Online Appendix

Economic Geography and Air Pollution Regulation in the United Statesy

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A Calculating Trade Costs

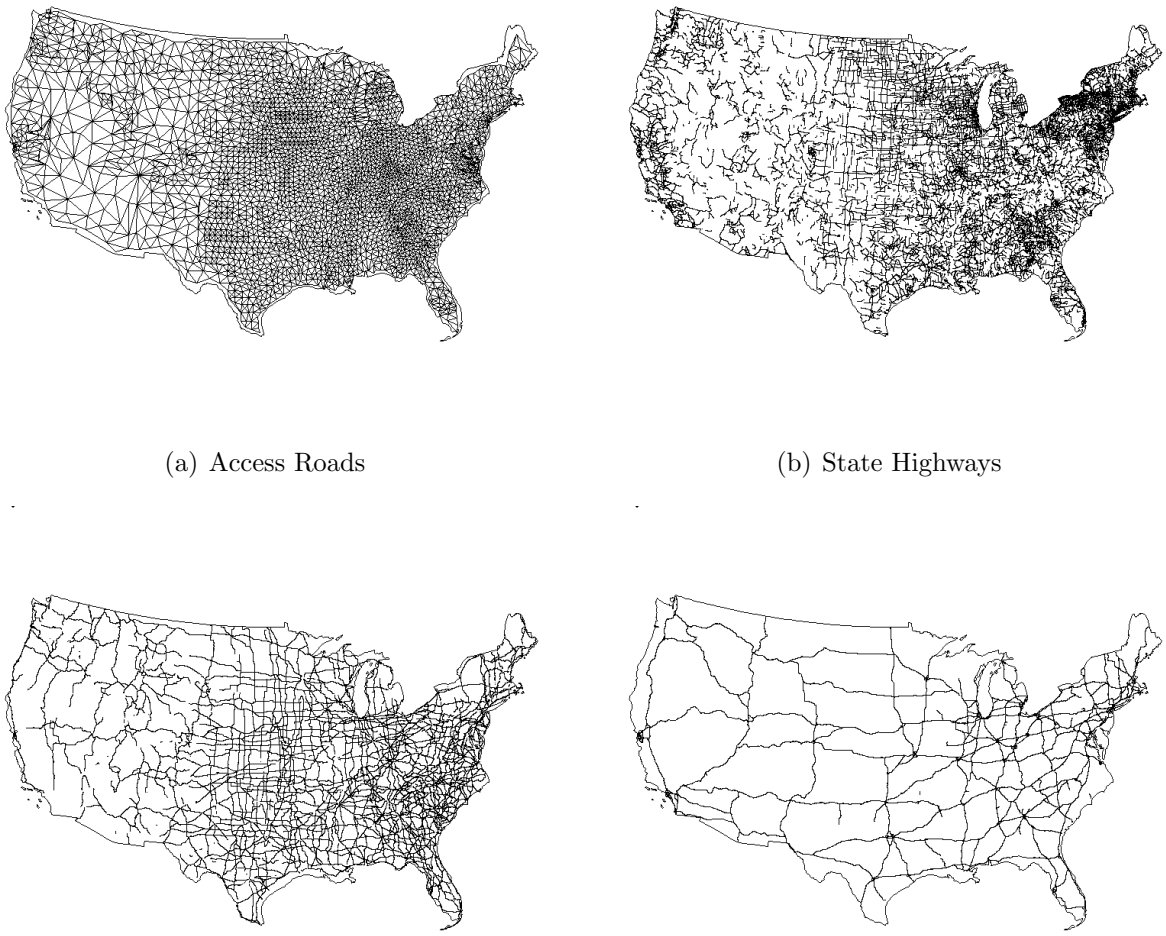
To construct trade costs, we utilize new data on the extent of the highway network in each year.[41] For 2000 and 2010, we use shapefiles maintained by the federal government. Prior to 1994, the federal government did not maintain shapefiles of the highway network, thus, for earlier periods, we construct our own network databases. To do this, we begin with the year 2000 shapefiles. We then overlay scans of the 1990 Rand McNally Road Atlas in ArcGIS, where we then re-code, edit, or delete segments of the 2000 network to generate the 1990 network. We follow this same procedure, overlaying the 1980 Rand McNally Road Atlas on the 1990 shapefiles. Thus, we have a harmonized panel data of the highway network from 1980 to 2010 that includes state highways, US federal highways, and Interstate highways. Additionally, we construct a set of "access" roads between each county centroid and its neighboring county centroid to ensure that all origins and destinations are connected to the network.[42] In Figure A1, Panels (a) through (d), we highlight the different components of the network for 1990.

We assign travel speeds to each type of segment based on its classification, 10 miles per hour (access roads), 35 miles per hour (state highways), 55 miles per hour (US Highways), and 70 miles per hour (Interstate Highways). These speeds are then used to construct the time cost associated with each segment. We represent each county in space by its geographic centroid and compute the minimum travel time through the network for each origin-destination pair using Dijkstra's Algorithm. For each route, we compute the travel time and distance traversed. Following Combes and Lafourcade (2005), we construct τ_{ij} by monetizing the travel time and distance using the hourly wage of a truck driver and national fuel prices for that year and fuel efficiency of a truck in the given year and normalizing by the average value of a shipment in the 2012 commodity flow survey. To construct market access, we then solve the system of equations outlined in Section 4.

[41] For our period of study we focus on trade costs via the highway network given that truck-only transportation accounted for more than 80 percent of the value of domestic trade (excluding the movement of parcels by the United States Post Office or by courier) according to the Commodity Flow Survey in 2002.

[42] Jaworski and Kitchens (2019) show that the choice of geographic or population-weighted centroid makes little difference empirically.

