Regulating Untaxable Externalities:
Are Vehicle Air Pollution Standards Effective and Efficient?

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Overview

Overview

- **Vehicle air pollution important**
  - Annual US environmental/health costs: $72 billion, 37,000 deaths
  - Annual global deaths: 250,000
- **Textbook solution infeasible**
  - Pigouvian tax requires observing pollution
  - Real-time monitoring infeasible, announced testing problematic
- **Alternative: exhaust standards**
  - Maximum standard for every vehicle; fleet-wide average
  - Separate from fuel economy (CAFE) standards
  - Important in U.S., EU, Japan, China, India, Brazil, ...
- **Research questions:**
  - Trends in vehicle pollution?
  - Causal effect of exhaust standards?
  - Cost-effective?
  - Gains from counterfactual policies?

Approach and Main Results

1. **Trends: 1957-2020**
   - 65 million vehicle emission tests
   - 99% decrease in “local” pollutants since 1960s
   - CO_2: $<$ 50% decrease

2. **Causes: regressions**
   - Variation across model years, vehicle classes, regions, pollutants
   - Exhaust standards caused 50-100% of the long-term decline

3. **Stylized facts**
   - $>$ 50% of emissions from old ('unregulated') vehicles
   - Existing property taxes/registration fees higher on cleaner vehicles

4. **Analytical and quantitative models**
   - Result: if production emissions are “small,” should tax used vehicles
   - Reforming registration fees increases welfare $>$ \$300 billion
   - Exhaust standards in 2000s: benefits $>>>$ costs
   - Distributional consequences important

What is New Here

1. **Comprehensive analysis of exhaust standards**
   - Policy papers describe them (Kahn 1996, Fullerton & West 2010)
   - Clean Air Act research focuses on industry (Henderson 1996; Carlson et al. 2000; Greenstone 2002; Walker 2013)
   - Environment-transportation research focuses on fuel economy (Goldberg 1998; West and Williams 2005; Goulder et al. 2012; Langer et al. 2017)

2. **Vintage capital and the environment** (Li, Linn, & Spiller 2013; Stavins & Schmalensee 2013; Barahona, Gallego, & Montero 2020)
   - Gruenspecht Effect: formalize, quantify

3. **Unique setting: one regulation mostly explains pollution time series**
   - Industry: less clear if pollution trends due to trade, regulation, productivity (Levinson 2009; Shapiro & Walker 2018)

Outline

- **Background**
- Data
- Trends
- Causes
- Stylized facts
- Analytical model
- Quantitative model
- Conclusions

Policy Background: Timeline

- **US timeline**
  - Tier 0 (1968-1993)
  - Tier 1 (1994-1998)
  - NLEV (1999-2003)
  - Tier 2 (2004-2016)
  - Tier 3 (2017-2025)
  - We provide separate estimates for each "Tier"

- **Fleet average standards begin around year 2000**

Policy Background: Levels and Enforcement

- **Standards vary**
  - California versus Federal
  - Light duty vehicles, classes of light duty trucks
  - Model year
- **Enforcement**
  - "In-use tests" + recalls

Policy Background

- **Technology**
  - Centerpiece: catalytic converters
  - Mechanism: rhodium, platinum, palladium
  - Complementary technologies: fuel injection, oxygen controls, etc.

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Data

- **New vehicle emissions tests** (N $\approx$ 20,000)
  - Determine compliance with Clean Air Act
- **Inspection and maintenance / smog check** (N $\approx$ 12 million)
  - Shorter version of new vehicle test
- **Remote sensing** (N $\approx$ 50 million)
  - Impervious to manufacturer "defeat devices"
- **In-use vehicle tests** (N $\approx$ 10,000)
  - Determine recalls
- **Synopsis**
  - Longest-lasting high-quality data on pollution for any country/sector

