Escalation of Scrutiny: The Gains from Dynamic Enforcement of Environmental Regulations

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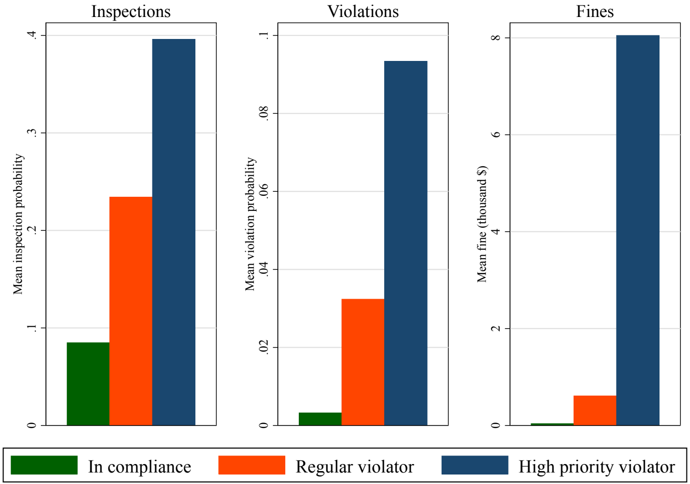
Motivation

- Between 1970 and 1990 the Clean Air Act reduced pollution damages by $35.3 trillion.
  - Regulatory and compliance costs were $831 billion.
  - This cost makes understanding efficient enforcement critical.
- Consider environmental enforcement with an example from a Texas oil refinery:
  - In 2011, a release valve was accidentally closed during process improvements.
  - This led to a leak from a pipeline that was not an authorized emissions source.
  - The plant was issued a fine and classified as a *High Priority Violator* (HPV).
  - This led to a doubling of future fines for minor violations in 2012.
  - It made two pollution abatement investments, including upgrades to monitoring systems.
  - The plant ultimately returned to compliance in 2013.

Dynamic Enforcement

- The EPA enforces the Clean Air Act Amendments (CAAA) with *dynamic enforcement*.
  - Characterized by regulatory actions being a function of the plant's regulatory state (Landsberger and Meilijson, 1982; Shimshack, 2014).
- The U.S. Environmental Protection Agency (EPA) scrutinizes and punishes repeat air pollution violators more severely than one-time offenders.
  - In part, through designation of repeat offenders as HPVs.
- Why might dynamic enforcement add value?
  - Lowers fines and imposing them may be costly to regulator.
  - Also useful when regulator cannot contract on plant's compliance costs.

Regulatory Actions by Lagged Plant Status



Note: Authors' calculations for plants covered by Clean Air Act Amendments, 2007-13.

Goals of This Paper

- To quantify the gains from dynamic enforcement of the CAAA.
- To do this, we:
  1. Estimate the compliance costs to industrial facilities under the EPA's current approach.
  2. Simulate the value of alternative enforcement regimes in affecting emissions and compliance.
- Our results are important given widespread use of dynamic enforcement in practice:
  - Modeling and estimation specific to CAAA.
  - But, similar approaches may be applicable to other sectors.
  - Theoretical value of dynamic enforcement is well understood: we add to empirical evidence.

Our Approach

- Idea of measuring value of dynamic enforcement:
  - Account for benefit of dynamic enforcement in lowering pollution damages.
  - Weigh this against costs of compliance to plants and regulators.
- We develop and estimate parameters of a dynamic game of a plant faced with a regulator enforcing environmental laws.
  - Regulator decides on inspections and fines.
    - Inspections help it detect CAAA violations.
    - Inspections and fines are costly.
  - Plant decides whether and when to invest in pollution abatement.
    - Investment increases chance of return to compliance, but is costly.
- We estimate the relative costs of investment and regulatory compliance:
  - For simplicity, we do not estimate EPA's utility parameters.
  - Instead, we estimate EPA's conditional choice probabilities.

Overview of Estimation and Counterfactuals

- Structural parameters: costs of investment, fines, and enforcement.
- Dependent variable is investment (like Rust, 1987).
- Main economic model has heterogeneous cost parameters across plants.
  - Each plant has a fixed vector of parameters, drawn from a finite grid.
  - Structural parameters are the population weights on the grid points.
  - Approximates non-parametric distribution.
  - Also estimate standard model with homogeneous cost parameters.
- We use the estimated model to simulate various counterfactuals with alternative regulatory regimes:
  - Remove state dependence of fines.
  - Increase stigma cost of HPV status.
  - Implement scaled Pigouvian fine structures.

