Denoting pass-through as ρ, the function is:

$$\rho = \frac{1}{1 + \theta\epsilon_\theta + \frac{\epsilon_D - \theta}{\epsilon_S} + \frac{\theta}{\epsilon_{ms}}}. \tag{2}$$

An important determinant of pass-through is demand curvature, which can be measured by $\frac{1}{\epsilon_{ms}}$: this reciprocal is positive if demand is log-concave and negative if demand is log-convex. Log-concavity is sufficient for marginal revenue to be globally decreasing in quantity, and often is assumed in the theoretical literature. However, log-convexity can arise in number of well-known demand systems, including the Almost Ideal Demand Systems (AIDS) of Deaton and Muellbauer (1980), some forms of Frechet demand, and the CES demand system.

In equation (2), the conduct parameter scales between monopoly ($\theta = 1$) and marginal cost pricing ($\theta = 0$). To push intuition further, consider that in the latter instance pass-

[8] The conduct parameter is equivalent to the Rothschild Index (Rothschild (1942)), a measure of monopoly power based on the ratio of the industry elasticity to the firm-specific elasticity. It equals one with monopoly, zero with perfect competition, $1/n$ with Nash-Cournot, and $1-D$ with differentiated products Nash Bertrand, where D is the aggregate diversion ratio defined in Shapiro (1996).

through is fully determined by the relative elasticities of demand and supply:

$$\lim_{\theta \to 0} \rho = \frac{1}{1 + \frac{\epsilon_D}{\epsilon_S}} \tag{3}$$

This is the familiar result that in perfect competition it is the inelastic side of the market that bears the burden of taxation. Pass-through converges to this limit *from above* if demand is log-convex because in that case $\frac{1}{\epsilon_{ms}} < 0$. This relies on ϵ_θ being negative or zero, as is the case in standard models.[9] Thus, for pass-through to exceed unity it is sufficient that marginal costs are constant, firms exercise market power, and demand is log-convex. (Mathematically, this corresponds to $\frac{\epsilon_D}{\epsilon_S} = 0$, $\theta > 0$, and $\frac{1}{\epsilon_{ms}} < 0$.) Under these conditions, pass-through decreases as the conduct parameter moves toward zero.[10]

We comment briefly on the role of demand curvature in driving pass-through. Greater convexity in demand can be conceptualized as corresponding to greater heterogeneity in willingness-to-pay (WTP) among consumers. Thus, for instance, markets with log-convex demand have some consumers with very high WTP as well as many consumers with relatively low WTP. Cost increases then can cause large price increases because firms are induced to abandon the low-WTP consumers and price to the high-WTP consumers. Analogously, cost decreases result in large price decreases because the many low-WTP consumers become profitable. The converse analysis hold for concave demand curves: the greater is consumer homogeneity, the less firms will be inclined to pass-through cost changes.[11]

We model market-based regulation as a per-unit tax, t, that is levied on all firms. The

[9] A number of nested models, including homogeneous-products Nash-Cournot competition, produce a θ that is invariant to quantity, but the restriction does not hold generally. For example, in models of differentiated-products Nash-Bertrand competition and discrete-choice based demand, θ decreases with quantity ($\epsilon_\theta < 0$). This amplifies pass-through because higher prices soften competitive conduct.

[10] Pass-through also exceeds unity if $\theta = 0$ and the industry marginal cost schedule decreases in output, in which case $\epsilon^S < 0$. That does not seem likely in our application. So long as firms have heterogeneous costs, the low cost firms will be on the left of the industry marginal cost curve and high cost firms will be on the right, and this suggests an upward-sloping industry marginal cost curve. This effect of heterogeneity could be dominated by downward-sloping plant-specific marginal cost curves, but that seems unlikely to us given the institutional details of the industry. Recent structural research assumes that the marginal costs of each plant are constant over a broad range, and then upward-sloping above some utilization threshold (e.g., Ryan (2012); Miller and Osborne (2014); Fowlie, Reguant, and Ryan (2016)).

[11] That pass-through can exceed unity does not depend on the symmetry of the model, and we refer interested readers to Appendix A for a short discussion of pass-through in asymmetric oligopoly.

following principles of incidence hold provided the tax is arbitrarily small:

$$\frac{dCS}{dt} = -\rho Q \tag{4}$$

$$\frac{dPS}{dt} = -\left(1-\rho(1-\theta)\right)Q \tag{5}$$

where CS and PS are consumer surplus and producer surplus, respectively. Equation (4) is obtained by applying the envelop theorem to consumers. Equation (5), initially derived in Atkin and Donaldson (2015), shows that pass-through moderates the loss of producer surplus but that, because higher prices generate fewer sales, this moderating effect diminishes with margins as summarized by the conduct parameter. In our counterfactual analysis we examine changes in the implicit price of carbon emissions that are potentially large. As a result we interpret our welfare findings as approximations. In principle, equations (4) and (5) could be adjusted using weighted-averages over relevant range, but because this range extends beyond the data there is little empirical basis for the adjustment.

4 Methodologies

4.1 Pass-through regression equation

Our econometric objective is to obtain an estimate of how market-wide cost changes affect price in the cement industry. The regression equation that we take to the data expresses the average price charged by plants in USGS region m and year t as

$$\overline{p}_{mt} = \alpha_{mt}\overline{c}_{mt} + \overline{x}'_{mt}\gamma + \overline{\mu}_{mt} + \overline{\epsilon}_{mt} \tag{6}$$

where $\overline{c}_{jt}$ is average fuel costs, $\overline{x}_{mt}$ is a vector of controls, $\overline{\mu}_{mt}$ is a region-time effect that we define later, and $\overline{\epsilon}_{mt}$ captures conditions unobserved by the econometrician. In some of our regressions, we impose that the pass-through parameter is invariant across regions and years (i.e., $\alpha_{mt} = \alpha_0 \; \forall m, t$). The OLS coefficient then is an unbiased estimate of the average effect of costs on prices if the standard orthogonality assumptions hold.

This regression equation can be derived from a broad class of oligopoly models. To demonstrate, we express the equilibrium prices of plant j in year t in the following linear form:

$$p_{jt} = \rho^*_{jjt}c_{jt} + \sum_{k\neq j}\rho^*_{jkt}c_{kt} + x'_{jt}\gamma + \sum_{k\neq j}x'_{kt}\gamma^* + \mu_j + \epsilon_{jt} \tag{7}$$

The equilibrium price response of firm j to a market-wide change in costs is determined by the sum of the firm-specific pass-through coefficients: $\rho_{jt} = \sum_k \rho^*_{jkt}$. This equation is easily obtained in differentiated products Nash-Bertrand models with linear demands, and is a linear approximation to equilibrium prices in many other models. We develop these connections in Appendix A using the model of Jaffe and Weyl (2013).[12]

The estimation of equation (7) is infeasible because there are more coefficients than observations. We make two restrictions to facilitate estimation. First, we let competitor costs affect equilibrium prices as follows:

$$\rho_{jkt} = \begin{cases} \beta g(z_{jkt}) & \text{if } g(z_{jkt}) > \overline{g} \\ 0 & \text{otherwise} \end{cases} \tag{8}$$

where the function $g(z_{jkt})$ provides the "closeness of competition" between any two plants $j \neq k$ given observable data z_{jkt}. The restriction imposes that closeness is both observable and unaffected by the characteristics of other plants. In implementation, we use measures of distance and competitor capacity to construct $g(z_{jkt})$, consistent with transportation costs being the main source of differentiation in the industry.[13] This treatment is directly analogous to the assumption of Pinske, Slade, and Brett (2002) that the strategic complementarity of prices in gasoline markets decreases in the geographic distance.

Second, we allow the pass-through of firm-specific cost changes to diminish with competition, consistent with the theoretical results of ten Kate and Niels (2005) for the undifferentiated Nash-Cournot model and Zimmerman and Carlson (2010) for the differentiated products Nash-Cournot and Nash-Bertrand models. We specify that each firm's costs affect its equilibrium prices according to

$$\rho_{jjt} = \alpha_0 + \alpha_1 \sum_{k \neq j,\, g(z_{jkt}) > \overline{g}} g(z_{jkt}) \tag{9}$$

Combining the two restrictions, the net effect of competition on the pass-through of market-

[12]This pricing equation is reduced-form because it expresses equilibrium prices as a function of exogenous determinants. It differs in this sense from the standard pricing equations that define the first order conditions for profit maximization (e.g., equation (1)) and that often are used to estimate the supply-side of structural models. In those first order conditions, prices appear on both sides of the equation due to the relationship between prices and markups. As we argue in Section 4.3, without auxiliary information the reduced-form approach does not allow for the recovery of markups or any structural parameters, and instead focuses on how exogeneous factors affect equilibrium prices (taking into account all the channels through which the factors affect prices).

[13]The approach can be applied to markets with product differentiation provided that a reasonable Euclidean distance in attribute-space can be calculated (e.g., as in Langer and Miller (2013)).

wide cost changes considered in Weyl and Fabinger (2013) is determined by the relative magnitudes of α_1 and β. The empirical model allows the data to determine whether this net effect is positive or negative. Thus, the restrictions solve the dimensionality problem while preserving flexibility in pass-through relationships.