Data

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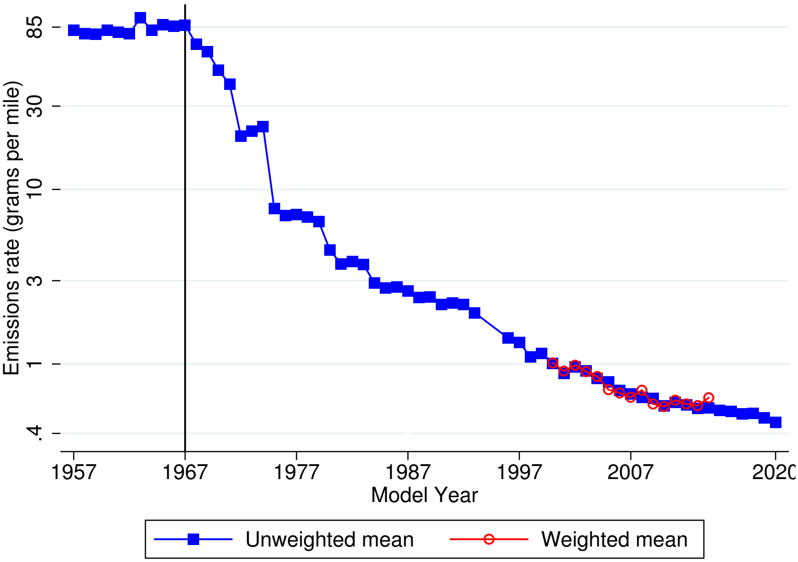
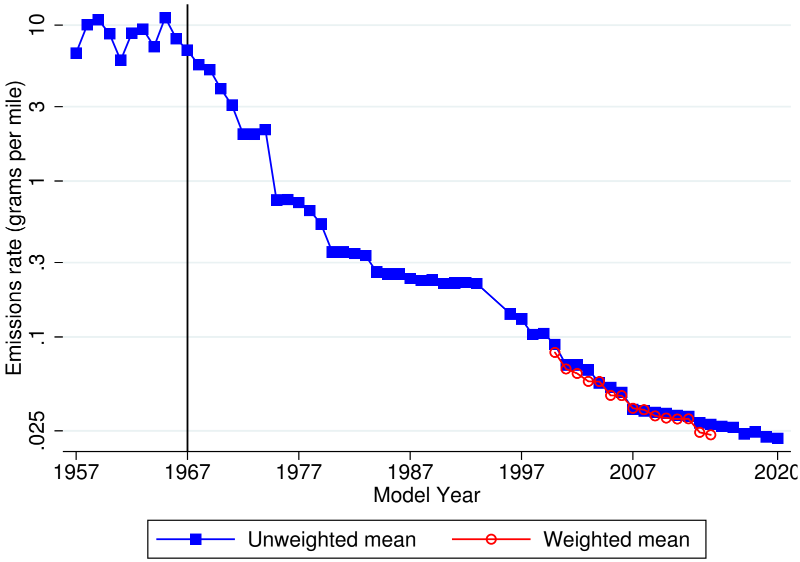
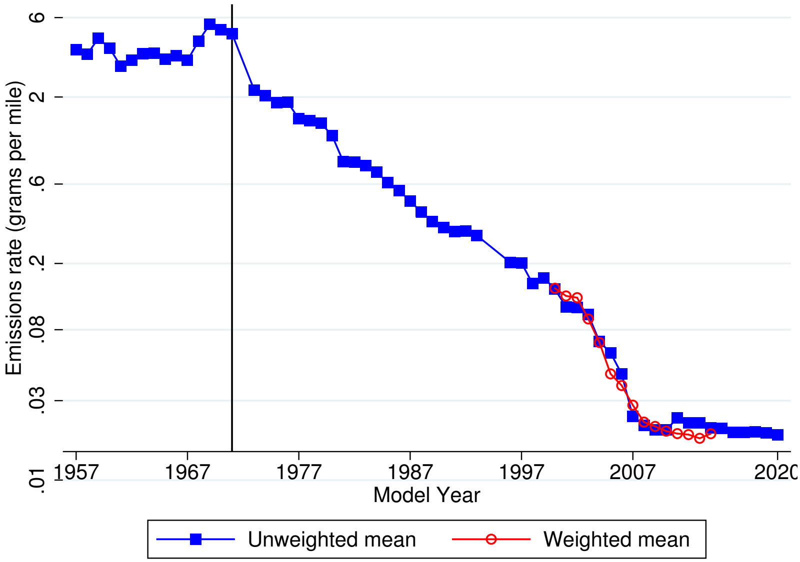
Trends: Carbon Monoxide