Paper Contributes to Three Literatures

1. Empirical studies of enforcement of environmental (and other) regulations.
   - Magat and Viscusi, 1990; Nadeau, 1997; Earnhart, 2004; Eckert, 2004; Shimshack and Ward, 2005; Maitra et al., 2007; Stafford, 2008; Keohane et al., 2009; Ko et al., 2010; Shimshack and Managi, 2012; Telle, 2013; Blondiau et al., 2015; Evans, 2016; Blundell, 2020.
2. Structural environmental economics literature.
   - Timmins, 2002; Ryan, 2012; Lim and Yurukoglu, 2015; Fowlie et al., 2016; Muehlenbachs, 2015; Fowlie et al., 2016; Houde, 2018; Duflo et al., 2018; Kang and Silveira 2018.
   - Most closely related to Duflo et al., 2018; Kang and Silveira, 2018.
3. Dynamic discrete choice models with random coefficients.
   - Arcidiacono and Miller 2011; Fox et al., 2011; Gowrisankaran and Rysman, 2012; Fox et al., 2016; Nevo, et al., 2016; Connault, 2017.
   - Our fixed grid model is similar to the Fox/Nevo et al. approaches.

Remainder of talk

1. Setting & Model
2. Data
3. Empirical Foundations
4. Estimation
5. Results & Counterfactuals
6. Conclusions

General Regulatory Setting

- We focus on enforcement of the Clean Air Act Amendments.
  - Congress passed Clean Air Act in 1963.
  - The Act was amended repeatedly between 1965 and 1990.
  - Environmental Protection Agency (EPA) established in 1970.
    - EPA enforces CAAA and other environmental laws.
- EPA regulates emissions of criteria and hazardous air pollutants via technology standards.
  - We focus on enforcement for industrial facilities.
  - Enforcement occurs through a system of inspections, violations, fines, and classification into different regulatory states (e.g. HPV).
- EPA divides country into 10 regions.
  - Significant portion of operations conducted through regional offices.
  - Policy differences across regions provides identifying variation.

CAAA Monitoring and Enforcement

- Inspections:
  - Both plants in compliance and violators are inspected regularly.
  - Plants with the greatest health and environmental impacts face the most inspections.
- Fines:
  - Fines are determined by *gravity*: actual and potential harm, with adjustments for reporting issues, compliance history, and ability to pay.
- Inspection rate and fines vary substantially with the region, industry, National Ambient Air Quality Standard (NAAQS) attainment status.
- Violators and violations:
  - Plants can be designated (regular) violators or HPVs.
  - Plants can also receive notices of violations.

High Priority Violator (HPV) Designation

- Egregious or repeated violators are designated as HPVs.
  - During our time period, the EPA used 10 “general” and 5 “matrix” criteria:
    - Some are dynamic (e.g. “violation by chronic or recalcitrant violator”).
    - Others indicate a *significant* risk to human health and environment.
  - Recent evidence indicates that publicizing regulatory status is costly to plants (Evans, 2016; Johnson, 2016).
- In 2014, the HPV classification system was updated to make it harder for plants to enter HPV status.
  - Implementation of HPV designation is still an open question, which makes our research even more important.

Economic Theories of Enforcement

- Bentham, 1789; Becker 1968:
  - Agents make a rational decision of whether to commit a crime.
- *Escalation mechanisms* build on this idea:
  - Repeat or severe violations are punished more severely than one-time or less-severe ones.
  - Landsberger and Meilijson (1982) and Harrington (1988) model dynamic enforcement.
  - Mookherjee and Png (1994) consider static escalation mechanism and "marginal deterrence": underpenalize low-level violations to prevent high-level ones.
- Why do escalation mechanisms add value?
  1. The regulator may find it costly to impose penalties.
  2. Heterogeneous plants and an inability of the regulator to contract on types.

Our Model of Environmental Enforcement

- Discrete-time, two-player, dynamic Markov Perfect game.
- Each period t, the plant starts with some regulatory state Ω_t.
- Timing each period is as follows:
  1. The regulator chooses whether to inspect.
  2. Regulator and plant observe signal $(e_t^1, \ldots, e_t^5)$ (from state and inspection).
     - Presence of violation is $Vio(\Omega_t, e_t^1)$.
     - Regulator assesses fines with policy $Fine(\Omega_t, e_t^2)$.
     - Compliance/regulator violator/HPV status updates to $\tilde{\Omega}_t = T(\Omega_t, e_t^3, e_t^4, e_t^5)$.
  3. Plant chooses whether to make a costly investment, $X_t \in \{0, 1\}$, which may help the plant return to compliance.
- Objective functions:
  - Plant minimizes expected investment and enforcement costs.
  - Regulator minimizes expected weighted sum of pollution, investment, and enforcement costs.

Illustrative Simple Case of our Model

- Main simplifications:
  1. Two period model with $\beta = 1$.
  2. Perfect inspections occur with probability $\mathcal{I}(\Omega) = 1$.
  3. A new violation occurs with probability p:
     - Violation and fines signals are equal: $e_t^1 = e_t^2$ and $e_t^1 \in \{0, 1, 2\}$.
  4. No costs of inspections or violations to plant or regulator.
     - Regulator enforcement costs are proportional to fines.
  5. Period 1 investment clears violation at period 2 with probability q.
     - Pollution cost in period t is $c_E \times e_t^1$.
- Regulatory state records investment and violations, so, e.g.: $\tilde{\Omega}_2 = (X_1, e_1^1, e_2^1)$.
  - Compliance / regulator violator / HPV if 0 / 1 / 2 violations, e.g., $e_t^3 = \mathbb{1}\{e_t^1 = 0\}$.
- Plant per-period objective function: minimize $\theta^X X + Fine(\Omega, e^1)$.
  - θ^X is investment cost.