Equations (7)-(9) provide the microfoundations of the regression equation. The linearity of the equilibrium pricing function facilitates aggregation to the region level, aligning the regressors with the observed price data. Suppose there exist $m = 1 \dots M$ regions, and denote as $\mathscr{J}_{mt}$ the set of plants that are in region m in period t. The USGS data provides the average price in a region as $\overline{p}_{mt} = \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} p_{jt}$, where ω_{jmt} is the fraction of the region's production accounted for by plant j. The same aggregation procedure can be applied to the regressors, and this obtains a region-level regression equation:

$$
\begin{aligned}
\overline{p}_{mt} &= \alpha_0 \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} + \alpha_1 \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \sum_{k \neq j,\, g(z_{jkt}) > \overline{g}} g(z_{jkt}) \\
&+ \beta \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} \sum_{k \neq j,\, g(z_{jkt}) > \overline{g}} c_{kt} g(z_{jkt}) \\
&+ \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} x'_{jt} \gamma + \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} \sum_{k \neq j,\, g(z_{jkt}) > \overline{g}} x'_{kt} \gamma^* \\
&+ \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} (\mu_j + \epsilon_{jt})
\end{aligned} \tag{10}
$$

The pass-through coefficients are separately identifiable if heterogeneity in the competitive conditions exists among regions (this distinguishes α_0 and α_1) and if plants have a sufficient number of out-of-region competitors with different fuel costs (this distinguishes α_1 and β). In our data, fuel costs tend to be highly correlated across plants, implying that the latter condition is unlikely to hold. As a result, we apply the normalization $\beta = 0$ and allow the net effect of competition to load onto α_1. We normalize $\gamma^* = 0$ for the same reason. The equivalence of equations (6) and (10) is completed with the following definitions:

$$
\begin{aligned}
\alpha_{mt} &= \alpha_0 + \alpha_1 \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} \sum_{k \neq j,\, g(z_{jkt}) > \overline{g}} g(z_{jkt}) \\
\overline{c}_{mt} &= \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \\
\overline{x}_{mt} &= \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} x_{jt} \\
\overline{\mu}_{mt} &= \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} \mu_{j} \\
\overline{\epsilon}_{mt} &= \sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} \epsilon_{jt}
\end{aligned}
$$

To proxy for the weights in aggregation, we assume that production within regions is proportional to capacity. This approach, necessitated by the lack of plant-level production data, is used by the EPA in its economic analysis of the industry (EPA (2010)). In the regression analysis, we weight the region-year observations by the number of plants so that the coefficients reflect the average plant-level effects (though this does not effect results).[14]

We wish to make two additional observations about the regression equation before proceeding. First, although the unit of observation is at the region level, competitive interactions that span the regional boundaries are incorporated. This is accomplished by defining all regressors at the plant level and then aggregating to the region level. Thus, regions need not comport with the local economic markets, and are better conceptualized as sets of plants loosely defined based on geographic criteria. Second, the restrictions we have placed on the empirical model enforce that pass-through is invariant to the magnitude of costs. This is not a general characteristic of oligopoly models, though a class of demand systems does generate constant pass-through (Bulow and Pfleiderer (1983)). To the extent that pass-through varies, our approach yields estimates of the average effect.

4.2 Identification

We estimate the empirical model with ordinary least squares (OLS). The error term in the model is a pricing residual that incorporates unobservable demand and cost conditions.

[14] Many of the plant fixed effects are collinear once aggregated to the region level. This is not always the case, however, because plants sometimes are observed in two or more regions within the sample period due to changes in region boundaries. We use the aggregated plant effects rather than region fixed effects in order to maintain a closer connection between the theory and empirical work.

Unbiasedness rests on orthogonality between fuel costs and the pricing residual. The institutional details support such an orthogonality assumption. That fuel costs could be correlated with unobserved costs is not obvious because the production process requires inputs (e.g., limestone and heat) in fixed proportions – there is no substitute for fossil fuel. Factor substitution causes more concern with Cobb-Douglas production functions.[15] Our regressions do not incorporate competitor costs, but this does not confound our estimates of market pass-through due to the high degree of collinearity mentioned above.[16] Fuel costs are plausibly uncorrelated with unobserved demand: bituminous coal and petroleum coke prices do not follow the pro-cyclical pattern of cement consumption, and the cement industry accounts for only a small fraction of the fossil fuels consumed in the United States.

It seems possible that our competition measures are correlated with the pricing residual. Competitors could locate where unobserved demand is high (generating a positive relationship) or where unobserved costs are low (generating a negative relationship). Because the median kiln age at retirement is 37 years but contracts often are negotiated annually, such correlations would have greater impact on our estimates if the unobserved factors exhibit a high degree of autocorrelation. To allay concern, we employ (aggregated) plant fixed effects in many of our regressions. Identification of how competition affects pass-through then rests on entry, exit, and changes in the diesel price, the last of which affects the transportation costs that differentiate plants. Our estimates of pass-through are robust to the inclusion or exclusion of the plant fixed effects, but the interactive effect of competition on pass-through stabilizes across specifications only if plant fixed effects are included.

4.3 Conduct and incidence

This section describes how we construct estimates of harm for consumers and producers, and addresses statistical inference in the counterfactual analysis. Equation (4) establishes that the loss of consumer surplus depends on pass-through and quantity. The corresponding sampling distribution is straightforward because quantity is observed and we can apply the estimated parameters from our region-level regression to put confidence bounds on pass-

[15] Consider a simple example in which the inputs are labor and capital. Under plausible parameterizations, wages increases result in greater labor and capital costs, creating a positive correlation between the two cost determinants.

[16] We estimate an augmented empirical model in Appendix A that accounts for competitor costs (i.e., does not impose the $\beta = 0$ normalization), and show that the main results are robust. The formulation of the empirical model also is consistent with our focus on how market-wide cost changes affect prices in a model of symmetric oligopoly. In such a setting, costs are perfectly correlated (because $c_{jt} = c_{kt}\ \forall j, k$), so estimation obtains the pass-through relationship of interest.

through. By contrast, equation (5) establishes that the loss of producer surplus depends on quantity, pass-through and conduct. This is more difficult because the reduced-form regressions do not support a point estimate on the conduct parameter.

We proceed by using the margins and the elasticities obtained from the structural model of Miller and Osborne (2014) to calculate an estimate of conduct. The structural model features differentiated-products Nash-Bertrand competition among plants. Consumers select plants according to county-specific nested logit demand systems, in which all cement plants and imports are within one nest and non-cement products are within another nest. Differentiation arises from transportation costs and varies based on the locations of plants and counties. Plants set prices at the county-level. The model is estimated with USGS and PCA data on Arizona, California, and Nevada (the "U.S. Southwest") over 1983-2003. Because the price data are observed at the region-year level, equilibrium plant-specific prices must by computed numerically given the structural parameters. The model fits the data used in estimation well, and also accurately predicts withheld data on cross-region shipments.

We derive a point estimate of conduct by computing equilibrium prices and calculating margins and the elasticity of market demand at the estimated structural parameters.[17] The quantity-weighted average margin, elasticity, and conduct parameter are 0.40, 0.92, and 0.33, respectfully. Similar margins and elasticities are obtained elsewhere in the literature. For instance, a recent EPA analysis calculated kiln-specific variable costs for each of 20 local markets; the costs imply an average margin of 43% when paired with market prices (EPA (2009)). Jans and Rosenbaum (1997) estimate a domestic elasticity of demand of 0.87, and the elasticity estimates of Fowlie, Reguant, and Ryan (2016) range between 0.89 and 2.03. Finally, Miller and Osborne (2014) also show that the estimated margins are consistent with margins that are published in cement producers' financial statements.

A drawback of combining reduced-form and structural estimates in this manner is that there is no straightforward way to compute the joint sampling distribution of pass-through and conduct, which would be needed to provide a formal confidence bound on the estimate of producer surplus loss. Consider that the structural model generates average pass-through of 0.89 and (because this is less than unity) a negative correlation between pass-through and conduct. By contrast, our reduced-form estimates of pass-through are above unity, and interaction terms support a positive correlation between pass-through and conduct. We view the reduced-form estimates as more reliable because the structural model imposes a

[17]The relevant demand elasticity measures the change in the quantity of domestically-produced cement with respect to the price of domestically-produced cement. The structural estimates indicate that most substitution away from domestic cement goes to imported cement.

particular demand system that restricts curvature and largely predetermines pass-through.[18]

Nevertheless, it is possible to compute a confidence bound on conduct alone using the same approach we use to compute a point estimate of conduct. With this confidence bound in hand, the magnitude of producer harm can be characterized for conduct and pass-through pairs for which each element of the pair is statistically likely. We compute a confidence bound on conduct using a bootstrap: we take 2,000 draws from estimated asymptotic distribution of the structural parameters, and compute the conduct parameter at each draw. The symmetric 90% confidence interval for the conduct parameter is (0.25,0.42).

There is an alternative approach that infers conduct directly from pass-through, which is in the spirit of the exercise we perform in this paper, and does not draw on estimates from existing work. To demonstrate how this approach works, we start with the symmetric oligopoly model of Weyl and Fabinger (2013) that is summarized in Section 3, and for simplicity of exposition suppose that conduct and marginal costs are constant. Equation (2) then can be rearranged to provide conduct as a function of pass-through:

$$\theta = \left(\frac{1-\rho}{\rho}\right)\epsilon_{ms} \tag{11}$$

where again ϵ_{ms} is the elasticity of marginal surplus with respect to quantity (recall that $ms = p'Q$). Conduct can be inferred from pass-through given knowledge of the slope and curvature of demand. Econometric estimates of these objects can be obtained with a demand model that is second-order flexible if the data provide the requisite empirical variation. In Appendix C, we show that there is not enough variation to estimate the curvature of demand with any reasonable degree of precision. The alternative approach of utilizing a demand-system that can be calibrated from pass-through is not promising because the relationship between elasticities and pass-through is not robust to functional form assumptions (Bulow and Pfleiderer (1983)). Lastly, if we were to relax the assumptions of constant marginal cost and conduct, the exercise of recovering conduct would be more complicated.[19]

[18] A second difference between the reduced-form regressions and the structural model arises due to the samples used in estimation. In principle, the structural model could be re-estimated with the broader dataset used here, but it is not clear to us whether such an endeavor is computationally feasible.