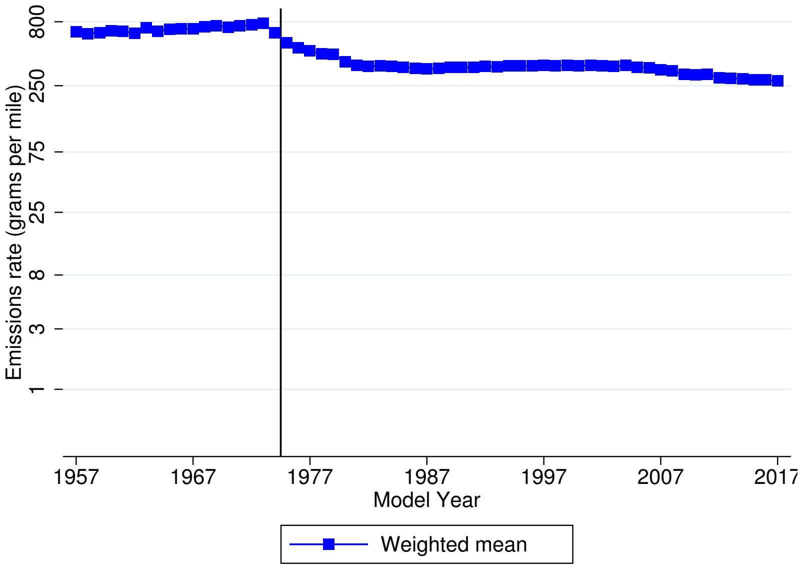
Trends: Hydrocarbons



Trends: Nitrogen Oxides



Trends: Carbon Dioxide



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Exhaust standards (1967-2025)

Policy	Model years	Light-duty vehicles CO	Light-duty vehicles HC	Light-duty vehicles NO_x	Light-duty trucks CO	Light-duty trucks HC	Light-duty trucks NO_x	Mean Limit	Mean Pollutant
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Uncontrolled	-1967	90.0	8.200	3.40	90.0	8.200	3.40	—	—
Tier 0	1968-1971	34.0	4.100	—	34.0	4.100	—	—	—
	1972-1974	28.0	3.000	3.10	28.0	3.000	3.10	—	—
	1975-1976	15.0	1.500	3.10	20.0	2.000	3.10	—	—
	1977-1978	15.0	1.500	2.00	20.0	2.000	3.10	—	—
	1979	15.0	1.500	2.00	18.0	1.700	2.30	—	—
	1980	7.0	0.410	2.00	18.0	1.700	2.30	—	—
	1981-1983	3.4	0.410	1.00	18.0	1.700	2.30	—	—
	1984-1987	3.4	0.410	1.00	10.0	0.800	2.30	—	—
	1988-1993	3.4	0.410	1.00	10.0	0.800	1.50	—	—
Tier 1	1994-1996	3.4	0.250	0.40	10.0	0.250	0.85	—	—
	1997-2000	3.4	0.250	0.40	5.2	0.250	0.85	—	—
NLEV (8 states)	1999-2000	3.4	0.250	0.40	5.2	0.250	0.85	0.075	NMOG
NLEV	2001-2003	3.4	0.139	0.40	5.2	0.250	0.80	0.075	NMOG
Tier 2	2004-2006	3.4	0.125	0.40	3.4	0.139	0.40	0.070	NO_x
	2007-2016	3.4	0.100	0.14	3.4	0.100	0.14	0.070	NO_x
Tier 3	2017-2025	4.2^+	0.16^+		4.2^+	0.16^+		0.030	NMOG+NO_x