Value of Escalation Mechanisms Under Simple Case

- Focus on case with period 1 violation—so $e_1^1 = 1$ and regulator pre-commitment.
- **Linear fine policy**: $c_F e_t^1$
  - With known θ^X, regulator incentivizes investment when investment costs + expected fine costs < expected avoided pollution costs.
  - Period 1 fines are byproduct that lower regulator objective function.
- **Static escalation mechanism**, $Fine(e_t^1)$
  - Can fine only when $e_t^1 = 2$, avoiding period 1 fines.
  - Can mimic same investment incentives with lower expected fines. (Regulator will optimally choose to incentivize investment for more θ^X values.)
- **Dynamic fine policy**, $Fine(\Omega_t, e_t^1)$
  - Fine when $e_{t-1}^1 > 0$ and $X_{t-1} = 0$ and want to incentivize investment.
  - Can again mimic same investment incentives with no fine cost!
- With non-contractable θ^X, escalation mechanisms may add even more value.
- Remainder of paper investigates extent to which value exists in practice.

Data Sources: Primary Sources

Our study primarily uses four publicly available databases:

1. Environmental Compliance History Online (ECHO) database.
   - This forms our main analysis data.
   - Actions: inspections, violations, fines, and investments.
   - Historical compliance: regular and high priority violator status.
   - We keep seven sectors with high pollution levels.
2. National Emissions Inventory (NEI) database.
   - We use the NEI to understand the distribution of pollution by location, industry, and regulatory status.
3. AP3 data on marginal pollution damages by county (Clay et al., 2019).
4. County-level NAAQS attainment status from EPA Green Book.

Variable and Sample Definitions

- We create a quarterly unbalanced panel from Q1:2007 until Q3:2013.
  - Period without significant regulatory or data changes.
- We define investment based on codes indicating the resolution of an environmental issue.
  - Consistent with data on pollution abatement device changes in Texas.
  - Remove investment in compliance: does not improve likelihood of remaining in compliance.
- We value damages from smokestack emissions that can lead to criteria air pollutants.
  - PM2.5, NO_X, SO_X, VOC, NH_3 from AP3 and Pb from Zahran et al. (2017).
- We define a time-invariant NAAQS non-attainment status: county is in non-attainment if any portion is in non-attainment for any pollutant in any year.

Investment Rates by Regulatory State

Status:	Compliance	Regular violator	HPV
Investment (%)	0.00	4.91	17.50
Investment (from resolution code) (%)	0.00	4.62	16.35
Investment (from PSD permit) (%)	0.00	0.34	0.43
Investment (from HPV exit) (%)	0.00	0.00	0.80
Dropped investment in compliance (%)	0.37	0.00	0.00
Plant / quarter observations	2,252,570	66,992	36,346

Note: authors' calculations based on estimation sample.

Summary Statistics on Industries and Pollutants

Table: Summary Statistics on Criteria Air Pollutants

Industrial sector	Observations in analysis data	Mean level in compliance	Mean level as regular violator	Mean level as HPV
Mining & extraction	687,400	$501	$3,829	$4,789
Utilities	112,554	$14,892	$58,630	$77,941
Manufacturing: food, textiles	139,826	$642	$2,831	$2,510
Manufacturing: wood, petroleum	617,572	$895	$2,800	$5,894
Manufacturing: metal	539,000	$319	$1,967	$2,652
Transportation	157,326	$416	$1,008	$2,881
Educational services	132,209	$785	$1,730	$1,943

Note: table reports summary statistics on total criteria air pollution damages in thousands of dollars per plant / quarter observation in our analysis data.

Defining the Regulatory State

- For our model, we need to define a tractable regulatory state.
  - Regulatory state records everything that might affect future expected discounted value from investing or not investing.
  - In principle, could include entire history of lagged violations and investments, as well as industry code and EPA region.
  - In practice, need to limit state space for tractability.
- We now show results from reduced-form analyses that motivate our state space and other modeling choices.

Investment and Resolution of Violations

Dependent variable: return to compliance		
Current investment	-0.115^{***}	(0.002)
One quarter lag of investment	0.380^{***}	(0.006)
Two quarters lag of investment	0.083^{***}	(0.007)
Three quarters lag of investment	-0.012^{**}	(0.005)
Four quarters lag of investment	-0.051^{***}	(0.005)
Number of observations	103,338	

Note: regression includes region, industry, and gravity state dummies. Regression uses the estimation sample restricted to plants not in compliance in the previous quarter. Standard errors, which are clustered at the plant level, are in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

- We allow for two lags of investment to affect transitions.
- Timing assumption: investment occurs at end of period.