[19] To accomplish this exercise, one would first solve for θ as a function of marginal surplus, observed prices, and costs, using the first order condition in equation (1). One could substitute this formula for θ into equation (2) to express pass-through in terms of observed prices, marginal costs, demand and supply elasticities, as well as marginal surplus and its derivative. Given estimates of the marginal surplus function derived from demand estimates, one could match estimated pass-through to predicted pass-through to estimate the parameters governing marginal cost, and derive conduct.

5 Variables and Summary Statistics

5.1 Fuel costs and prices

Table 2 provides mathematical definitions of the dependent variable and all the regressors, along with their means and standard deviations. We describe first the fuel cost variable, which we calculate based on the energy requirements of the plant's least efficient kiln and the price of the primary fuel:

$$\text{Plant Fuel Cost}_{jt} = \text{Primary Fuel Price}_{jt} \times \text{Energy Requirements}_{jt}$$

where the fuel price is in dollars per mBtu and the energy requirements are in mBtu per metric tonne of clinker. We use the least efficient kiln because it is most likely to produce the marginal output. We provide details on the calculation in Appendix B, along with a discussion about potential sources of measurement error. The plant-level fuel costs are aggregated to the region level prior to estimation following equation (10).

Table 2: Definitions and Summary Statistics for Selected Variables

Regressor	Definition	Mean	St. Dev.	Description
		Dependent Variable		
Price	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} p_{jt}$	98.62	(16.25)	The average cement price in the region.
		Control Variables		
Proximity of Rival Capacity	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{k\neq j,\ d_{jkt}<\overline{d}} CAP_{kt}/d_{jkt}$	0.25	(0.23)	Competitor capacity, normalized by distance, totaled for each plant and then aggregated to the region level.
Total Rival Capacity	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{d_{jkt}<\overline{d}} CAP_{kt}$	19.67	(10.53)	Competitor capacity within the distance threshold, totaled for each plant and then aggregated to the region level.
Proximity of Rivals	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{k\neq j,\ d_{jkt}<\overline{d}} 1/d_{jkt}$	0.34	(0.29)	The count of competitors normalized by distance and aggregated to the region level.
Number of Rivals	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{d_{jkt}<\overline{d}} 1$	27.75	(15.34)	The count of competitors within the distance threshold, aggregated to the region level.
Construction Employment	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{d_{ajt}<\overline{d}} EMP_{at}$	835.27	(556.03)	Total construction employment in nearby counties, aggregated to the region level.
Building Permits	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt} \sum_{d_{ajt}<\overline{d}} PER_{at}$	216.35	(150.03)	Total building permits in nearby counties, aggregated to the region level.
Port Proximity	$\sum_{j\in\mathscr{J}_{mt}} \omega_{jmt}/\log(d_{jt}^{cd})$	0.27	(0.55)	The inverse log distance to the nearest customs district, through which foreign imports arrive, aggregated to the region level.

Notes: The cement price is observed at the region-year level. For all other variables, aggregation to the region level is conducted using capacity shares as proxies for the weights ω_{jmt}. In all equations, $p_j t$ is the price of plant j in period t, c_{jt} is the fuel cost of plant j in period t, d_{jkt} is the distance between plants j and k in period t, d_{ajt}^{c} is the distance between county a and plant j in period t, d_{jt}^{cd} is the distance between plant j and the nearest customs district in period t, PER_{at} and EMP_{at} are building permits and construction employment in county a in period t, respectively, and CAP_{kt} is the capacity of plant k in period t. Summary statistics are calculated from 773 region-year observations.

Table 2: Definitions and Summary Statistics for Selected Variables (continued)

Regressor	Definition	Mean	St. Dev.	Description
		Pass-Through Regressors		
Fuel Costs	$\sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt}$	14.08	(5.79)	Fuel costs of the plant as defined in the text, aggregated to the region level.
Fuel Costs × Proximity of Rival Capacity	$\sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \sum_{k \neq j,\, d_{jkt} < \bar{d}} CAP_{kt}/d_{jkt}$	3.25	(3.02)	Fuel costs times the competitors capacity, normalized by distance, totaled for each plant and aggregated to the region level.
Fuel Costs × Total Rival Capacity	$\sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \sum_{k \neq j,\, d_{jkt} < \bar{d}} CAP_{kt}$	255.65	(139.30)	Fuel costs times total nearby competitor capacity, totaled for each plant and aggregated to the region level.
Fuel Costs × Proximity of Rivals	$\sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \sum_{k \neq j,\, d_{jkt} < \bar{d}} 1/d_{jkt}$	4.54	(4.21)	Fuel costs times the count of competitors normalized by distance, aggregated to the region level.
Fuel Costs × Number of Rivals	$\sum_{j \in \mathscr{J}_{mt}} \omega_{jmt} c_{jt} \sum_{k \neq j,\, d_{jkt} < \bar{d}} 1$	373.40	(229.89)	Fuel costs times total nearby competitor capacity, aggregated to the region level.

Notes: The cement price is observed at the region-year level. For all other variables, aggregation to the region level is conducted using capacity shares as proxies for the weights ω_{jmt}. In all equations, $p_j t$ is the price of plant j in period t, c_{jt} is the fuel cost of plant j in period t, d_{jkt} is the distance between plants j and k in period t, d^c_{ajt} is the distance between county a and plant j in period t, d^{cd}_{jt} is the distance between plant j and the nearest customs district in period t, PER_{at} and EMP_{at} are building permits and construction employment in county a in period t, respectively, and CAP_{kt} is the capacity of plant k in period t. Summary statistics are calculated from 773 region-year observations.

Table 3: Cement Prices and Fuel Costs

	Average Price	Average Fuel Costs			
		Wet Kilns	Long Dry Kilns	Dry with Preheater	Dry with Precalciner
1980	103.98	20.43	16.72	14.62	12.26
1985	81.61	15.75	13.17	10.01	9.60
1990	67.55	11.90	10.21	7.92	7.91
1995	73.83	9.45	7.90	6.70	6.26
2000	78.56	8.56	7.43	5.82	5.63
2005	80.51	11.12	9.52	7.56	7.39
2010	71.04	13.82	12.08	9.40	9.05

Notes: Cement prices and fuel costs are in real 2010 dollars per metric tonne.

Table 3 provides fuel costs at five year intervals, by kiln technology and in unweighted national averages. The table also shows the national average price of portland cement. Time-series variation in fuel costs arises primarily due to changes in fossil fuel prices and the technological shift toward modern precalciner kilns. Cross-sectional variation across kiln technologies arises according to the heterogeneity in the energy requirements of production. Both fuel costs and prices decrease through the first two decades of the sample, and then increase. Depending on the year and technology, average fuel costs account for between 7% and 20% of average revenues.

Figure 2 explores the empirical distributions of regional prices and fuel costs over the sample period of 1980-2010. Panels A and B show the univariate distributions. The price distribution is nearly symmetric around the mean of $98.62 per metric tonne. The fuel cost distribution is tighter and left-centered. Panel C provides separate kernel density estimates for plants with wet and dry kilns. Panel D provides a scatterplot of the 773 region-year observations on prices and fuel costs. Observations with higher fuel costs also have higher prices: the correlation coefficient is 0.46, and a univariate regression of prices on fuel costs yields a coefficient of 1.28 that is statistically significant at the one percent level. This univariate regression coefficient ends up being close to the average pass-through that we obtain with the reduced-form regression analysis.

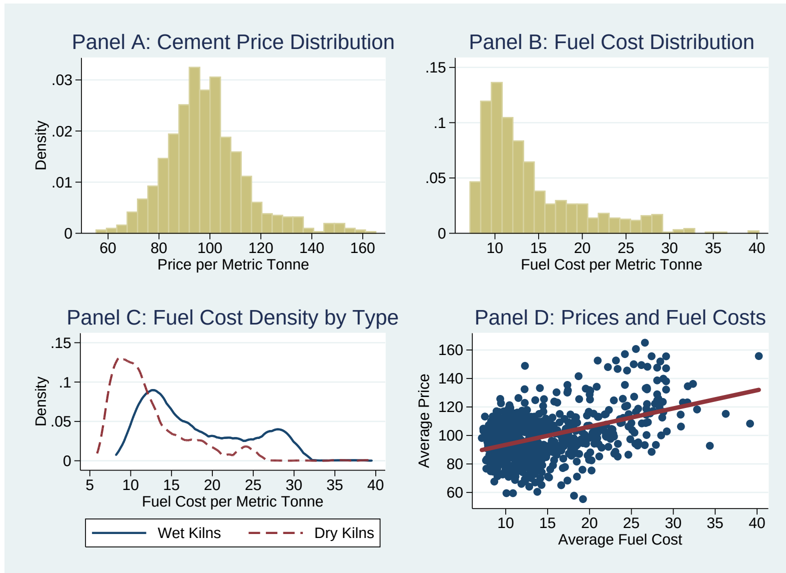

Figure 2: Regional Prices and Fuel Costs over 1980-2010

Notes: Panels A and B show the empirical distributions of cement price and fuel costs, and are based on 773 region-year observations. Panel C shows the kernel density of fuel costs, separately for plants with wet and dry kilns, and is based on 3,445 plant-year observations. Panel D shows a scatterplot of regional cement prices and fuel costs, as well as a line of best fit, and is based on 773 region-year observations. All prices and fuel costs are in real 2010 dollars per metric tonne of cement.