Causes: Econometrics

- Tier 0 (1957-1971):

$$lnE_{pry} = \beta_1 lnS_{pry} + \eta_{pr} + \lambda_y + \epsilon_{pry}$$

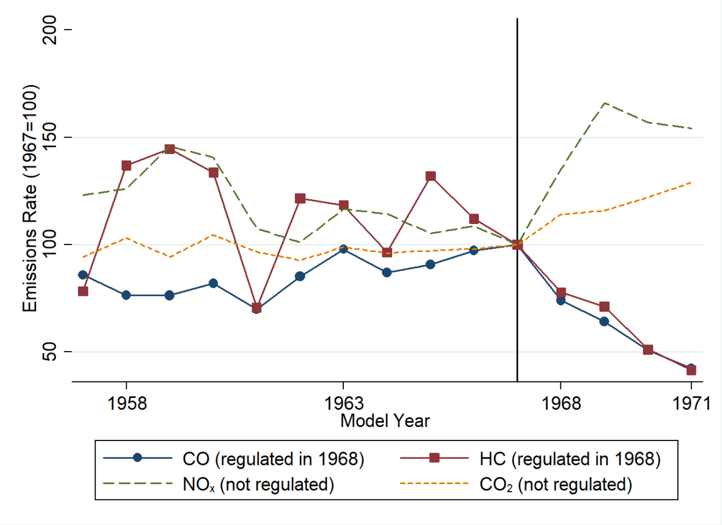
- Tier 1 (1990-2000):

$$lnE_{picy} = \beta_2 lnS_{picy} + X'_{picy}\pi + \mu_{pc} + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

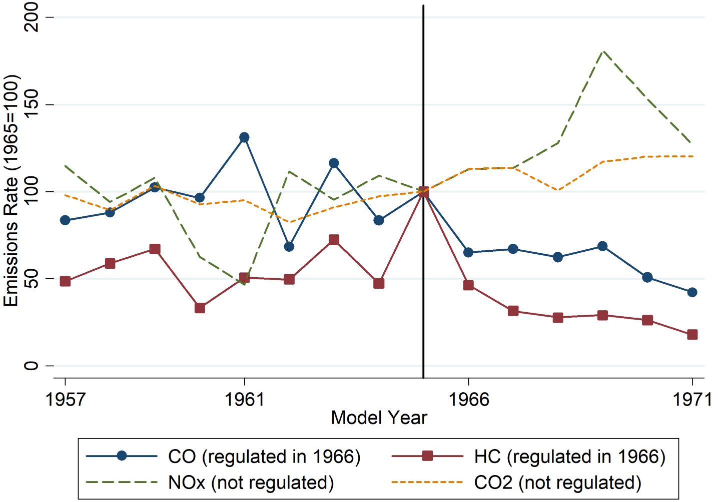
- Tier 2 (2000-2010)

$$lnE^u_{picy} = \beta_3 lnE^n_{picy} + X'_{picy}\zeta + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

Tier 0 Graph, Non-California (1957-1971)



Tier 0 Graph, California (1957-1971)

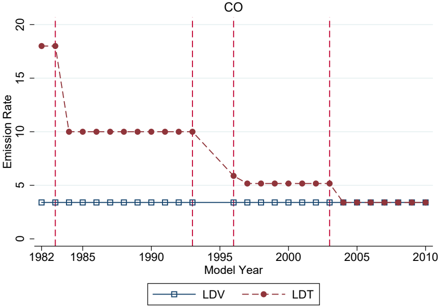


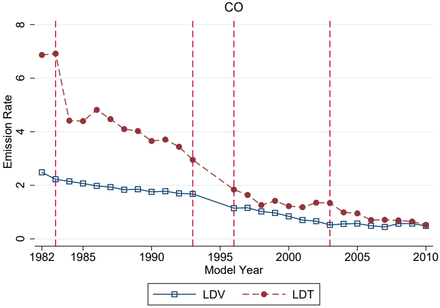
Tier 0 Table (1957-1971)