Figure A1: Components of Highway Network.



(a) Access Roads

(b) State Highways

(c) US Highways

(d) Interstate Highway System

Note: The figure shows the four components of the US highway network used to calculate travel time and trade costs. Panel (a) shows the access road network with an assigned speed of 10 miles per hour, Panel (b) shows the state highway network with an assigned speed of 35 miles per hour, Panel (c) shows the US highway network with an assigned speed of 55 miles per hour, and Panel (d) shows the Interstate Highway System with an assigned speed of 70 miles per hour.

B Amenities in Reduced Form

In the quantitative model we model the relationship between nonattainment, emissions, and the spatial transport of pollution. The model assumes that households have perfect information and reallocate across space in response to changes in the spatial distribution of pollution. To validate this assumption and to gauge the size of our model estimates of welfare impacts through amenities, we estimate a reduced form relationship between nonattainment and amenities using the households' spatial equilibrium conditions.

In general, we can represent amenities similarly to how we represent the regulatory shadow price of emissions η_i^{kp} in the main text:

$$B_i = \bar{B}_i \exp\left(\beta_B N_{i,t}\right). \tag{16}$$

$\bar{B}_i$ is the county's baseline level of amenities, and $\exp\left(\beta_B N_{i,t}\right)$ captures how nonattainment status N_i affects local amenities. $\beta_{\mathbf{B}}$ can be interpreted as the percent change in amenity-related welfare from imposing nonattainment.

We obtain our equation of interest by manipulating equation (4) to obtain an expression for the log share of workers who migrate to j relative to those who stay in i $\log(\pi_{ij}/\pi_{ii})$:

$$\log\left(\frac{\pi_{ij}}{\pi_{ii}}\right) = \log\left(\frac{V_j B_j \delta_{ij}}{V_i B_i \delta_{ii}}\right) = \log\left(\frac{w_j/P_j}{w_i/P_i}\right) + \log(\delta_{ij}) + \log(\bar{B}_j/\bar{B}_i) + \beta_B\left(N_j - N_i\right)$$

where $\delta_{ii} = 1$. We drop sector superscripts because we do not observe sector of employment in the county-to-county migration data. Next, rearrange this expression to obtain an equation with data on the left-hand side as a function of parameters to estimate and capture with fixed effects:

$$\log\left(\frac{\pi_{ij}}{\pi_{ii}}\right) = \beta_B\left(N_j - N_i\right) + \log(\bar{B}_j/\bar{B}_i) + \log\left(\frac{w_j/P_j}{w_i/P_i}\right) + \log(\delta_{ij}). \tag{17}$$

The difference in the share of people in i who migrate to j relative to those who stay in i is equal to the difference in amenities, differences in real wages, and migration costs.

Assuming amenities are common across workers in both sectors, we use a difference-in-differences approach:

$$\log\left(\frac{\pi_{ij,t}}{\pi_{ii,t}}\right) = \beta_B\left(N_{j,t} - N_{i,t}\right) + \log\left(\frac{w_j/P_j}{w_i/P_i}\right) + \phi_{ij} + \nu_t + \varepsilon_{ij,t} \tag{18}$$

where migration costs are absorbed by the origin-destination fixed effect ϕ_{ij} and $\varepsilon_{ij,t}$ is the error term. Standard errors are clustered two ways at the origin and destination counties.

This reduced form estimate of nonattainment's effects on amenities provides two important benefits. First, the estimate is identified off of variation in migration flows and quasi-experimental regulatory variation. If our model assumption that households observe and respond to pollution is incorrect, it will show up as a zero estimate here. Second, this approach allows us to be agnostic about the precise ways in which nonattainment status can induce improvements in amenities. In addition to reductions in air emissions reducing mortality, there may be other benefits not captured in our quantitative model such as reductions in noise, or improved foliage from better air quality. This, along with the fact that we are not capturing all pollutants, suggests that the reduced form impact on amenities should exceed the model-based estimates and gives us another sanity check on our model. We note that this is a rough test since the IRS data do not report wages, and so we must use county average real wages as an alternative.

B.1 The Effect of Nonattainment on Amenities

Table B1 shows the results from estimating models building up to our preferred specification in equation (18). Column 1 presents results with origin-by-destination and year fixed effects, the real wage control omitted, and forcing the coefficients on origin nonattainment status and destination nonattainment status to be identical. Column 1 suggests that nonattainment status improves local amenities such that, on average, utility increases by 2.3 percent. Column 2 adds in the real wage control and fixes the coefficient on real wages to equal one to be consistent with the model. Column 3 further allows nonattainment status to have differential effects depending on whether its the origin or destination county. All specifications generate relatively noisy estimates that nonattainment status improves utility between about 1.5 and 2.5 percent, holding real wages fixed. This is slightly larger than the amenities estimates from our model as hypothesized.

Table B1: Difference-in-differences estimates of the effect of nonattainment on local amenities.

	(1)	(2)	(3)
1(Dest. Nonattainment) - 1(Orig. Nonattainment)	0.023	0.014	
	(0.017)	(0.015)	
1(Destination Nonattainment)			0.015
			(0.015)
1(Origin Nonattainment)			−0.014
			(0.015)
Observations	1,048,420	1,048,420	1,048,420
Origin-Destination FE	Yes	Yes	Yes
Year FE	Yes	Yes	Yes
Real Wage	Omitted	Coef. Fixed	Coef. Fixed
Origin vs Destination	Fixed	Fixed	Free

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Robust standard errors are clustered two ways at the origin state and destination state levels.