5.2 Other variables

We construct measures of domestic competition based on the location of plants, their capacity, and the magnitude of diesel prices (which scales transportation costs). The first measure, which we refer to as *Proximity of Rival Capacity*, is the count of competing plants within some distance threshold, weighted by capacity and inverse distance. It increases with the number, capacity, and proximity of competitors. The second measure, *Total Rival Capacity*, is total competitor capacity within some distance threshold. The third and fourth measures, *Proximity of Rivals* and *Number of Rivals*, are analogous but do not weight competitors by capacity. Each of these are calculated at the plant level and then aggregated to the region level prior to estimation. We also interact these measures with fuel costs, as in equation (10), in order to allow pass-through to vary with competition.

In the construction of these measures, we use a distance metric defined by the interaction of the diesel price index and the straight-line miles between plants. This approach reflects the predominant role of trucking in distribution.[20] Straight-line miles are highly

[20] A fraction of cement is shipped to terminals by train (6% in 2010) or barge (11% in 2010), and only then is trucked to customers. Some plants may be closer than our metric indicates if, for example, both are located on the same river system.

correlated with both driving miles and driving time and, consistent with this, previously published empirical results on the industry are not sensitive to which of these measures is employed (e.g., Miller and Osborne (2014)). The baseline distance threshold is 400. This is motivated by prior findings that 80-90 percent of portland cement is trucked less than 200 miles (Census Bureau (1977); Miller and Osborne (2014)), so that plants separated by more than 400 miles are unlikely to compete for many customers. We obtain similar results with alternative thresholds, and in some regressions we employ multiple variables constructed with different thresholds to allow for a more nonparametric treatment.

We control for demand conditions using county-level data on building permits and construction employment. The USGS provides consumption data at the state (not region) level, and when aggregated to the state level, building permits and construction employment together explain nearly 90% of the variation in cement consumption. To construct the controls, we calculate the total building permits and construction employment in counties within the distance threshold of each plant, and then aggregate to the region level. We similarly control for port proximity based on the plants' inverse log distances to the nearest port; we use log distance to reduce skewness in this variable.

6 Empirical Evidence on Pass-Through

6.1 Main regression results

Table 4 summarizes a first set of regressions in which *Fuel Costs* is the sole pass-through regressor. The *Fuel Costs* coefficient thus represents the average effect of fuel costs on prices. The regressions differ in the specification of the control variables and fixed effects. Columns (i)-(iv) control for domestic competition using different combinations of variables. Columns (v)-(viii) examine the same specifications but also include plant fixed effects. All standard errors and confidence intervals are calculated using a Newey-West correction for first degree autocorrelation among observations from the same region. Breusch-Godfrey tests provide no statistical support for higher degrees of autocorrelation.

The *Fuel Cost* regression coefficient ranges from 1.03 in column (i) to 1.65 in column (viii). The point estimates are therefore consistent with pass-through that exceeds unity. The precision of the estimates also is notable: the magnitude of the coefficients tend to be nearly an order of magnitude larger than their standard error. In some of the regressions, this produces a symmetric 95% confidence interval that excludes unity on the lower end (columns (iv), (vi), (vii), and (viii)). In the other regressions, pass-through that is substantially

Table 4: The Average Effect of Fuel Costs on Prices

	(i)	(ii)	(iii)	(iv)	(v)	(vi)	(vii)	(viii)
			Pass-Through Regressor					
Fuel Costs	1.03	1.11	1.30	1.37	1.47	1.58	1.63	1.65
	(0.16)	(0.16)	(0.16)	(0.18)	(0.27)	(0.26)	(0.25)	(0.27)
			Control Variables for Domestic Competition					
Proximity of Rival Capacity	-13.68	-8.46		-7.38	-5.89	4.07		-16.84
	(2.39)	(2.81)		(6.72)	(9.72)	(9.96)		(23.89)
Total Rival Capacity ($d < 400$)	-0.97	-0.58		0.48	-1.31	-0.68		-0.12
	(0.10)	(0.17)		(0.26)	(0.20)	(0.22)		(0.35)
Total Rival Capacity ($d < 300$)		-0.39				-0.83		
		(0.33)				(0.32)		
Total Rival Capacity ($d < 200$)		-1.24				-1.95		
		(0.38)				(0.46)		
Proximity of Rivals			-11.09	-4.80			-8.35	-22.36
			(1.93)	(5.72)			(8.07)	(20.89)
Number of Rivals ($d < 400$)			-0.69	-0.99			-0.89	-0.78
			(0.06)	(0.18)			(0.12)	(0.25)
			Other Control Variables					
Construction Employment	-0.004	0.003	-0.005	-0.006	0.024	0.032	0.020	0.020
	(0.002)	(0.003)	(0.002)	(0.002)	(0.004)	(0.004)	(0.004)	(0.004)
Building Permits	0.046	0.044	0.054	0.056	0.017	0.027	0.026	0.026
	(0.009)	(0.009)	(0.009)	(0.009)	(0.010)	(0.011)	(0.010)	(0.010)
Port Proximity	2.34	2.52	2.26	2.28	-5.93	-2.96	-4.87	-4.15
	(1.02)	(0.97)	(1.08)	(1.08)	(3.21)	(3.79)	(2.93)	(3.23)
			Fixed Effects					
Plant fixed effects	no	no	no	no	yes	yes	yes	yes

Notes: The table reports the results of OLS regressions. The sample includes 773 region-year observations over 1980-2010. The dependent variable is the cement price. Distance (d) is measured in miles times a diesel price index. All regressions also include fixed effects for the kiln technology of the plant. Observations are weighted by the number of plants within the region. Standard errors are calculated using a Newey-West correction for first-order autocorrelation within regions.

incomplete still can be rejected. The *Fuel Cost* coefficient tends to be somewhat larger if plant fixed effects are incorporated, and if the control variables are constructed based on competitor counts rather than competitor capacity.

The control variables have coefficients that are consistent with expectations. The coefficients on the controls for domestic competition typically are negative; the only statistically significant exception arises in column (iv), which excludes plant fixed effects. Columns (ii) and (vi) provide a nonparametric treatment of the distance metric. The results imply that the effect of competitor capacity on prices increases with the proximity of that capacity. This is consistent transportation costs providing localized market power, and with prices being constrained by nearby competitors.[21] Port proximity, which proxies for the competitive impact of imported cement, also has a negative effect on prices if plant fixed effects are included in the specification. Finally, the construction employment and building permits variables tend to be associated with higher prices.[22]

Table 5 summarizes a second set of regressions that examine whether competition affects pass-through. We motivate these regressions based on the auxiliary prediction of the Weyl and Fabinger (2013) model that competition should lessen pass-through if, as we estimate, pass-through exceeds unity. Columns (i)-(vi) use different measures of domestic competition and consistently supports that competition lessens pass-through. The median pass-through that arises with these regressions ranges over 1.37-1.79. Next we use multiple distance metrics to capture the interactive effect of competition, based on competitor capacity (column (v)) and competitor counts (column (vi)). Each of the interactions is negative and statistically significant, and the resulting median pass-through remains well above unity. The symmetric 95% confidence intervals exclude unity in columns (i), (iii), (iv), and (vi). The results are consistent with the auxiliary prediction of the model.

We have subjected these regression results to a battery of robustness checks, and do not believe that they are the product of particular sample selection or functional form choices. In addition to areas of robustness mentioned elsewhere in the paper and appendices, the results prove robust to (1) the use of feasible generalized least squares as a correction for

[21] The *Total Rival Capacity* regressors in columns (ii) and (vi) are cumulative. Thus, for example, in column (vi) the total effect of capacity within a distance threshold of 200 equals $-0.68 - 0.83 - 1.95 = -3.46$.

[22] The construction employment coefficient is negative in some specifications that exclude plant fixed effects. The net effect of these demand shifters nonetheless is positive. In alternative regressions (not shown), we use a linear combination of construction employment and building permits to control for demand conditions. The weights in the linear combination are determined by regressing observed state-level consumption on (suitably aggregated) versions of construction employment and building permits, following Miller and Osborne (2014). The linear combination consistently has a positive effect on prices when it replaces construction employment and building permits in the regressions.

Table 5: The Effect of Competition on Pass-Through

	(i)	(ii)	(iii)	(iv)	(v)	(vi)
			Pass-Through Regressors			
Fuel Costs	2.38	2.05	2.48	2.15	2.60	2.76
	(0.28)	(0.36)	(0.27)	(0.37)	(0.30)	(0.31)
Fuel Costs ×	-4.45				-4.17	
Proximity of Rival Capacity	(0.84)				(0.88)	
Fuel Costs ×		-0.42			-0.03	
Total Rival Capacity ($d < 400$)		(0.16)			(0.01)	
Fuel Costs ×			-3.05			-2.88
Proximity of Rivals			(0.47)			(0.45)
Fuel Costs ×				-0.30		-0.20
Number of Rivals ($d < 400$)				(0.01)		(0.10)
			Derived Statistics			
Median Pass-Through	1.64	1.37	1.79	1.46	1.30	1.51

Notes: The table reports the results of OLS regressions. The sample includes 773 region-year observations over 1980-2010. The dependent variable is the cement price. All regressions include the same control variables as column (viii) of Table 4, as well as technology and plant fixed effects. Observations are weighted by the number of plants within the region. The derived statistics are calculated by applying the regression coefficients to the 3,445 plant-year observations. Standard errors are calculated using a Newey-West correction for first-order autocorrelation within regions.

autocorrelation; (2) the exclusion of particularly influential observations, as determined by Cook's D statistic; and (3) the incorporation of addition control variables constructed with a variety of distance thresholds. Tests for structural breaks in the data provide modest support for somewhat higher pass-through over the most recent decade in the sample.