Investment In Compliance

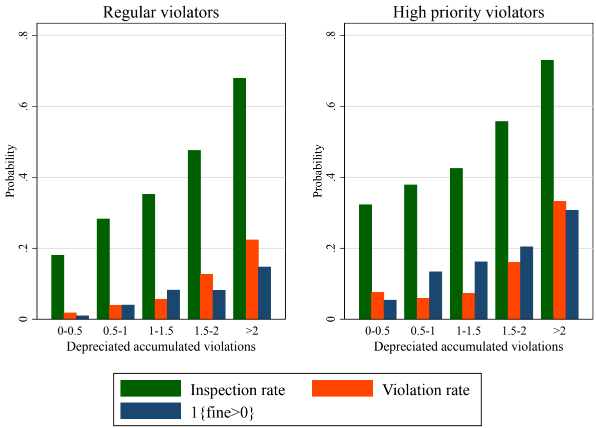
Table: State Transitions After Investment in Compliance

Outcome: transition to regular violator status		
One quarter lag of investment	1.29***	(.09)
Two quarters lag of investment	1.21***	(.17)
Outcome: transition to HPV status		
One quarter lag of investment	0.48***	(.12)
Two quarters lag of investment	1.11***	(.17)

Note: table shows estimates from a multinomial logit regression. Regression includes region, industry, and gravity state dummies. Regression uses the estimation sample restricted to plants in compliance at the start of the period. Standard errors, which are clustered at the plant level, are in parentheses. ***, **, and * indicate statistical significance at the 1%, 5%, and 10% levels, respectively.

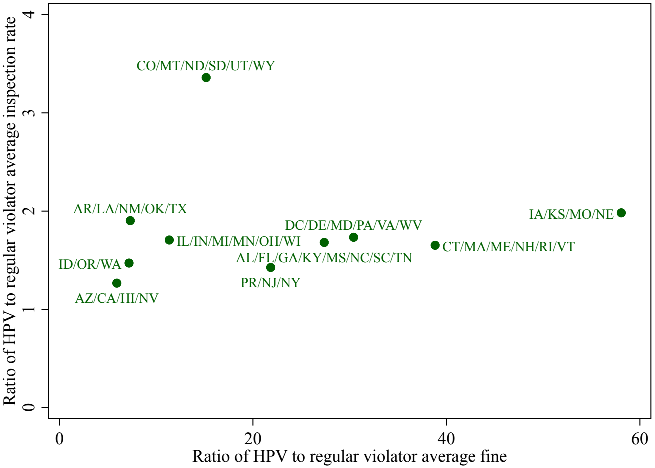
- Investments in compliance *increase* future violations:
- We assume only *economic* and not pollution mitigation investments in compliance.
  - Don't allow investment in compliance to avoid future violations.

Depreciated Accumulated Violations



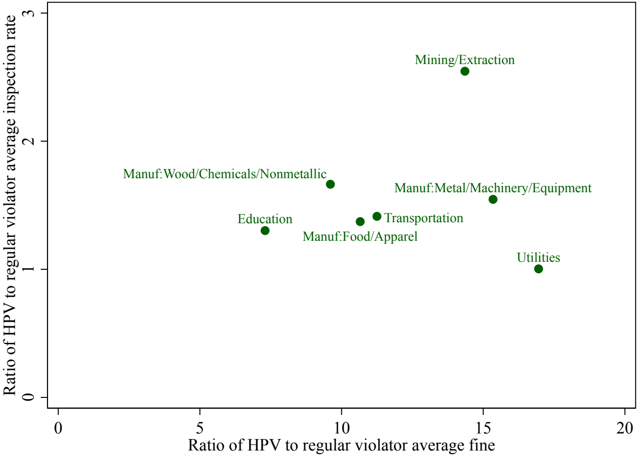
- Sum of depreciated violations, back to quarter plant left compliance.
- Use 10% quarterly depreciation rate (most predictive).

Heterogeneity in Regulatory Actions: EPA Regions



- Variation across EPA regions in effect of regulatory status on inspections and fines.

Heterogeneity in Regulatory Actions: Industry



- Variation across 2-digit NAICS also.

Gravity

- Gravity of a violation based on actual and potential harm.
  - Data do not report gravity, pollutants, or quantity emitted.
- We construct expected gravity of violation for each plant.
  1. Use NEI data to get the emissions nationally by industry.
  2. Calculate damages by county and pollutant from AP3 data.
     - Generates distribution of potential damages by industry/county.
  3. Recover mean and 90th percentile by industry/county.
     - Mean: actual harm, damages of the expected plant.
     - 90th percentile: potential harm, damages of extreme polluter.
  4. Divide each plant into above/below median for both:
     - Further divide plants above the median in both by county attainment status.