C Simulating Counterfactuals

C.1 Solution Algorithm

To simulate our counterfactual we first need to invert the model and solve for the level of productivity T_i^k and the regulatory shadow price of emissions η_i^{kp}. We will not need to solve for the level of amenities B_i^k since observed mobility shares are effectively sufficient statistics for the composition of moving costs and differences in base amenities across locations.[43]

C.1.1 Solving for η_i^{kp} and T_i^k

First we solve for the regulatory shadow price of emissions using observed data under the 1997 nonattainment designations. To recover η_i^{kp} we use the equilibrium condition for emissions intensity in equation (5) and recognizing that with Cobb-Douglas technology, labor is paid a fixed share: $w_i^k L_i^k = \gamma \left(1 - \sum_{q=1}^{P} \xi^{kq}\right) Y_i^k$ to obtain:

$$\eta_i^{kp} = \frac{\xi^{kp}}{\gamma \left(1 - \sum_{q=1}^{P} \xi^{kq}\right)} \frac{w_i^k L_i^k}{e_i^k}$$

where w_i^k, L_i^k, and e_i^k are data and the remaining variables are calibrated constants. This allows us to identify the regulatory shadow price of emissions. Using our empirical estimates for β_η^p and the observed set of nonattainment designations, we can then recover the base regulatory shadow price of emissions:

$$\bar{\eta}_i^{kp} = \eta_i^{kp} \exp\left(-\beta_\eta^p N_i\right).$$

This gives us the shadow price that firms face for emissions in the absence of nonattainment or first-best emissions pricing.

Next we solve for productivity. From equation (10) we have that:

$$Y_i^k = \kappa_2 \left[c_i^k\right]^{-\theta^k} T_i^k F M A_i^k \tag{19}$$

We can manipulate equation (19) and expand out the unit cost term c_i^k to obtain an expression

[43] If we observed county-level trade flows we could simulate counterfactuals without solving for T_i or estimating τ_{ji}.

that gives us T_i^k up to a normalization:

$$T_i^k = \rho_1 \frac{L_i^k \left[w_i^k\right]^{\left((1+\theta^k\gamma\left(1-\sum_{q=1}^P \xi^{kq}\right)\right)} \prod_{q=1}^P (\eta_i^{kq})^{\xi^{kq}\theta^k}}{FMA_i^k}. \tag{20}$$

In equation (20) we still need to identify the firm market access variables FMA_i^k to obtain productivity T_i^k for $k = 1, \ldots, K$. We can do so by performing function iteration on the system of equations that implicitly define firm market access and consumer market access from Section 3:

$$FMA_i^k = \sum_{j=1}^N \frac{\left(\tau_{ji}^k\right)^{-\theta^k}}{CMA_j^k} X_j^k \tag{21}$$

$$CMA_i^k = \kappa_3 \sum_{j=1}^N \frac{\left(\tau_{ij}^k\right)^{-\theta^k}}{FMA_j^k} Y_j^k \tag{22}$$

where $Y_i^k = \frac{w_i^k L_i^k}{\gamma\left(1-\sum_{q=1}^P \xi^{kq}\right)}$, and $X_i^k = \alpha^k \sum_{l=1}^K w_i^l L_i^l$. Iterating on these equations yields both market access vectors up to a normalization. Next we insert the recovered FMA_i^k terms into equation (20) and use the observed 1997 data on labor, wages, and nonattainment status to recover T_i^k.

C.1.2 Simulating the Model Under Different Scenarios

Now that we have recovered the regulatory shadow price under the 1997 nonattainment designations η_i^{kp}, the base regulatory shadow price $\bar{\eta}_i^{kp}$, and productivity T_i^k, we can simulate the welfare effects of changing the regulatory shadow price of emissions through different nonattainment designations or first-best emissions pricing. Consider the case of computing the equilibrium outcomes under some set of counterfactual regulatory shadow prices of emissions $\eta_i^{kp\prime}$, which may be the base regulatory shadow prices in the case of no counties in nonattainment, the first-best emissions prices, or any other choice. Other primed variable indicate endogenous quantities under $\eta_i^{kp\prime}$.

0a. Solve for the 1997 price indices Use the observed labor and wages from 1997 in equations (21) and (22) to solve for consumer market access and thus the price indices for the observed 1997 nonattainment designations that generate the regulatory shadow prices of emissions η_i^{kp}.

0b. Initial guess Guess a vector of market wages and the labor distribution across markets under the counterfactual $\eta_i^{kp\prime}$.

1. Solve for the counterfactual price indices Use these guesses in equations (21) and (22) to solve for consumer market access and thus the price indices under the counterfactual nonattainment designations.

2. Solve for the change in amenities Compute the level of manufacturing emissions using the expression for relative expenditures on inputs for a Cobb-Douglas producer:

$$e_i^{p\prime} = \frac{w_i^{k\prime} L_i^{k\prime}}{\eta_i^{kp\prime}} \frac{\xi^{kp}}{\gamma\left(1 - \sum_{q=1}^{P} \xi^{kq}\right)},$$

where nonmanufacturing emissions are always zero. Then, along with the 1997 wages, the counterfactual wage guess, and the price indices from steps 0a and 1, solve for the change in amenities in equation (2) from going from the 1997 designations to the counterfactual designations.

$$\frac{B_j^{l\prime}}{B_j^l} = \underbrace{\frac{\bar{B}_j}{\bar{B}_j}}_{=1} \left[\left(1 - \frac{\sum_{n=1}^{N} \sum_{p=1}^{P} md_{in}^p e_n^{p\prime}}{V_i^{k\prime}} \right) \Bigg/ \left(1 - \frac{\sum_{n=1}^{N} \sum_{p=1}^{P} md_{in}^p e_n^p}{V_i^k} \right) \right].$$

We assume that baseline, non-pollution component of amenities $\bar{B}_j$ does not change in response to nonattainment.[44]