$$lnE_{pry} = \beta_1 lnS_{pry} + \eta_{pr} + \lambda_y + \epsilon_{pry}$$

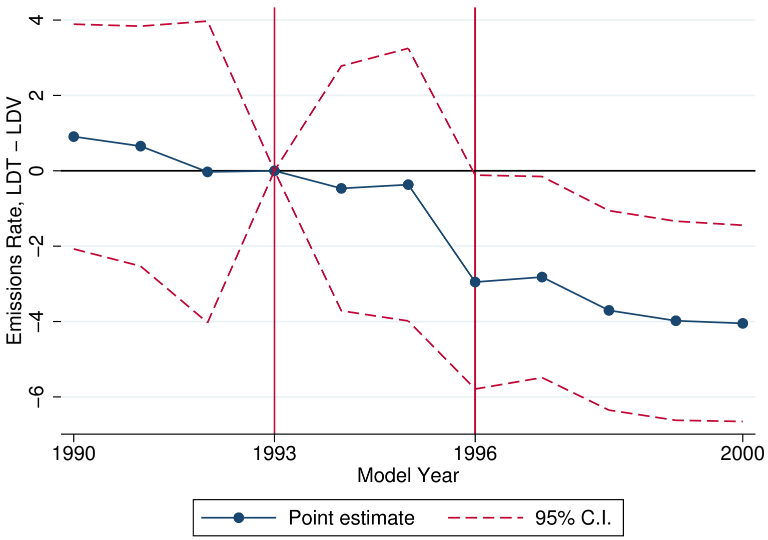
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
				Panel A. All pollutants			
Exhaust standards	0.61***	0.80***	1.22***	0.62***	0.90***	0.59***	0.83***
	(0.07)	(0.07)	(0.19)	(0.08)	(0.09)	(0.12)	(0.13)
N	120	120	120	60	60	60	60
				Panel B. Carbon monoxide (CO)			
Exhaust standards	0.48***	0.46**	0.76***	0.52***	—	0.52***	—
	(0.07)	(0.18)	(0.18)	(0.07)	—	(0.07)	—
N	30	30	30	15	—	15	—
				Panel C. Hydrocarbons (HC)			
Exhaust standards	0.76***	0.22	0.52*	0.71***	—	0.71***	—
	(0.11)	(0.20)	(0.28)	(0.13)	—	(0.13)	—
N	30	30	30	15	—	15	—
Pollutant*region fixed effects	X	X	X	X	X	X	X
Model yr. fixed effects	—	X	X	—	X	—	X
California only	—	—	—	X	X	—	—
Federal only	—	—	—	—	—	X	X
Levels	—	—	X	—	—	—	—

Tier 1-2 graph (1982-2010)

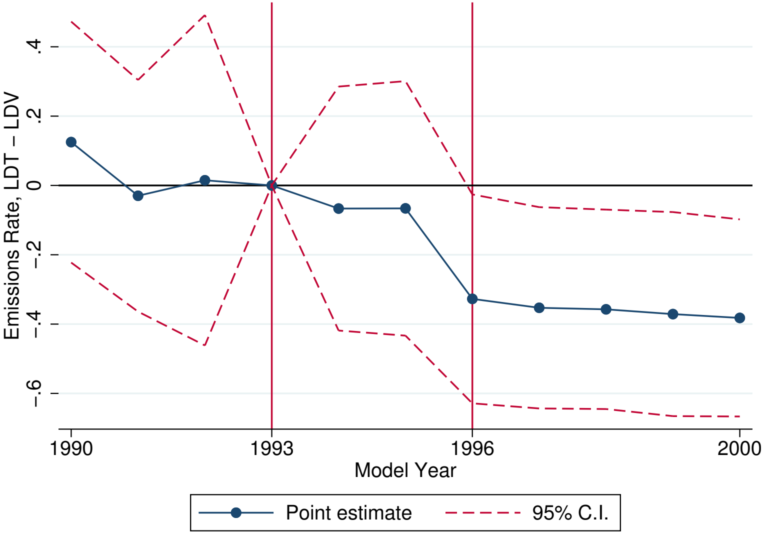




Tier 1 Graph: Carbon Monoxide (1990-2000)



Tier 1 Graph: Hydrocarbons (1990-2000)



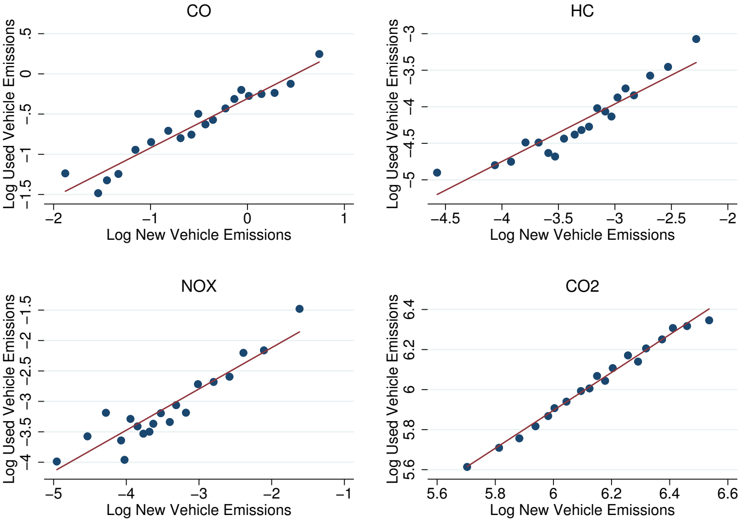
Tier 1 Table (1990-2000)