Summary Statistics: Percent of Observations with Gravity State

Gravity	Actual damage	Potential damage	NAAQS attainment	In compliance	Regular violator	HPV
1	Low	Low	Either	37.19	36.29	38.98
2	Low	High	Either	2.89	2.44	2.08
3	High	Low	Either	4.07	4.16	3.64
4	High	High	Yes	28.22	29.34	26.58
5	High	High	No	27.63	27.77	28.72
Total:				100	100	100

Note: authors' calculations based on the estimation sample. Regulatory actions and outcomes are based on start of period regulatory status.

Regulatory CCPs Marginal Effects: Fines

Status:	Compliance	Regular violator	HPV
Regulator actions			
Violation (0 to 1)	0.000	0.020	0.279
Inspection (0 to 1)	0.000	0.024	0.176
Plant states			
Lag investment (0 to 1)	—	0.002	−0.592
2nd lag investment (0 to 1)	—	0.002	0.139
Deprec. accum. vio. (mean to mean + 1)	—	0.000	0.000
Non-attainment (given highest gravity)	0.000	0.005	0.196
Highest gravity and attainment (vs. lowest)	0.000	−0.001	−0.117
SE EPA region (vs. SW)	0.000	−0.150	0.125
Utility sector (vs. manuf. food)	0.000	−0.005	0.025
Mean	0.035	0.637	8.268
Pseudo R^2	0.187	0.245	0.108

Note: table shows marginal effects from tobit regressions. Regressions include region, industry, and gravity state dummies. Most regressions also include inspection $\times$ gravity state interactions. We run each regression separately by start of period regulatory status (compliance, a regular violator, or HPV). Each entry reports a marginal effect as described in the table.

Specialization of the Model to Estimation

- Infinite horizon with $\beta < 1$.

Assumption (1)

The environmental compliance signal e is a function only of the state, current inspection decision, and the regulator's inspection CCPs.

- This assumption rules out the possibility that an investment that is not in regulatory state (e.g. one that occurred long ago) could change signal distribution.
- Highlights importance of regulatory state including all relevant information.
- Stronger than needed for estimation:
  - For estimation, could have made an assumption directly on regulator actions.
  - But critical for counterfactuals: makes explicit that plants' state-contingent priors will not change under certain counterfactual regimes.
  - Conditioning on inspection CCPs adds to credibility.

Plant's Enforcement and Investment Cost

- Plant flow utility from regulatory actions it:

$$U(\Omega, e) = \theta^I Ins(\Omega) + \theta^V Vio(\Omega, e^1) + \theta^F Fine(\Omega, e^2) + \theta^H HPV(T(\Omega, e^3, e^4, e^5))$$

- If T indicates non-compliance, plant chooses whether to invest, $X = 1$, or not, $X = 0$.
  - Investment costs to plant are: $X\theta^X + \varepsilon_X$.
- Plants in compliance obtain only ε_0 at this point.
- The (fixed) structural parameters for any plant are $\theta \equiv (\theta^I, \theta^V, \theta^F, \theta^H, \theta^X)$.
  - We model random coefficients: θ can vary across plants.
  - Regulator cannot condition its monitoring and enforcement on θ.

Plant dynamic optimization problem

Estimation Algorithm

- GMM estimation with random coefficients over fixed grid of θs.
  - Assumes that θ takes one of a finite number of values, $(\theta_1, \ldots, \theta_J)$.
    - Large number of grid points, J=10,001.
  - Each plant i gets a draw from the distribution of potential θ values.
  - Point of estimation is to recover η_j, $\forall j$, population prevalence of θ_j.
  - Estimator takes the form:

$$G_k(\eta) = m_k^d - \sum_{j=1}^{J} \eta_j m_k(\theta_j)$$

  where m_d^k are moments in data and $m_k(\theta_j)$ are moments predicted by model.

- We also estimate a homogeneous coefficient model with quasi-maximum likelihood.

Details of Estimation Algorithm

- Estimation parameters are the weights on each of 10,001 potential plant costs.
- Each plant is assumed to have one set of costs, but the weights tell us how these costs are distributed across the population of plants.
- Estimate via constrained GMM where the weights must sum to 1.

Assumption (2)

The data reflect plants at the steady state distribution of variable states (e.g. compliance status), conditional on fixed states (industry, region, gravity).

- We use the following $m_k(\theta_j)$ for moments:
  1. Long-run probability of variable state.
  2. Long-run probability of variable state times investment.
  3. Long-run probability of variable state times investment times sum of investments in next six quarters.

Identification

- Consider homogeneous cost model with two parameters, fines and investment:
  - At violator states, plant can observe expected change in discounted future fines from investment.
  - If investment reduced expected discounted fines more than the cost of investment, plant will invest.
  - Cutoff identifies the ratio of investment cost to fine cost, $\frac{\theta^X}{-\theta^F}$.
  - Need plants to not have private information about regulatory actions.
  - Scale is identified by rate of investment probability increase.
- Our actual model includes three other regulatory outcomes.
  - Need non-collinear variation in those outcomes.
  - Variation across fixed geography and industry is helpful here.
- Random coefficient model needs to identify heterogeneity in utility parameters:
  - Steady-state equilibrium regulatory state and investment rate distribution identifies heterogeneity.
  - Panel nature of data allows us to match serial correlation in investment to data.