3. Solve for the counterfactual mobility shares and labor distribution Manipulating equation (4), we can obtain the counterfactual mobility shares and labor distribution as a function of the wage and labor guesses; the observed wages, labor, and mobility shares under 1997 nonattainment; the computed 1997 and counterfactual price indices; and the computed change in amenities:

$$\pi_{ij}^{kl\prime} = \frac{\left[\frac{V_j^{l\prime} B_j^{l\prime}}{V_j^l B_j^l}\right]^{\iota} \pi_{ij}^{kl}}{\sum_{m=1}^{K} \sum_{n=1}^{N} \left[\frac{V_n^{m\prime} B_n^{m\prime}}{V_n^m B_n^m}\right]^{\iota} \pi_{in}^{km}} \tag{23}$$

$$L_i^{k\prime} = \sum_{m=1}^{K} \sum_{n=1}^{N} \pi_{ni}^{mk\prime} L_n^{m\prime} \tag{24}$$

[44] We are not able to recover the level of amenities, but we can recover the change in amenities given a change in the set of nonattainment statuses from the structure of equation (2).

where the V terms are real wages, $V_n^{0\prime} = V_n^0$ so that nonattainment does not change the payoff from nonemployment. The $L_n^{m\prime}$ terms on the right-hand side of equation (24) are the guesses while the left-hand side is the newly updated labor distribution guess.

4. Solve for wages We can then use the solved counterfactual labor distribution from step 3, counterfactual market access from step 1, counterfactual regulatory shadow prices of emissions, and the fundamental productivity in equation (20) to back out a new guess for the counterfactual level of wages.

5. Iterate on steps 1-4 until convergence We then repeat the process of solving for new distributions of labor, amenities changes, prices, and wages until the vector of real wages converges, where we define convergence to be that the sup norm of the relative change in real wages between two different iterations of step 4, is sufficiently small.

We run the solution algorithm with $\eta_i^{kp\prime} = \bar{\eta}_i^{kp}$ to recover our baseline of no counties in nonattainment. We run the solution algorithm with $\eta_i^{kp\prime}$ equal to the county-specific marginal damages of emissions in the case of first-best emissions pricing. For first-best emissions pricing we need to update the marginal damages in each iteration, reflecting that the distribution of workers changes as we iterate through the algorithm. Finally we compute the equilibrium outcomes under tighter nonattainment thresholds by setting $\eta_i^{kp\prime} = \bar{\eta}_i^{kp} \exp(\beta_\eta^p \tilde{N}_i^T)$ where $\tilde{N}_i^T$ is equal to 1 if the observed level of pollution in 1997 is above some counterfactual nonattainment threshold T and zero otherwise.

C.2 Welfare Derivation

With the model solutions in hand we can now compute the welfare consequences of changes in the regulatory shadow price of emissions. Let variables with primes be associated with a vector $\eta_i^{kp\prime}$, while unprimed variables be associated with η_i^{kp}. Recall that indirect utility from consumption and amenities is given by $V_i^k B_i^k$ and that mobility shares are governed by $\pi_{ij}^{kl} = \frac{(V_j^l B_j^l \bar{\delta}_{ij}^{kl})^\iota}{\sum_{m=0}^K \sum_{n=1}^N (V_n^m B_n^m \bar{\delta}_{in}^{km})^\iota}$. Rearrange and take the log of the expression for own-mobility shares to get:

$$\iota \log V_i^k B_i^k - \log \pi_{ii}^{kk} = \log \left[\sum_{m=0}^K \sum_{n=1}^N (V_n^m B_n^m \bar{\delta}_{in}^{km})^\iota \right]. \tag{25}$$

Let W_i be the expected total welfare for a household in location i net of moving costs:

$$W_i^k = \frac{1}{\iota} \log \left[\sum_{m=1}^K \sum_{n=1}^N (V_n^m B_n^m \bar{\delta}_{in}^{km})^\iota \right]$$

which is a function of unobserved moving costs. Next rearrange equation (25) and solve for W_i:

$$W_i^k = \log\left(V_i^k B_i^k\right) - \frac{1}{\iota}\log \mu_{ii}^{kk}.$$

Define the equivalent variation at some market (i,k) to be χ_i^k where:

$$W_i^{k\prime} = W_i^k + \log \chi_i^k.$$

Let $\widehat{x} \coloneqq x'/x$ for some variable x.

The consumption-equivalent welfare under $\eta_i^{kp\prime}$ relative to η_i^{kp} is χ_i:

$$\chi_i^k = \frac{\widehat{V}_i^k \widehat{B}_i^k}{\left(\widehat{\mu}_{ii}^{kk}\right)^{1/\iota}}.$$

D Robustness Checks

Sample Periods for Estimation Table D1 presents robustness checks of the effect of nonattainment on emissions prices with respect to the sample period. Our estimates are highly robust to the chosen years of inclusion.

Alternative Quantitative Parameters Table D2 reports the total welfare effect of 1997 nonattainment relative to no counties in nonattainment, but under different calibrated parameter values and structural assumptions.

The first row reports the base welfare outcomes in the main text. Panel A shows the effect of changing parameter values. The first two rows vary the trade elasticity θ and show that the quantitative values are sensitive to it, but the qualitative takeaways remain the same. Why do the welfare impacts of 1997 nonattainment designations decline in θ? First, recall that the trade elasticity governs the dispersion in productivities within a location-sector: the larger this value is, the less variation there is in productivity across firms within a location-sector. Second, recall that consumer market access CMA_i, a measure of consumers' access to cheap suppliers, was proportional to $\sum_{n=1}^{N} T_n^k \left[c_n^k \tau_{in}^k\right]^{-\theta^k}$. The expression for consumer market access makes clear that under a larger trade elasticity, consumer market access becomes more sensitive to producer cost shocks driven by nonattainment designations, which is reflected in lower welfare.