6.2 Validation exercise

Our regression results allow for an evaluation of an implicit pass-through assumption that is made in recent research on the portland cement industry (e.g., Ryan (2012); Fowlie, Reguant, and Ryan (2016)). Those articles estimate a structural oligopoly model relying on the same data sources employed here, and then use simulation to examine the effects market-based regulation of CO_2 and other environmental policies. The structural model incorporates dynamics and, to facilitate tractable estimation, state-space payoffs are specified as arising from homogeneous products Nash-Cournot competition among firms in local markets. ten Kate and Niels (2005) derive pass-through in the Nash-Cournot setting as

$$\rho = \frac{N}{N + 1 - \phi} \tag{12}$$

where N is the number of firms and ϕ is a measure of demand curvature that is positive with convex demand, negative with concave demand, and zero with linear demand. Pass-through converges to unity as the number of firms grow large, either from above or below.[23]

The structural models use a constant elasticity assumption that imposes convexity on the demand curve. Because this in turn determines pass-through, the constant elasticity assumption matters for the simulated economic outcomes. As a validation exercise, we calculate the pass-through implied by the model, for the local markets delineated by the EPA and used in Fowlie, Reguant, and Ryan (2016), and over a range of demand elasticities considered in that article. Table 6 provides the results for selected markets. (Calculations for all 20 EPA markets are available from the authors upon request.) The similarity between

[23]The curvature term is $\phi = -\left(Q\frac{\partial^2 P}{\partial^2 Q}\right) \Big/ \left(\frac{\partial P}{\partial Q}\right)$. This derivation of Nash-Cournot pass-through requires constant marginal costs, but firms need not be symmetric. The structural models of Ryan (2012) and Fowlie, Reguant, and Ryan (2016) assume that marginal costs are constant up to some threshold capacity utilization level, beyond which they begin to increase. The formula nonetheless should be roughly accurate because plants are found to seldom produce above the utilization threshold. A major emphasis of the ten Kate and Niels (2005) article is that the pass-through of a firm-specific cost change is quite different from that of a market-wide cost change. The relevant formula for the firm-specific pass-through is $\frac{1}{N+1-\phi}$. Thus, firm-specific pass-through converges to zero as the number of firms grows large. It is theoretically possible for this to exceed unity, though only with a very convex demand curve.

Table 6: Industry Pass-Through in Selected EPA Markets

		Theoretical Predictions		
	N	$\epsilon^D = 1.0$	$\epsilon^D = 1.5$	$\epsilon^D = 2.0$
Atlanta	6	1.20	1.13	1.09
Birmingham	5	1.25	1.15	1.11
Chicago	4	1.33	1.20	1.14
Cincinnati	3	1.50	1.29	1.20
Detroit	2	2.00	1.50	1.33

Notes: Theoretical predictions are derived from a model of Cournot competition among firms with constant but heterogenous marginal costs and a constant elasticity market demand schedule. We denote the number of firms with active plants in the EPA market in 2010 as N and the market elasticity as ϵ^D.

the theoretical predictions and our empirical estimates is apparent: pass-through somewhat exceeds unity, and competition has a damping effect. Thus, our regression results support the validity of the structural models.

7 Regulatory Implications

7.1 Market-based regulation of CO_2

Table 7 summarizes the welfare implications of market-based regulation. Panel A provides the change in producer surplus (in millions) per dollar of carbon price. Panel B provides the change in consumer surplus. Calculations are shown for pass-through ranging from 1.00 to 1.60 and conduct ranging from 0.25 to 0.45, reflecting respectively the statistical variance of the reduced-form pass-through regressions and the bootstrap of the Miller and Osborne (2014) results.[24] We provide results in this manner because we are unable to put a confidence interval on the change in producer surplus due to the difficulty of recovering the covariance between conduct and pass-through (as discussed in Section 4.3).

Evaluating at the middle of estimated distributions, the loss of producer surplus is \$10.52 million per dollar of carbon price with pass-through of 1.30 and a conduct parameter of 0.35, and the loss of consumer surplus is \$88.26 million. These numbers indicate that consumers would bear about 89% of the burden of regulation. Official estimates of the social cost of carbon range from \$12 to \$129 per metric tonne for the year 2020, depending on the

[24]The 95% confidence interval on pass-through from specification (iv) of Table 4, which we use as our baseline, is $[1.03, 1.73]$, and the confidence interval on conduct is $[0.25, 0.43]$.

Table 7: Impacts of Market-Based Regulation

Panel A: Change in Producer Surplus

	Pass-Through				
Conduct	1.00	1.20	1.30	1.40	1.60
0.25	-16.97	-6.78	-1.70	3.39	13.58
0.30	-20.37	-10.86	-6.11	-1.36	8.15
0.35	-23.76	-14.94	-10.52	-6.11	2.72
0.40	-27.16	-19.01	-14.94	-10.86	-2.72
0.45	-30.55	-23.08	-19.35	-15.62	-8.15

Panel B: Change in Consumer Surplus

	Pass-Through				
	1.00	1.20	1.30	1.40	1.60
ΔCS	-67.90	-81.47	-88.26	-95.05	-108.63

Notes: All numbers are in millions of real 2010 dollars per dollar of carbon tax. Calculations are based on a general model of symmetric oligopoly, and use the 2011 industry output of 67.90 million metric tonnes. We use the ratio of 0.88 metric tonnes of CO_2 per metric tonne of cement to convert from an output tax to a carbon tax.

social discount rate (Working Group on Social Cost of Carbon (2013)). With a \$40 price on carbon, the producer surplus loss scales to \$421 million and the consumer surplus loss scales to \$3.5 billion. This can be compared to industry revenues of roughly \$7 billion in 2012. The fraction of revenues needed to fully compensate producers equals $1 - \rho(1 - \theta)$. Again evaluated at the middle of the estimated distributions, producers could be fully compensated with 15.5% of the revenues obtained from market-based regulation.

At least three important caveats apply to this counterfactual analysis. First, our approach for producer surplus does not account for the statistical covariance between pass-through and conduct. Still, it is not necessary to remain entirely agnostic because theory indicates that if pass-through exceeds unity then it decreases as conduct parameter gets small. Thus, we view the combinations along the diagonal of Table 7 (i.e., low conduct and low pass-through, or high conduct and high pass-through) as being more likely to reflect actual market conditions.[25] Second, our estimates do not inform how consumer surplus loss is distributed downstream. Disentangling these impacts among ready-mix concrete plants,

[25]Notice that producer surplus increases with some combinations of high pass-through and low conduct parameters (e.g., $\rho = 1.60$ and $\theta = 0.25$). This has long been recognized as a theoretical possibility (Kimmel (1992)), but one that cannot be true globally as that would imply infinite consumer surplus.

construction firms, and end users would require additional data and is beyond the scope of this research. Finally, our analysis in this section incorporates that cement purchasers could turn to unregulated imports after the imposition of market-based regulation. In regulatory parlance, such substitution is known as "leakage," and typically an effort is made to design regulation in a manner that limits leakage.[26] To the extent that these efforts are successful, the burden of regulation would shift downstream to a greater degree than we calculate.

7.2 NESHAP Amendments

We turn now to an economic analysis of recent regulation promulgated by the EPA that reduces dramatically the legally permissible emissions of hazardous air pollutants (HAPs) including particulate matter, mercury, hydrocarbons, and hydrogen chloride. EPA analysis indicates that monetized health benefits, which it predicts exceed \$7-\$18 billion, far outweigh economic costs (EPA (2009); EPA (2010)). We revisit the price predictions of the EPA using our pass-through estimates. The EPA relies on a Cournot model of competition to simulate the effect of regulation in each of 20 local markets based on conditions in 2005. The model incorporates a constant elasticity market demand curve and, for markets that are adjacent to a customs office, a constant elasticity import supply curve. It is calibrated using methodologies that we detail in Appendix D.

We replicate the EPA modeling results up to the restriction that compliance costs are public only at the market-average level. We update the analysis to 2010, the most recent year of our sample, and compare the price predictions to an alternative based on our pass-through estimates. While the EPA approach is grounded in modeling techniques and functional forms that are standard in the literature of industrial organization (e.g., Fowlie, Reguant, and Ryan (2016)), the drawback is that pass-through is fully determined by functional forms and the first order properties of the system. Relying on empirical estimates of pass-through relaxes these assumptions and allows the data to inform predictions more directly. We use the pass-through estimates from column (iv) of Table 4. Scaling pass-through up or down across the range of our estimates would have a commensurate effects on the prediction.

Figure 3 provides a scatter-plot of market-specific predictions from the EPA's Cournot model (on the vertical axis) and the predictions from our pass-through estimates (on the hor-

[26]The first-best solution to leakage is a border tax adjustment (BTA) that raises the effective price of unregulated imports. However, BTAs may violate World Trade Organization (WTO) prohibitions on trade restrictions because by design they apply differentially to certain countries. Thus, some existing emissions trading systems instead utilize a production-based updating of permit allocations that compensate regulated firms for profit losses related to leakage. The 2009 Waxman-Markey bill proposed to apply production-based updating to "trade-vulnerable" industries, including the portland cement industry.