$$lnE_{picy} = \beta_2 lnS_{picy} + X'_{picy}\pi + \mu_{pc} + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

Table 3—Effects of Tier 1 Exhaust Standards on Used Vehicle Emissions

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A. Carbon monoxide and hydrocarbons (CO and HC), used vehicles							
Exhaust standard	1.61***	0.83***	0.94***	0.51**	1.08***	0.83***	0.77***
	(0.13)	(0.10)	(0.10)	(0.19)	(0.12)	(0.07)	(0.12)
N	14,253,650	14,253,650	14,253,650	14,253,650	3,402,740	18,469,406	14,253,650
Panel B. Carbon monoxide (CO), used vehicles							
Exhaust standard	1.60***	0.71***	0.82***	0.51**	0.94***	0.76***	0.77***
	(0.14)	(0.09)	(0.12)	(0.24)	(0.11)	(0.07)	(0.11)
N	7,112,383	7,112,383	7,112,383	7,112,383	1,695,559	9,220,274	7,112,383
Panel C. Hydrocarbons (HC), used vehicles							
Exhaust standard	1.61***	1.57***	1.80***	1.55**	1.93***	1.08***	1.41***
	(0.13)	(0.24)	(0.27)	(0.66)	(0.25)	(0.17)	(0.23)
N	7,141,267	7,141,267	7,141,267	7,141,267	1,707,181	9,249,132	7,141,267
Fixed effects							
Model yr. × pollutant	X	X	X	X	X	X	X
Truck × pollutant	—	X	X	X	X	X	X
Age × pollutant	X	X	X	X	X	X	X
Odometer	X	X	X	X	X	X	X
CAFE standards	—	—	X	—	—	—	—
Smog check stds.	—	—	X	—	—	—	—
Gasoline cost per mile	—	—	X	—	—	—	—
Ethanol share	—	—	X	—	—	—	—
Sulfur content	—	—	X	—	—	—	—
Model yr. × truck trend	—	—	—	X	—	—	—
Ages 4-6	—	—	—	—	X	—	—
Model yrs. 1982-2000	—	—	—	—	—	X	—
Levels	—	—	—	—	—	—	X

Tier 2 Graph: New Predict Used Emissions (2000-2010)



Tier 2: New Versus Used Emissions (2000-2010)

$$lnE^u_{picy} = \beta_3 lnE^n_{picy} + X'_{picy}\zeta + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

Table 4—Assessment of Tier 2 Exhaust Standards: Do New Predict Used Vehicle Emissions?

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A. Carbon monoxide (CO) and hydrocarbons (HC) and nitrogen oxides (NO_x)								
New vehicle emission rate	0.68***	0.53***	0.51***	0.53***	0.49***	0.70***	0.23***	0.45***
	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.05)	(0.01)	(0.06)
N	429,468	429,468	429,468	429,468	58,080	429,468	10,178,601	10,178,601
Age, model year FE	—	X	X	X	X	X	—	—
Truck indicator	—	X	X	X	X	X	—	—
Odometer	—	X	X	X	X	X	—	—
CAFE standards	—	—	X	—	—	—	—	—
Smog check standards	—	—	X	—	—	—	—	—
Gasoline cost per mile	—	—	X	—	—	—	—	—
Ethanol share	—	—	X	—	—	—	—	—
Sulfur content	—	—	X	—	—	—	—	—
Model year × truck trend	—	—	—	X	—	—	—	—
Ages 4-6	—	—	—	—	X	—	—	—
Levels	—	—	—	—	—	X	—	X
Include abbreviated tests	—	—	—	—	—	—	X	X

Tier 2: New Versus Used Emissions (2000-2010)

$$lnE^u_{picy} = \beta_3 lnE^n_{picy} + X'_{picy}\zeta + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

Table 4—Assessment of Tier 2 Exhaust Standards: Do New Predict Used Vehicle Emissions?