The next four rows vary the consumption share parameter α and the labor share parameter γ. The quantitative results are insensitive to their values.

The next two rows vary the migration elasticity parameter ι. The smaller of the two values is similar to annual elasticities estimated for US workers in Artuc et al. (2010) and Caliendo et al. (2019).[45] This value for ι generates similar results to our baseline.

In general, a larger ι leads to smaller aggregate gains from 1997 nonattainment. The decline in welfare gains is slightly larger for nonattainment counties compared to attainment counties, and the decline is borne by nonmanufacturing. Nonmanufacturing welfare gains are smaller because if ι is larger, the idiosyncratic shock to the household ε is less dispersed, making it less likely they get a large positive draw to overcome moving costs that prohibit them from moving to nonattainment counties to take advantage of the improved amenities. Since nonmanufacturing is a majority of the working population, this leads aggregate welfare gains to be smaller with a larger migration elasticity.

The last three rows of the panel change the pollution elasticity parameters ξ^p by halving, doubling, or quadrupling them. Greater pollution elasticities tend to worsen the effect of

[45]These papers estimate the *inverse* migration elasticity and recover values of around 2.

nonattainment designations on manufacturing workers. Larger pollution elasticities mean that production is more emissions intensive and amplifies the importance of the costs of emissions for firms. Thus, nonattainment has greater negative effects, leading to larger decreases in nominal manufacturing wages and manufacturing welfare.

Alternative Quantitative Structure Panel B shows the effect of making structural changes to the model. The first row of the panel introduces congestion and agglomeration externalities. With congestion externalities, amenities can be written as:

$$\tilde{B}_i^k = B_i^k L_i^{\zeta^c}$$

where B_i^k is amenities without congestion, and ζ^c is the congestion elasticity and equal to -0.3 following Allen and Arkolakis (2014). With agglomeration externalities, variety-specific productivity can be written as:

$$\tilde{z}_i^k(\omega) = z_i^k(\omega) \left[L_i^k(\omega)\right]^{\zeta^a}.$$

where $\zeta^a = 0.2$ following Allen and Arkolakis (2014). The existence of congestion and agglomeration slightly raises the aggregate benefits of nonattainment because of higher gains to nonmanufacturing.

The second row allows for marginal damages to depend on income, recognizing that richer people are willing to pay more to avoid mortality risk. Here we re-specify marginal damages as:

$$\widehat{md}_{ij}^k = md_{ij} \left(\frac{w_i^k}{\bar{w}_i^k}\right)^{\epsilon}$$

where $\epsilon = 0.4$ is the EPA's value of the income-elasticity of the value of a statistical life (VSL), and $\bar{w}_i^k$ is median household income. Marginal damages remain the same for the median household, but are increasing in income. Allowing for the VSL and marginal damages to be income-elastic decreases the benefits of the NAAQS by a quarter, relatively uniformly across sectors and county types.

The final two rows show the effect of nonattainment additionally increasing or decreasing productivity (T_i^k) by 3 percent. 3 percent is about the productivity effect estimated in the prior literature (Greenstone et al., 2012) which does not distinguish between declines in productivity and increases in the cost of emissions. A decrease would be consistent with nonattainment making capital or labor less productive because, for example, workers must now tend to abatement technology in addition to their regular tasks. An increase is consistent with the strong Porter hypothesis where environmental regulation leads to increased innovation

and firm competitiveness. 3 percent changes in productivity has little effect in the aggregate, however it does increase or decrease manufacturing welfare by 0.25pp because productivity shocks directly affect demand for manufacturing labor and manufacturing wages.

Table D1: Difference-in-differences estimates of the effect of nonattainment on the implicit emissions price varying the sample period.

	(1)	(2)	(3)	(4)	(5)	(6)
	(1)	(2)	(3)	(4)	(5)	(6)
β_η^p	0.51**	0.50**	0.33**	0.50**	0.49**	0.48**
	(0.23)	(0.21)	(0.17)	(0.22)	(0.23)	(0.24)
Observations	19,005	28,940	38,890	49,245	59,610	70,225
County FE	Yes	Yes	Yes	Yes	Yes	Yes
Year FE	No	No	No	No	No	No
Pollutant FE	No	No	No	No	No	No
Pollutant-Year FE	Yes	Yes	Yes	Yes	Yes	Yes
Latest Year	1996	1997	1998	1999	2000	2001

Note: The coefficients are estimated using data from 1990, and from 1996 to the year listed in the Latest Year row. The 1991–1995 gap reflects years in which NEI data are not available. Robust standard errors are clustered at the state level.
p < 0.1, ** p < 0.05, *** p < 0.01

Table D2: Welfare impacts of nonattainment in 1997 under different model parameters or structural assumptions.

Change	Total %	Manuf. %	Nonmanuf. %	Attain. %	Nonattain. %
No Changes					
Base Model	0.57	0.18	0.63	0.36	0.78
A. Parameter Changes					
$\theta = 2$	1.22	0.88	1.26	0.75	1.68
$\theta = 8$	0.31	-0.19	0.38	0.19	0.42
$\alpha = 0.137$	0.57	0.18	0.63	0.36	0.78
$\alpha = 0.548$	0.57	0.18	0.63	0.36	0.78
$\gamma = 0.2405$	0.56	0.09	0.62	0.39	0.72
$\gamma = 1$	0.57	0.26	0.62	0.31	0.84
$\iota = 0.495$	0.63	0.12	0.7	0.36	0.89
$\iota = 2$	0.4	0.15	0.43	0.23	0.56
ξs Halved	0.6	0.35	0.63	0.36	0.83
ξs Doubled	0.52	-0.18	0.62	0.36	0.68
ξs Quadrupled	0.42	-0.9	0.59	0.35	0.48
B. Structural Changes					
Add Congestion/Agglomeration	0.62	0.04	0.71	0.37	0.87
VSL Increases in Income	0.42	0.08	0.47	0.24	0.59
Increase Productivity 3 Percent	0.61	0.43	0.64	0.36	0.85
Decrease Productivity 3 Percent	0.53	-0.08	0.62	0.35	0.71

Note:
Welfare is computed as the equivalent variation of the observed nonattainment statuses in 1997 relative to a counterfactual where no counties are in nonattainment. Each row only makes one change relative to the base model in the first row.