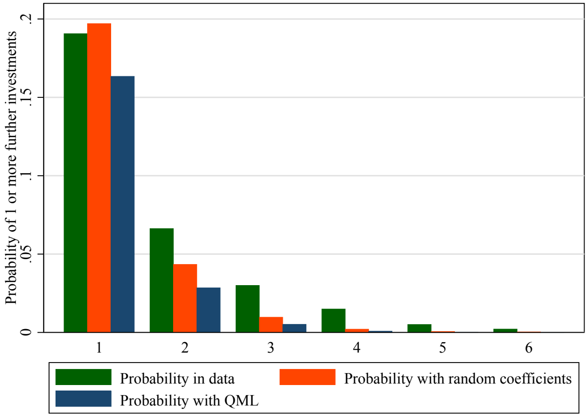
Structural Parameter Estimates

	QML estimates	GMM random coefficient estimates (1)	(2)	(3)	(4)	(5)	(6)
Investment cost ($-\theta^X$)	-2.872^{***} (0.041)	-2.334	-1.326	-2.498	-2.540	-1.988	0.153
Inspection utility (θ^I)	-0.049 (0.049)	-0.194	0.444	-0.096	0.897	0.001	-2.483
Violation utility (θ^V)	-0.077 (0.197)	0.143	0.128	0.650	-0.100	-2.169	-2.006
Fine utility (mil. \$, θ^F)	-5.980^{***} (1.005)	-5.181	-6.073	-6.766	-8.460	-7.494	-7.524
HPV status utility (θ^H)	-0.065^{***} (0.015)	-0.029	-0.234	-0.078	-0.411	0.070	-2.437
Weight	1	0.438	0.174	0.170	0.126	0.049	0.019

- Six parameter values account for 98% of plants:
  - Investment costs ($-\theta^X/\theta^F$) for 96% of plants: \$218,000-450,000/investment.
  - HPV costs (θ^H/θ^F) for these plants: \$5,600-48,600/quarter.
- Comparing to Becker (2005), \$1 in fines may cost plants \$3.

Random Coefficients and QML Model Fit

Figure: Further Investments After Initial Investment, in Steady State



- Random coefficients estimates closer to data.

Counterfactuals

- Long-run averages of regulator and plant actions and pollution damages when:
  1. State-dependence of fines removed: equilibrium fines constant.
  2. State-dependence of fines removed: equilibrium pollution damages constant.
  3. Fines reflect scaled Pigouvian cost of state (with 0 fines in compliance).
     - All these counterfactuals set $\theta^H = 0$.
  4. Double cost of HPV status.
- We present changes in long-run statistics from changing policies.
- Limitations of counterfactuals:
  - Policy rule on inspections is unchanged:
    - The same distribution of signals, e, will occur in each state.
  - Consistent with plant optimization, not necessarily dynamic equilibrium.

Counterfactuals: Changing the Escalation Rate of Fines

	Data	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	HPV fines doubled
Compliance (%)	95.62	95.11 (0.22)			
Regular violator (%)	2.88	3.47 (0.25)			
HPV (%)	1.50	1.42 (0.05)			
Investment rate (%)	0.40	0.54 (0.05)			
Inspection rate (%)	9.65	9.41 (0.06)			
Fines (thousands $)	0.18	0.32 (0.03)			
Pollution damages (mil. $)	1.65	1.53 (0.03)			

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

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Regular violator (%)	2.88	3.47 (0.25)	2.53 (0.57)		
HPV (%)	1.50	1.42 (0.05)	30.75 (14.43)		
Investment rate (%)	0.40	0.54 (0.05)			
Inspection rate (%)	9.65	9.41 (0.06)	20.54 (5.41)		
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Pollution damages (mil. $)	1.65	1.53 (0.03)			

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Changing the Escalation Rate of Fines

	Data	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	HPV fines doubled
Compliance (%)	95.62	95.11 (0.22)	66.72 (13.91)		
Regular violator (%)	2.88	3.47 (0.25)	2.53 (0.57)		
HPV (%)	1.50	1.42 (0.05)	30.75 (14.43)		
Investment rate (%)	0.40	0.54 (0.05)	0.47 (0.06)		
Inspection rate (%)	9.65	9.41 (0.06)	20.54 (5.41)		
Fines (thousands $)	0.18	0.32 (0.03)	0.32 (0.03)		
Pollution damages (mil. $)	1.65	1.53 (0.03)	4.04 (1.19)		

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Changing the Escalation Rate of Fines