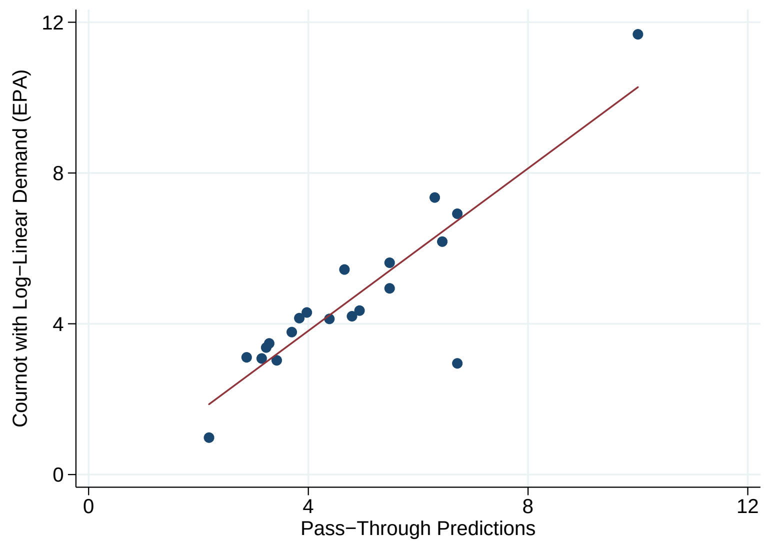

Figure 3: Price Effects of NESHAP Amendments for Portland Cement

Notes: Each dot represents the price predictions based on (i) the EPA model of Cournot competition between firms facing a constant elasticity demand curve and (ii) our estimates of pass-through. Also shown is a line of best fit.

izontal axis). Across the 20 local markets, the Cournot model yields average price increases of \$4.66 per metric tonne and the pass-through calculations yield average increases of \$4.78. The predictions are highly correlated, with a univariate correlation statistic of 0.88.[27] The similarity between the two methodologies arises because the pass-through that is implicit in the EPA model is close to our econometric estimates.

8 Conclusion

Recent theoretical advances highlight the usefulness of extending empirical pass-through research to imperfectly competitive markets (e.g., Weyl and Fabinger (2013); Fabinger and Weyl (2015)). In this paper, we develop an empirical model that incorporates oligopoly interactions and is theoretically capable of identifying both firm-specific and market pass-through. We take the model to data on the portland cement industry and find robust econometric evidence that market pass-through exceeds unity. The results have direct bearing on distributional effects of market-based environmental regulation. In particular, we calculate that the burden of cap-and-trade programs to limit CO_2 emissions falls predom-

[27]The exceptions are Pittsburgh, for which the EPA under-predicts by \$3.76 relative to the pass-through calculation, and Cincinnati, for which the EPA over-predicts by \$1.68 relative to the pass-through calculation.

inately downstream, and that cement producers could be fully compensated with a small fraction of the government revenues obtained.

We conclude with a brief discussion of two limitations that we encountered in this project, keeping in mind that these limitations provide opportunity for future research. First, our data on the portland cement industry do not allow for the identification of firm-specific pass-through. This is due to the decision of the USGS to aggregate prices in the *Minerals Yearbook* (which protects confidentiality of business data). While our empirical model is theoretically capable of disentangling the firm-specific pass-through rates, this requires a greater number of plants having out-of-region competitors with different fuel costs than we observe in the data. As a result, we have focused the counter-factual analyses on regulatory questions for which estimates of market pass-through are sufficient. Future studies that succeed in estimating firm-specific pass-through rates could address a range of other interesting topics, in environmental economics and elsewhere.

A second limitation is that the welfare formulas of Weyl and Fabinger (2013) require information on both pass-through and a conduct parameter. Reduced-form studies of pass-through (including ours) typically obtain estimates only of the former. We sidestep the problem by bringing information to bear on the conduct parameter from the structural results of Miller and Osborne (2014), an approach that is possible because portland cement is so widely studied in the field of industrial organization. It would be conceptually advantageous to estimate pass-through and conduct jointly, in the context of a single structural model. It is possible, for example, that pass-through variation could be exploited to pin down a demand curvature parameter that otherwise would be difficult to identify empirically. In the context of portland cement, this would require more flexible models of demand than have been used in recently published structural models.

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Appendix Materials for Publication

A Model of Asymmetric Oligopoly

In this appendix, we provide a theoretical treatment of pass-through in asymmetric oligopoly, using the framework of Jaffe and Weyl (2013). We distinguish between responses to firm-specific cost shocks ("firm-specific pass-through") and responses to market-wide cost shocks ("market pass-through"). We then discuss how omitting the costs of competitors from a reduced-form regression affects the interpretation of coefficients, following MacKay, Miller, Remer, and Sheu (2014). Finally, we estimate an augmented empirical model that accounts explicitly for competitor costs, and find that our main results are robust.

Consider an oligopoly of firms, each of which produces one or more products and sets a single price per product. Let prices, quantities, and marginal costs of firm i be given by the vectors P_i, Q_i, and $MC_i(P)$, respectively, where P is a vector of all firms' prices. Each firm may conjecture that changes in its prices induce changes in competitors' prices. This allows the model to nest the Nash-Bertrand and Nash-Cournot models, among others.[28] Finally, assume that each firm has well-behaved, twice-differentiable demand and cost functions. The first order conditions that characterize equilibrium are given by:

$$f_i(P) \equiv -\left[\frac{dQ_i(P)^T}{dP_i}\right]^{-1} Q_i(P) - P_i + MC_i(P) = 0 \quad \forall i \in I \tag{A.1}$$

Let $f(P) = [f_1'(P)\ f_2'(P)\ldots]'$ denote the stacked first order conditions. The imposition of quantity taxes, represented by a vector t, results in a new equilibrium characterized by $f(P)+t=0$. An application of the implicit function theorem yields the pass-through matrix:

$$\rho^F = -\left(\frac{\partial f(P)}{\partial P}\right)^{-1} \tag{A.2}$$

As in Section 3, pass-through depends on the elasticities and curvatures of the demand, as well as on the slope of the marginal cost function. The key difference is that equation (A.2) provides firm-specific pass-through while equation (2) provides market pass-through.

To fix ideas, consider an oligopoly of three single-product firms in differentiated-products Nash-Bertrand competition. Each firm has a margin of 0.50 and a 30% market

[28]The Nash-Cournot model obtains from conjectures that competitors change their price such that their quantity remains constant.

share (let a non-strategic outside good capture the remaining share). The demand system is logit and marginal costs are constant. Based on the calibration technique of Miller, Remer, Ryan, and Sheu (2015), pass-through is given by

$$\rho^F = \begin{bmatrix} 0.728 & 0.107 & 0.107 \\ 0.107 & 0.728 & 0.107 \\ 0.107 & 0.107 & 0.728 \end{bmatrix} \quad \text{and} \quad \rho = \begin{bmatrix} 0.942 \\ 0.942 \\ 0.942 \end{bmatrix} \tag{A.3}$$

Each diagonal element in ρ^F shows how a firm changes its price in response to a change in its own marginal cost, and each off-diagonal element shows the response of a firm to a change in a competitor's marginal cost. These latter effects are indirect and arise if prices are strategic complements or strategic substitutes, in the sense of Bulow, Geanakoplos, and Klemperer (1985). If all marginal costs go up by the same magnitude – as in the Weyl and Fabinger (2013) models – then the effect on prices can be obtained by summing across the columns of ρ^F, which obtains the vector ρ of market pass-through.

Although the relationship between pass-through and demand curvature is more opaque in the asymmetric case (e.g., compare equations (2) and (A.2)), it is still the case that pass-through tends to increase with the curvature of the demand system. Miller, Remer, Ryan, and Sheu (2015) develop Monte Carlo evidence based on hundreds of four-firm oligopolies with randomly drawn market shares and margins. Competition is differentiated-products Nash-Bertrand. Market pass-through is always less than unity with the log-concave linear and logit demand systems. It often exceeds unity with the almost ideal demand system, and always exceeds unity with the constant elasticity demand system.

It follows from equation (A.2) that a linear approximation to equilibrium prices takes the form provided in equation (7). The role of competitor costs is notable. To develop this further, consider a simplified equation:

$$p_j = \rho^F_{jj} c_j + \sum_{k \neq j} \rho^F_{jk} c_k + \epsilon_j \tag{A.4}$$

where we have allowed the error term to absorb all demand-side considerations. The population parameters are given by equation (A.2) in the general case, or by equation (A.3) in the specific numerical example. Suppose that the econometrician ignores competitor costs in the regression, i.e., that the equation taken to the data is

$$p_j = \alpha_j c_j + \epsilon^*_j \tag{A.5}$$

where $\epsilon_j^* = \epsilon_j + \sum_{k \neq j} \rho_{jk}^F c_k$. The regression coefficients $\widehat{\alpha}_j$ are unbiased estimates of firm-specific pass-through if marginal costs are uncorrelated across firms, unbiased estimates of market pass-through if costs are perfectly correlated, and biased estimates of both firm-specific and market-wide pass-through if costs are imperfectly correlated.[29]

Our application most closely resembles the second case. To see this, consider two regressors constructed according to equation (10): *Fuel Costs* $\times$ *Proximity of Rival Capacity*, which enters multiplied by the parameter α_1 and also appears in the main regression model; and *Rival Fuel Costs* $\times$ *Proximity of Rival Capacity* which enters multiplied by the parameter β but does not appear in the main regression model. The correlation coefficient between these two regressors is 0.995. While cost heterogeneity exists at the plant-level, there are too few plants having out-of-region competitors with different costs to create useful variation at the region level. With that level of correlation, a regression that excludes competitor costs obtains unbiased estimates of market pass-through.

Table A.1 summarizes the results from a regression that includes both interactive regressors. The specification in the first column includes plant fixed effects and is analogous to column (viii) in the main regression table. The median market pass-through rate is quite similar to that from the main results (1.61 vs. 1.65). The second column omits plant fixed effects and is analogous to column (iv) in the main results table. The median market pass-through rate is again similar (1.33 vs. 1.37). This latter regression also resembles the regressions that appeared in the working drafts of this paper. The standard errors for the interactive variables in this appendix table are understated due to biases that arise with collinearity (e.g., Mela and Kopalle (2002)). Still, these results confirm that excluding competitor costs from the main regressions does not distort market pass-through estimates.