E Supporting Results

Exogenous Nonattainment and the Length of Nonattainment Designations Figure E1 plots the share of counties that remaining in nonattainment over a 10 year period from 1992–2001 amongst the set of counties that were induced to go into nonattainment under the 1990 amendments. In the first full year, 1992, all of the counties are in nonattainment. Five years later, only one-third of counties exited nonattainment, and ten years later less than half of these counties exited nonattainment. This indicates that nonattainment designations are generally long-lasting and supports our assumption that nonattainment designations persist into a new equilibrium.

Congestion and Agglomeration Figure E2 plots the change in welfare gains if the model accounts for congestion and agglomeration effects. Similar to reallocation, congestion and agglomeration have highly heterogeneous welfare effects. Congestion effects tend to dominate agglomeration effects given our parameterization from Allen and Arkolakis (2014). Thus, incumbents in places where people are migrating to tend to be worse off with congestion and agglomeration while incumbents in places they are leaving tend to be better off.

Productivity Effects Figure E3 plots the change in the welfare impact of nonattainment if, in addition to its effect on emissions prices, it also has either a negative 3 percent or positive 3 percent effect on manufacturing productivity. Incorporating potential productivity effects has welfare impacts in nonattainment counties about one-tenth the size of the productivity effect, but does not meaningfully change the geography of the results as the magnitudes of the effects are relatively small.

First-Best Versus Actual 1997 Nonattainment Welfare Figure E4 plots the welfare benefits of moving from the 1997 nonattainment designations to the first-best emission price policy. Counties in the east benefit most from emissions pricing and all counties are better off.

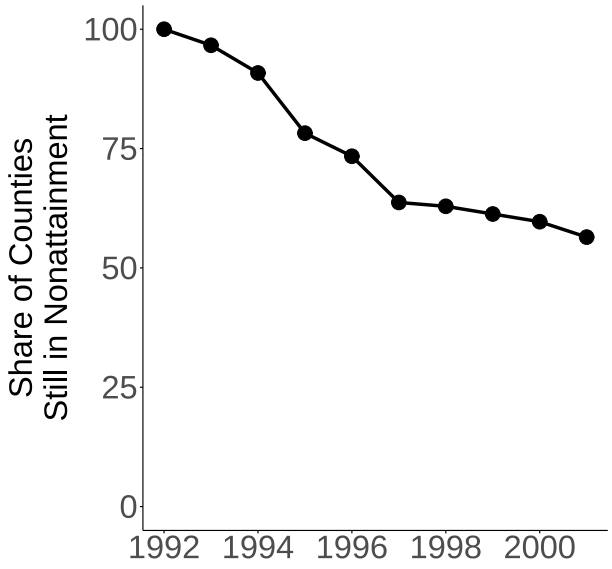
First-Best Emission Prices Figure E5 plots the emission prices under the first-best emission pricing policy. Recall that these prices are on top of the base regulatory shadow price of emissions from other prevailing regulations besides CAA nonattainment. Prices are highly heterogeneous across space and pollutants. Prices tend to be highest around urban areas and for $PM_{2.5}$ and SO_2. Notice that first-best prices are near-zero in some nonattainment counties and are substantially positive in some attainment counties. The

figure also shows why counties in the east benefit the most from first-best pricing: the price that firms face for emissions is too low.

Across all pollutants, the regulatory shadow price of emissions is too high in nonattainment counties and too low in attainment counties. For example, for $PM_{2.5}$, the average difference between the regulatory shadow price and the first-best price in nonattainment counties is nearly \$250,000/ton, while in attainment counties it is -\$800/ton. These kinds of mismatches between first-best prices and the regulatory shadow price of nonattainment are why first-best pricing leads to significant welfare gains, it corrects a mispricing of emissions under the NAAQS.