	Data	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	HPV fines doubled
Compliance (%)	95.62	95.11 (0.22)	66.72 (13.91)		
Regular violator (%)	2.88	3.47 (0.25)	2.53 (0.57)		
HPV (%)	1.50	1.42 (0.05)	30.75 (14.43)		
Investment rate (%)	0.40	0.54 (0.05)	0.47 (0.06)		
Inspection rate (%)	9.65	9.41 (0.06)	20.54 (5.41)		
Fines (thousands $)	0.18	0.32 (0.03)	0.32 (0.03)		
Pollution damages (mil. $)	1.65	1.53 (0.03)	4.04 (1.19)	1.53 (0.03)	

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Changing the Escalation Rate of Fines

	Data	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	HPV fines doubled
Compliance (%)	95.62	95.11 (0.22)	66.72 (13.91)	94.49 (0.62)	
Regular violator (%)	2.88	3.47 (0.25)	2.53 (0.57)	2.72 (0.56)	
HPV (%)	1.50	1.42 (0.05)	30.75 (14.43)	2.79 (0.65)	
Investment rate (%)	0.40	0.54 (0.05)	0.47 (0.06)	0.65 (0.09)	
Inspection rate (%)	9.65	9.41 (0.06)	20.54 (5.41)	9.88 (0.23)	
Fines (thousands $)	0.18	0.32 (0.03)	0.32 (0.03)	1.98 (1.62)	
Pollution damages (mil. $)	1.65	1.53 (0.03)	4.04 (1.19)	1.53 (0.03)	

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Changing the Escalation Rate of Fines

	Data	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	HPV fines doubled
Compliance (%)	95.62	95.11 (0.22)	66.72 (13.91)	94.49 (0.62)	95.52 (0.24)
Regular violator (%)	2.88	3.47 (0.25)	2.53 (0.57)	2.72 (0.56)	3.47 (0.26)
HPV (%)	1.50	1.42 (0.05)	30.75 (14.43)	2.79 (0.65)	1.01 (0.03)
Investment rate (%)	0.40	0.54 (0.05)	0.47 (0.06)	0.65 (0.09)	0.55 (0.05)
Inspection rate (%)	9.65	9.41 (0.06)	20.54 (5.41)	9.88 (0.23)	9.28 (0.05)
Fines (thousands $)	0.18	0.32 (0.03)	0.32 (0.03)	1.98 (1.62)	0.36 (0.03)
Pollution damages (mil. $)	1.65	1.53 (0.03)	4.04 (1.19)	1.53 (0.03)	1.48 (0.02)

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the value of each statistic in our data. Column (2) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines and HPV cost faced by plants. Columns (3) and (4) impose the same fines for all regular and high-priority violators for a given fixed state. Column (5) doubles the fines for plants in HPV status. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Scaled Pigouvian Fines

	Baseline	Pigouvian fines	Pigouvian fines scaled by 1/3	Pigouvian scaled to base damages
Compliance (%)	95.11 (0.22)	96.69 (1.05)	95.38 (1.78)	
Regular violator (%)	3.47 (0.25)	1.60 (0.30)	2.09 (0.30)	
HPV (%)	1.42 (0.05)	1.72 (1.02)	2.52 (1.80)	
Investment rate (%)	0.54 (0.05)	0.86 (0.05)	0.79 (0.06)	
Inspection rate (%)	9.41 (0.06)	9.34 (0.33)	9.60 (0.58)	
Fines (thousands $)	0.32 (0.03)	55.24 (1.81)	19.06 (0.69)	
Pollution damages (mil. $)	1.53 (0.03)	1.32 (0.02)	1.32 (0.02)	

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines faced by plants. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Scaled Pigouvian Fines

	Baseline	Pigouvian fines	Pigouvian fines scaled by 1/3	Pigouvian scaled to base damages
Compliance (%)	95.11 (0.22)	96.69 (1.05)	95.38 (1.78)	
Regular violator (%)	3.47 (0.25)	1.60 (0.30)	2.09 (0.30)	
HPV (%)	1.42 (0.05)	1.72 (1.02)	2.52 (1.80)	
Investment rate (%)	0.54 (0.05)	0.86 (0.05)	0.79 (0.06)	
Inspection rate (%)	9.41 (0.06)	9.34 (0.33)	9.60 (0.58)	
Fines (thousands $)	0.32 (0.03)	55.24 (1.81)	19.06 (0.69)	
Pollution damages (mil. $)	1.53 (0.03)	1.32 (0.02)	1.32 (0.02)	1.53 (0.03)

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines faced by plants. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactuals: Scaled Pigouvian Fines

	Baseline	Pigouvian fines	Pigouvian fines scaled by 1/3	Pigouvian scaled to base damages
Compliance (%)	95.11 (0.22)	96.69 (1.05)	95.38 (1.78)	82.44 (4.60)
Regular violator (%)	3.47 (0.25)	1.60 (0.30)	2.09 (0.30)	2.88 (0.37)
HPV (%)	1.42 (0.05)	1.72 (1.02)	2.52 (1.80)	14.68 (4.89)
Investment rate (%)	0.54 (0.05)	0.86 (0.05)	0.79 (0.06)	0.53 (0.06)
Inspection rate (%)	9.41 (0.06)	9.34 (0.33)	9.60 (0.58)	14.18 (1.72)
Fines (thousands $)	0.32 (0.03)	55.24 (1.81)	19.06 (0.69)	1.58 (1.67)
Pollution damages (mil. $)	1.53 (0.03)	1.32 (0.02)	1.32 (0.02)	1.53 (0.03)

Note: each statistic is the long-run equilibrium mean, weighting by the number of plants by region, industry, and gravity state in our data. Column (1) presents the results of our model given the estimated coefficients and the existing regulatory actions and outcomes. Other columns change the state-contingent fines faced by plants. All values are per plant / quarter. Bootstrapped standard errors are in parentheses.