[29] The regression coefficients $\widehat{\alpha}_j$ are unbiased estimates of *both* firm-specific and market-wide pass-through in the special case that prices are neither strategic complements nor strategic substitutes, because then $\rho_{jk}^F = 0 \quad \forall j \neq k$.

Table A.1: Augmented Regression Results

	(i)	(ii)
Pass-Through Regressors		
Fuel Costs	2.41	1.40
	(0.27)	(0.19)
Fuel Costs × Proximity of Rival Capacity	-2.39	-4.86
	(1.40)	(1.04)
Rival Fuel Costs × Proximity of Rival Capacity	-0.67	4.89
	(2.35)	(1.24)
Specification Details		
Controls Variables	yes	yes
Plant Fixed Effects	yes	no
Kiln Fixed Effects	yes	yes
Derived Market Pass-Through Statistics		
Median	1.61	1.33

Notes: The sample includes 773 region-year observations over 1980-2010. The dependent variable is the cement price. Standard errors are calculated using a Newey-West correction for first-order autocorrelation within regions.

Online Appendix

B Details on the Data Collection

We discuss details of the data collection process here in order to assist replication. We start with the *Plant Information Survey* (PIS) of the PCA. Our sample includes annual observations over 1980-2010. The PIS is published annually over 1980-2003 and also semi-annually in 2004, 2006, 2008 and 2010. We make use of all of the publications with the exception of 1981. The data provide snapshots as of December 31 of each year. We impute values for the capacity, technology, and primary fuel of each kiln in the missing years based on the preceding and following data. In most instances, imputation is trivial because capacity, technology and fuel are persistent across years. When the data from the preceding and following years differ, we use the data from the preceding year. We are able to identify kilns that are built in the missing years because the PIS provides for each kiln the year of construction. We remove from the analysis 198 kiln-year observations for which the kiln is identified in the PIS as being idled. These occur mostly in the late 1980s and over 2009-2010. There are 49 plant-year observations – out of 3,494 – for which all kilns at a plant are observed to be idled. A handful of kilns drop out of the PIS and then reappear in later years. We treat those observations on a case-by-case basis, leveraging detailed qualitative and quantitative information provided in the *Minerals Yearbook* of the USGS. We detail the available evidence and the selected treatment in our annotated Stata code. Lastly, we remove from the analysis a small number of kilns that produce white cement, which takes the color of dyes and is used for decorative purposes. The production of white cement requires higher kiln temperatures and iron-free raw materials, and the resulting cost differential makes it a poor substitute for gray cement in most instances.

We obtain data on delivered bituminous coal prices for the industrial sector from the annual *Coal Reports* of the Energy Information Agency (EIA). Averages are available at the national, regional and state levels over 1985-2012. We convert prices from dollars per short ton to dollars per metric tonne using the standard conversion factor. Many of the state values are withheld and must be imputed. We first use linear interpolation to fill in missing strings no longer than three years in length. We then calculate the average percentage difference between the observed data of each state and the corresponding national data, and use that together with the national data to impute missing values. For 14 states, all or nearly all of the state-level data are withheld, and we instead set the state price equal to the regional price.[30] We backcast the coal price data to the period 1980-1984 using data on the national average free-on-board (FOB) price of bituminous coal over 1980-2008 published in the 2008 *Annual Energy Review* of the EIA. Backcasting is based on (1) the state-specific average percentage differences between the delivered state and national prices; and (2) the percentage differences between the delivered national prices and the FOB national prices over the 1985-1990. The coal price data are reported in dollars per metric tonne. We convert to dollars per mBtu using the conversion factor of 23 mBtu per metric tonne of bituminous coal, which we calculate based on the labor-energy input surveys of the PCA.

We obtain state-level data on the prices of petroleum coke, natural gas, and distillate fuel oil, again for the industrial sector, from the State Energy Database System (SEDS) of the EIA. The imputation of missing values is required only for petroleum coke. To perform the imputation, we first calculate average percentage difference between the observed data of each state and the corresponding national data, and use that together with the national data to impute missing values. In five states with active kilns, all or nearly all of the state-level data are withheld so we base imputation instead on the average petroleum coke prices that arise in adjacent states and nationwide.[31] The SEDS data are in dollars per mBtu.

Plants sometimes list multiple primary fuels in the Plant Information Survey. There is little data available on the mix of primary fuels in those instances, however, and we allocate such plants based on a simple decision rule. We calculate fuel costs with the price of coal if coal is among the primary fuels. If not, we use petroleum coke prices if coke is among primary fuels. Otherwise we use natural gas prices if natural gas is among the multiple fuels. We use oil prices only if oil is the only fossil fuel listed. The exception to the above decision rule is when plants use a mix of coal and petroleum coke – there we assign equal weights to coal and petroleum coke prices. We have experimented with more sophisticated methodologies, leveraging data published in the *Minerals Yearbook* of the USGS on the total amounts of each fossil fuel burned by cement plants nationally. These methodologies are not fully satisfactory because, among other reasons, the USGS numbers include fuel burned (especially natural gas) to reheat kilns after maintenance periods. Our regression results are not sensitive to methodology on this subject and, given this, we prefer the simple rule.

[30]These states are Connecticut, Delaware, Louisiana, Massachusetts‘, Maine, Mississippi, Montana, North Dakota, New England, New Jersey, New Mexico, Nevada, Oregon and Vermont.

[31]We use the national price here because the prices in many adjacent states similarly are withheld. We impute the price of Maine using the national price because data for adjacent states are withheld (there are no kilns in adjacent states). We impute the price of Iowa using the arithmetic mean of the Illinois price and the national price. We impute the price of Nevada and Arizona using the arithmetic mean of the California price and the national price. We impute the price of Kansas using the arithmetic mean of the Oklahoma price, the Missouri price, and the national price.

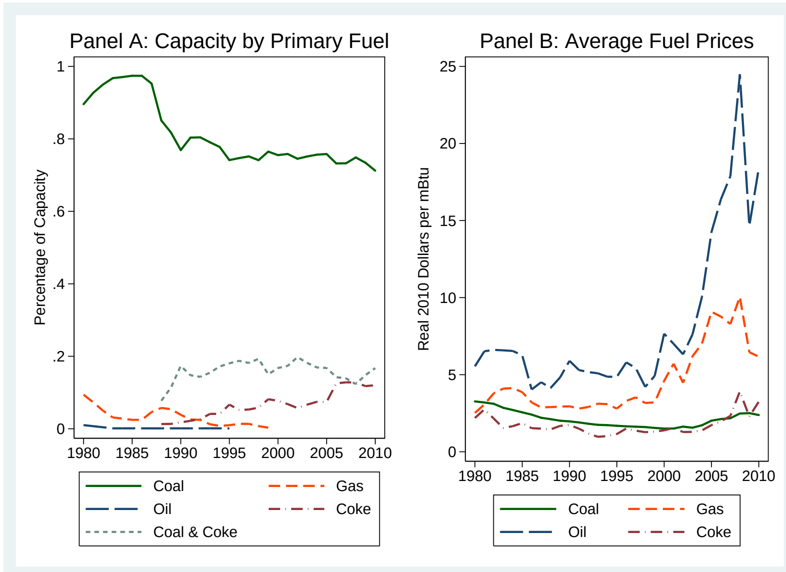

Figure B.1: Primary Fuels and Fuel Prices

Notes: Panel A plots the fraction of kiln capacity that burns as its primary fuel (i) bituminous coal, (ii) natural gas, (iii) fuel oil, (iv) petroleum coke, and (v) bituminous coal and petroleum coke. Data are obtained from the PCA Plant Information Surveys. Panel B plots the average national prices for these fuel in real 2010 dollars per mBtu. Coal prices are obtained from the Coal Reports of the Energy Information Agency (EIA); the remaining prices are obtained from the State Energy Data System of the EIA.

Figure B.1 plots in Panel A the fraction of industry capacity that uses each fossil fuel as its primary source of energy, based on this methodology. The dominant primary fuel sources are coal and petroleum coke, which completely displace natural gas and oil midway through the sample period. Panel B shows why coal and petroleum coke are used: on a per-mBtu basis, they are more cost efficient than natural gas and oil. The variation in fuel choices and fuel prices, together with the heterogeneous kiln technologies, produces variation in fuel costs that we exploit in the empirical analysis.

We calculate energy requirements of each kiln technology based on the labor-energy input surveys of the PCA. There is no discernible change in the energy requirements of production, conditional on the kiln type, over 1990-2010. We calculate the average mBtu per metric tonne of clinker required in 1990, 2000, and 2010, separately for each kiln type, and apply these averages over 1990-2010. These requirements are 3.94, 4.11, 5.28, and 6.07 mBtu per metric tonne of clinker for dry precalciner kilns, dry preheater kiln, long dry kiln, and wet kilns, respectively. A recent survey of the USGS accords with our calculations (Van Oss (2005)). By contrast, technological improvements are evident over 1974-1990, conditional on kiln type. The labor-energy surveys indicate that in 1974 the energy requirements were 6.50 mBtu per metric tonne of clinker at dry kilns (a blended average across dry kiln types), and 7.93 mBtu per metric tonne of clinker at wet kilns. We assume that technological improvements are realized linearly over 1974-1990 and scale the energy requirements over the early years of the sample period accordingly. Lastly, we scale down by our calculated energy requirements by five percent to reflect that a small amount of gypsum is ground together with the kiln output (i.e., clinker) to form cement.