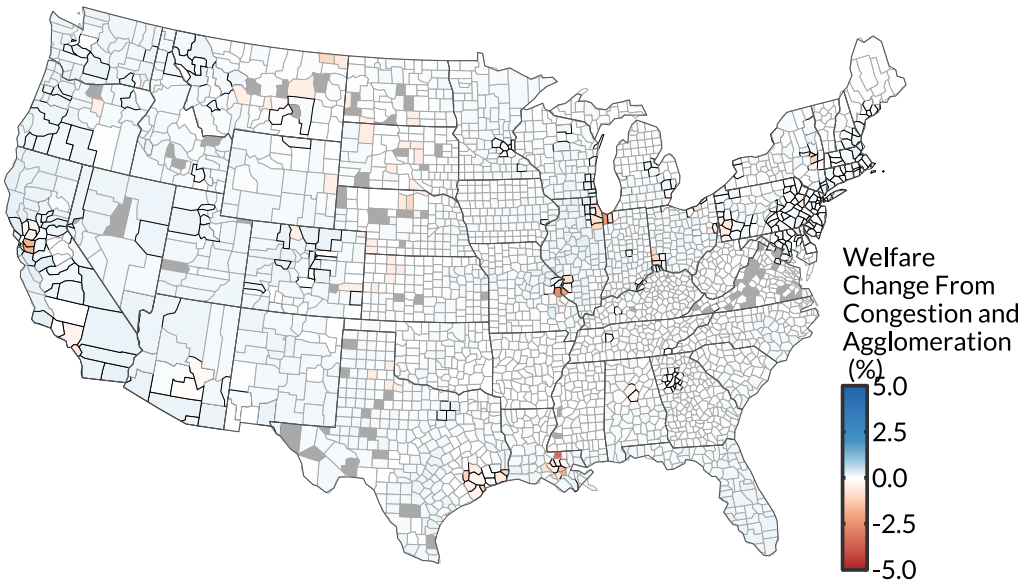
Reallocation Under First-Best Figure E6 shows the welfare gain from endogenous labor reallocation under the first-best pricing scheme. Notice that this looks substantially different than the gains under nonattainment shown in Figure 6. Under 1997 nonattainment, the value of labor reallocation is highest in nonattainment counties and the counties nearby as manufacturing workers can switch jobs or move to avoid the real wage penalty of nonattainment, and nonmanufacturing workers can move into nonattainment counties to reap the improved amenities. Under the first-best, reallocation is most valuable in the Southeast where emissions are underpriced by the prevailing nonattainment designations, while reallocation actually has negative consequences in the West. This is because workers in the Southeast move westward in response to first-best pricing, depressing incumbents' real wages in the West. In terms of sectoral reallocation, the aggregate changes in the share of workers across manufacturing, nonmanufacturing, and nonemployment are largely similar between the 1997 nonattainment outcomes and the first-best. The first-best results in a slightly smaller share of workers transitioning out of manufacturing, however the difference between the two is only 0.07pp, under one-tenth of the transition caused by 1997 nonattainment.

Figure E1: The share of new nonattainment counties remaining in nonattainment by year 1992–2001.



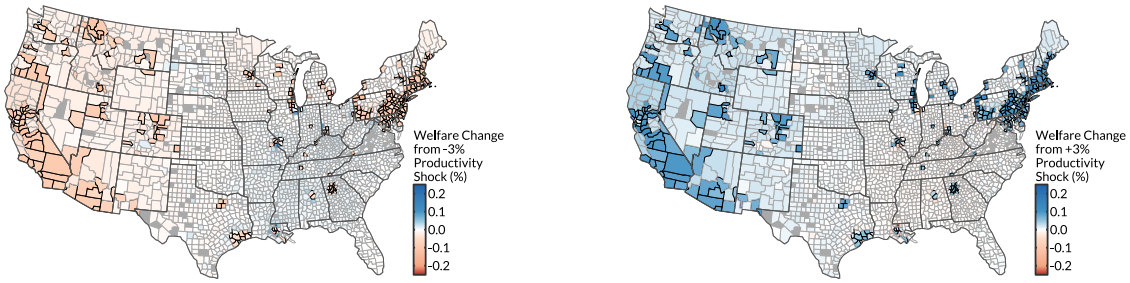
Note: Each point denotes the share of counties, amongst the set that newly went into nonattainment after the 1990 amendments, that remain in nonattainment each year.

Figure E2: The change in welfare gains from 1997 nonattainment from congestion and agglomeration.



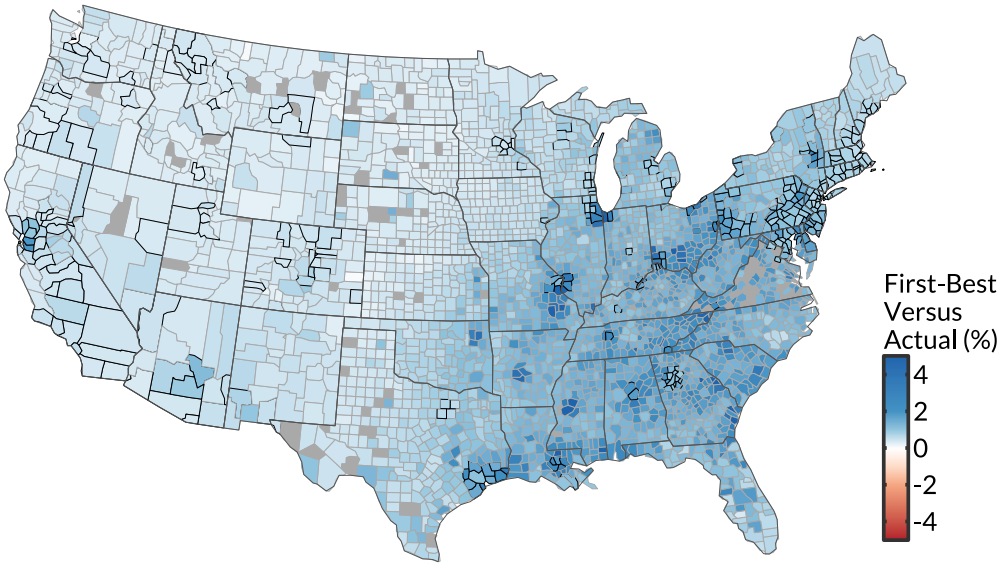
The change in welfare is the difference between the welfare calculated by the model using the 1997 nonattainment status provisions relative to the welfare calculated under a counterfactual scenario in which no counties are in nonattainment, with congestion and agglomeration effects versus without. Welfare is calculated as equivalent variation; it is reported in consumption-equivalent terms. Counties outlined in a dark border were in nonattainment in 1997. Dark gray counties are those that were omitted from the simulations due to missing data.

Figure E3: The change in welfare gains from 1997 nonattainment from if there are ±3 percent effects on total factor productivity in manufacturing.