Counterfactual Results: By Industry

	Baseline	All violators same fines (fines constant)	All violators same fines (damages constant)	Pigouvian fines scaled by 1/3	Pigouvian fines scaled to base damages
Mining & extraction (NAICS 21)					
Fines (thousands $)	0.17	0.17	2.03	6.10	0.69
Pollution damages (mil. $)	0.58	2.34	0.58	0.53	0.62
Regular violator (%)	4.86	3.71	3.58	3.36	4.16
HPV (%)	0.76	26.23	1.16	1.93	13.81
Utilities (NAICS 22)					
Fines (thousands $)	0.88	0.88	3.38	260.83	5.82
Pollution damages (mil. $)	18.78	41.69	18.78	15.81	16.00
Regular violator (%)	4.11	2.82	3.43	1.68	2.54
HPV (%)	3.93	35.31	5.89	3.51	7.41
Manufacturing: metal (NAICS 33)					
Fines (thousands $)	0.25	0.25	1.51	5.10	1.39
Pollution damages (mil. $)	0.40	1.50	0.40	0.33	0.55
Regular violator (%)	2.58	1.83	2.18	1.50	2.13
HPV (%)	1.48	31.95	2.87	2.64	15.55

Interpretation of Counterfactuals

- Dynamic enforcement is effective at lowering pollution keeping fines constant.
  - Also, at lowering fines keeping pollution constant.
- Scaled Pigouvian taxes charge different fines to different industries.
  - Utilities pay a lot more fines and have relatively lower pollution.
  - This is an advantage of Pigouvian taxes relative to current CAAA enforcement.
- But, dynamic enforcement “underdeters” regular violators relative to HPVs.
  - This hugely lower equilibrium fines relative to scaled Pigouvian taxes.
- Multiple types (and non-contractability on type) adds hugely to value of dynamic enforcement.
  - Paper appendix gives counterfactuals from QML model.

Conclusion

- We provide a structural framework for evaluating dynamic enforcement.
  - Estimate computationally tractable random coefficients specification.
- Dynamic enforcement of the Clean Air Act Amendments has large benefits:
  - Non-state-dependent fines would result in 164% increase in pollution (fines constant) or a 519% increase in fines (pollution constant).
  - Scaled Pigouvian taxes optimally exploit sectoral differences but still result in higher fines.
  - Results demonstrate empirically the theoretical point that dynamic enforcement underdeters first-time violators to increase marginal deterrence.
- Some limitations of our approach:
  - We lack detailed pollution data and have to aggregate this information.
  - Investment measure is imprecise and indirect, derived from regulator responses.
  - Identification relies on plants' expectations matching CCPs.
  - We cannot vary inspection probabilities in counterfactuals.

Appendix

Plant Dynamic Optimization

- Let $V(\Omega)$ be the plant's value function at the beginning of the period:

$$V(\Omega) = \sum_{i \in 0,1} \mathcal{I}(\Omega)^i (1 - \mathcal{I}(\Omega))^{1-i} \int \left[U(\Omega, e) + \tilde{V}(T(\Omega, e)) \right] dP(e|\Omega, \mathcal{I}, i) dP(e|I, \Omega),$$

  where $dP(e|I(\Omega))$ is integral over e given the inspection decision.

- Let $\tilde{V}(\tilde{\Omega})$ denote the value function at the point right after the regulator has moved but before the plant receives its draws of ε:

$$\tilde{V}(\tilde{\Omega}) = Com(\tilde{\Omega})[\beta V(\tilde{\Omega}, \theta) + \gamma] + (1 - Com(\tilde{\Omega})) \times \\ [\ln(\exp(\beta V(\Omega|\tilde{\Omega}, X = 0)) + \exp(-\theta^X + \beta V(\Omega|\tilde{\Omega}, X = 1)) + \gamma],$$

  where Com indicates compliance.

- Finally, define the probability of a plant choosing investment as:

return

$$\Pr(X = 1|\tilde{\Omega}, \theta) = \frac{(1 - Com(\tilde{\Omega})) \exp(\theta^X + \beta V(\Omega|\tilde{\Omega}, X = 1))}{\exp(\theta^X + \beta V(\Omega|\tilde{\Omega}, X = 1)) + \exp(\beta V(\Omega|\tilde{\Omega}, X = 0))}.$$