Our methodology does not incorporate secondary fuels, the most popular of which are waste fuels such as solvents and used tires. The labor-energy input surveys of the PCA indicate that waste fuels account for around 25% of the energy used in wet kilns and 5% of the energy used in dry kilns. We do not have data on the prices of waste fuels but understand them to be lower on a per-mBtu basis than those of fossil fuels. Accordingly, we construct an alternative fuel cost measure in which we scale down the fossil fuel requirements of wet and dry kilns in accordance with the survey data. Whether this adjustment better reflects the fuel costs of marginal output depends in part on (i) the relative prices of waste and fossil fuels and (ii) whether the average fuel mix reported in the survey data reflect the marginal fuel mix. On the latter point, if marginal clinker output is fired with fossil fuels then our baseline measurement should reflect marginal fuel costs more closely than the alternative measurement. Regardless, our regression results are not very sensitive to the adjustment.

The USGS *Minerals Yearbook* publishes average prices per region. In total, there are 56 regions, fully contained in the contiguous United States, that appear at least once.[32] In Table B.1, we list the number times we observe each region over the sample period 1980-2010. Only five regions are observed in every year – Alabama, Illinois, Maine/New York, Missouri, and Ohio. Regions more commonly are observed for a portion of the sample. The regions exhibit numerous features that make it difficult to interpret them as local markets. We highlight two here. First, regions are not always contiguous. An example is Georgia, which in 14 years is grouped with Virginia and West Virginia but not with South Carolina. Second, the regions exhibit little constancy over the sample period. An example is Nevada, which in 19 years is grouped with Idaho, Montana and Utah and in nine years is grouped with Arizona and New Mexico. Nonetheless, the data provide useful information on prices throughout the United States and serve to motivate our empirical framework, which we develop to accommodate such data.

The *Minerals Yearbook* provides, for each year, a list of the customs districts through which foreign importers enter the domestic market. The number of customs districts grows during the sample period. The control variable we use for imports (i.e., inverse distance to

[32]We do not include regions that incorporate states and territories outside the contiguous United States. For example, we exclude Oregon/Washington/Alaska/Hawaii, which exists over 1983-1985.

Table B.1: Number of Observations by USGS Region

Region	Observations	Region	Observations
AL	31	GA/TN	9
IL	31	OK	9
ME/NY	31	SD	9
MO	31	AR/MS/LA	7
OH	31	MD/VA/WV	6
FL	30	KY/VA/WV	6
East PA	30	WA	6
West PA	30	ID/MT	5
North TX	29	ID/MT/UT	5
South TX	29	AZ/CO/UT/NM	3
North CA	29	GA/SC	3
South CA	29	ID/MT/WY	3
KS	28	IN/KY	3
IN	28	KS/NE	3
SC	28	KY/NC/VA	3
CO/WY	26	MD/WV	3
AR/OK	22	NE/WI	3
MI	21	TN	3
MD	20	UT	3
AZ/NM	19	AR/MS	2
IA/NE/SD	19	CA	2
ID/MT/NV/UT	19	GA	2
KY/MS/TN	19	GA/MD/VA/WV	2
GA/VA/WV	14	LA/MS	2
OR/WA	13	OR/NV	2
IA	12	TX	2
MI/WI	10	CO/NE/WY	1
AZ/NM/NV	9	PA	1

Notes: The table provides the number of observations and the mean number of active plants for each USGS region over the period 1980-2010. In total there are 56 regions and 773 region-year observations. We do not include regions that incorporate states and territories outside the contiguous United States.

the nearest customs district) is calculated based on the location of *active* customs districts. We treat each customs district as active starting in the first year in which imports through the district exceed five thousand metric tonnes, and continuing through all subsequent years. The two exceptions are Duluth MN and Milwaukee WI, which we code as inactive starting in 2005 due to the cessation of importing activity. Using an alternative definition of active, based on the first year that any imports flow through the district, does not affect results.

We obtain county-level data from the Census Bureau on construction employees and building permits to help control for demand. Construction employment is part of the County Business Patterns data. We identify construction as NAICS Code 23 and (for earlier years) as SIC Code 15. The data for 1986-2010 are available online.[33] The data for 1980-1985 are obtained from the University of Michigan Data Warehouse. The building permits data are maintained online by the U.S. Department of Housing and Urban Development.[34] We base the permits variable on the number of units so that, for example, a 2-unit permit counts twice as much as a 1-unit permit. For both the construction employment and building permits, it is necessary to impute a small number of missing values. We calculate the average percentage difference between the observed data of each county and the corresponding state data, and use that together with the state data to fill in the missing values.

C Flexible Demand Estimates

In Section 4.3, we develop conditions under which it is possible to infer conduct from pass-through if the slope and curvature of demand are known. There is too little empirical variation in our data to obtain second-order flexible estimates of demand along the lines required by equation (11). To illustrate, we plot prices against squared prices in Figure C.1. Each dot represents a single region-year observation. As shown, the relationship is nearly linear because prices are observed over too narrow a range. The univariate correlation coefficient between these variables is 0.99, and that level of collinearity makes it difficult to separately identify the slope of demand and the curvature of demand.

Suppose that the USGS regions represent valid economic markets. Then linear demand curves can be estimated by regressing quantity on average price (this obtains the slope) and second-order flexible demand curves can be estimated by regressing quantity on average price and its square. We implement by instrumenting for average price with average fuel costs,

[33]See `http://www.census.gov/econ/cbp/download/`, last accessed April 16, 2014.
[34]See `http://socds.huduser.org/permits/`, last accessed April 16, 2014.

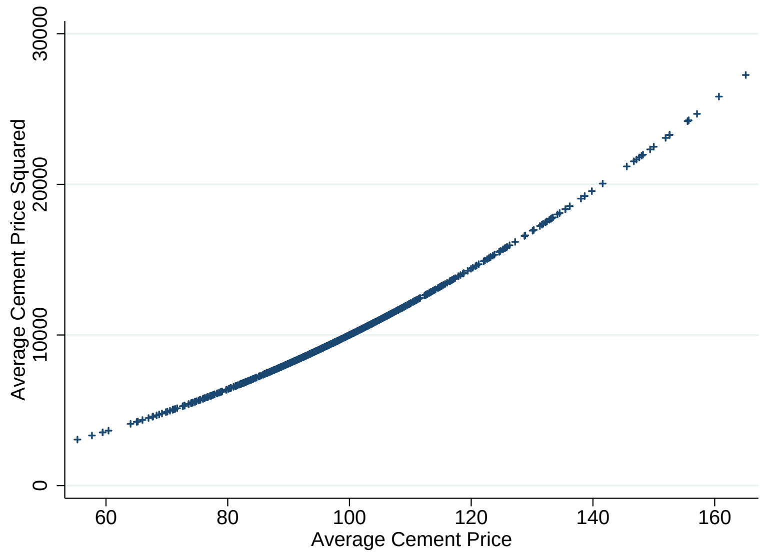

Figure C.1: Cement Prices and Cement Prices Squared

Table C.1: Demand Estimation

	(i)	(ii)
Price	-13.92	-2251
	(6.70)	(7359)
Price^2		10.26
		(33.87)
Region Fixed Effects	yes	yes

Notes: The table reports the results of 2SLS regression. The sample includes 769 region-year observations over 1980-2010. The dependent variable is the quantity of portland cement produced. The instrument in column (i) is the average fuel cost and the instruments in column (ii) are the average fuel cost and its square. Standard errors are clustered within regions.

and controlling for region fixed effects.[35] The results are reported in Table C.1. The slope of the linear demand curves imply a mean elasticity of 0.57, and the confidence interval encompasses the elasticities of Miller and Osborne (2014). The point estimates that arise with the flexible demand curve are very imprecise due to the lack of empirical variation.

[35]The number of observations is slightly less than what appears in the baseline pass-through regressions because quantity data are sometimes withheld by the USGS even if price data are published.

D EPA Analysis of NESHAP Ammendments

The EPA relies on a Cournot model of competition to simulate the effect of regulation in each of 20 local markets based on conditions in 2005. The model incorporates a constant elasticity market demand curve and, for markets that are adjacent to a port, a constant elasticity import supply curve. It is calibrated to elasticity estimates in the existing literature. We provide details on the model here. After the implementation of regulation, the first order conditions of firm i can be expressed

$$dMC_i = dP\left[1 + \frac{s_i}{\eta}\right] + dq_i\left[\frac{P}{\eta}\frac{1}{Q}\right] - dQ\left[\frac{P}{\eta}\frac{q_i}{Q^2}\right], \tag{D.1}$$

P is the market price, s_i is the share of sales for plant i, q_i is the quantity sold by plant i, Q is market consumption including imports, MC is marginal cost, and η is the elasticity of consumption with respect to price. Thus the object dMC is the compliance cost of regulation. Equation D.1 governs how compliance costs, represented by dMC_i, affect output and, in turn, market price. Imports are supplied according to an elasticity ϕ, such that

$$dI = \phi\left(\frac{dP}{P}\right)I, \tag{D.2}$$

where I is the quantity of imports. Total consumption in a market (again including imports) evolves according to

$$dQ = \eta\left(\frac{dP}{P}\right)Q. \tag{D.3}$$

Finally, the model is closed with supply equaling demand,

$$dQ = \sum_i dq_i + dI. \tag{D.4}$$

The EPA calibrates the model with a price elasticity of consumption of 0.88, based on EPA (1998), an import elasticity of 2.0, based on Broda, Limao, and Weinstein (2008). Prices and plant-level production are calculated by manipulating the region-level data published in the *Minerals Yearbook* of the USGS, following a methodology that is detailed in Section A.1 of EPA (2009). We are able to replicate the calibration process exactly so that discrepancies between our predictions and those of the EPA are due solely to the decision of the EPA not to publish plant-level compliance costs.