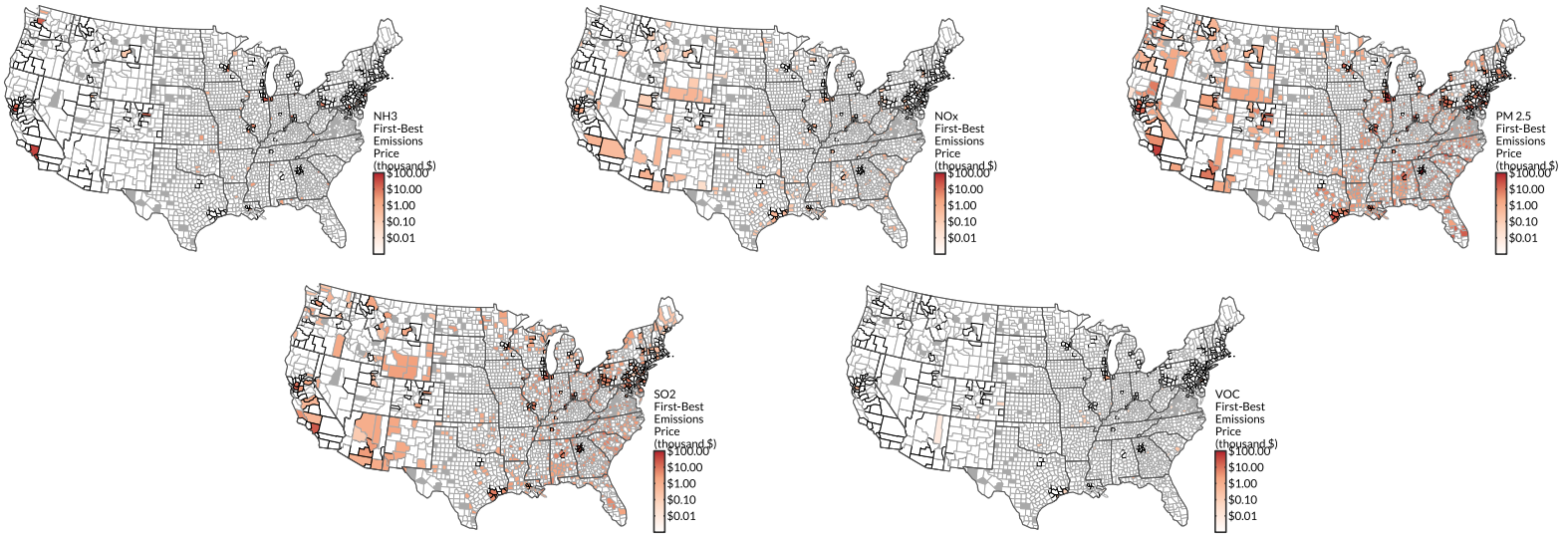
Note: The left panel decreases manufacturing productivity by 3 percent on top of the emissions price effects. The right panel increases manufacturing productivity by 3 percent on top of the emissions price effects. The change in welfare is the difference between the welfare calculated by the model using the 1997 nonattainment status provisions relative to the welfare calculated under a counterfactual scenario in which no counties are in nonattainment, with the productivity effect versus without. Welfare is calculated as equivalent variation; it is reported in consumption-equivalent terms. Counties outlined in a dark border were in nonattainment in 1997. Dark gray counties are those that were omitted from the simulations due to missing data.

Figure E4: Change in county welfare from first-best relative to 1997 nonattainment.



Note: The change in welfare is the difference between the first-best relative to the model with the 1997 nonattainment status in effect. Welfare is calculated as equivalent variation; it is reported in consumption-equivalent terms. Counties outlined in a dark border are in nonattainment in 1997. Grayed-out counties are omitted from the simulations due to missing data. The model includes impacts on emissions prices and allows for trade and labor mobility across counties and sectors.

Figure E5: First-best counterfactual emission prices.



Note: Each panel plots the pollutant-specific first-best emission price as the spatially differentiated tax equal to the marginal damages caused by a unit of emissions in a county, above the base regulatory shadow price of emissions which captures other regulations besides CAA-induced nonattainment. The tax accounts for how workers may have migrated or changed industries in response to the tax. Counties outlined in a dark border were in nonattainment in 1997. Dark gray counties are those that were omitted from the simulations due to missing data.

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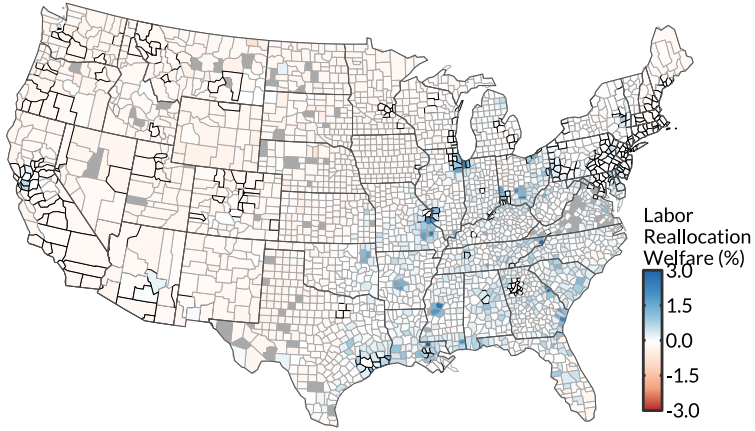
Figure E6: The change in welfare from endogenous labor reallocation under first-best emissions pricing.



Note: The top right panel shows the change in total welfare from labor reallocation through migration and changing sector of employment under first-best emission pricing. The change in welfare is the difference between the welfare calculated by the model using the first-best prices with labor reallocation versus without labor reallocation. Welfare is calculated as equivalent variation; it is reported in consumption-equivalent terms. Counties outlined in a dark border were in nonattainment in 1997. Dark gray counties are those that were omitted from the simulations due to missing data.

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