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				Panel B. Carbon monoxide (CO)				
New vehicle emission rate	0.61***	0.64***	0.67***	0.64***	0.63***	0.71***	0.19***	0.57***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.05)	(0.01)	(0.06)
N	143,156	143,156	143,156	143,156	19,360	143,156	3,392,867	3,392,867
				Panel C. Hydrocarbons (HC)				
New vehicle emission rate	0.79***	0.62***	0.50***	0.61***	0.40***	0.81***	0.36***	1.38***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.05)	(0.08)	(0.01)	(0.07)
N	143,156	143,156	143,156	143,156	19,360	143,156	3,392,867	3,392,867
				Panel D. Nitrogen oxides (NO_x)				
New vehicle emission rate	0.68***	0.37***	0.37***	0.36***	0.35***	1.04***	0.21***	1.42***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.08)	(0.01)	(0.10)
N	143,156	143,156	143,156	143,156	19,360	143,156	3,392,867	3,392,867
Age, model year FE	—	X	X	X	X	X	—	—
Truck indicator	—	X	X	X	X	X	—	—
Odometer	—	X	X	X	X	X	—	—
CAFE standards	—	—	X	—	—	—	—	—
Smog check standards	—	—	X	—	—	—	—	—
Gasoline cost per mile	—	—	X	—	—	—	—	—
Ethanol share	—	—	X	—	—	—	—	—
Sulfur content	—	—	X	—	—	—	—	—
Model year × truck trend	—	—	—	X	—	—	—	—
Ages 4-6	—	—	—	—	X	—	—	—
Levels	—	—	—	—	—	X	—	X
Include abbreviated tests	—	—	—	—	—	—	X	X

Tier 2: New Versus Used Emissions (2000-2010)

$$lnE^u_{picy} = \beta_3 lnE^n_{picy} + X'_{picy}\zeta + \upsilon_{py} + \xi_{pa} + \epsilon_{picy}$$

Table 4—Assessment of Tier 2 Exhaust Standards: Do New Predict Used Vehicle Emissions?

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
				Panel E. Carbon dioxide (CO_2)				
New vehicle emission rate	0.95***	0.87***	0.85***	0.87***	0.83***	0.76***	0.78***	0.72***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
N	143,156	143,156	143,156	143,156	19,360	143,156	3,392,867	3,392,867
Age, model year FE	—	X	X	X	X	X	—	—
Truck indicator	—	X	X	X	X	X	—	—
Odometer	—	X	X	X	X	X	—	—
CAFE standards	—	—	X	—	—	—	—	—
Smog check standards	—	—	X	—	—	—	—	—
Gasoline cost per mile	—	—	X	—	—	—	—	—
Ethanol share	—	—	X	—	—	—	—	—
Sulfur content	—	—	X	—	—	—	—	—
Model year × truck trend	—	—	—	X	—	—	—	—
Ages 4-6	—	—	—	—	X	—	—	—
Levels	—	—	—	—	—	X	—	X
Include abbreviated tests	—	—	—	—	—	—	X	X

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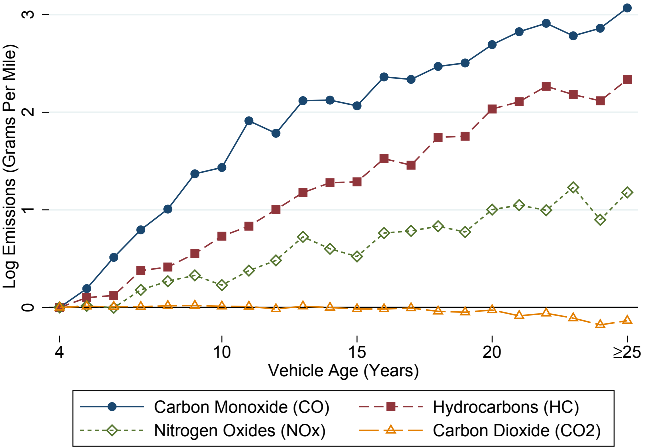
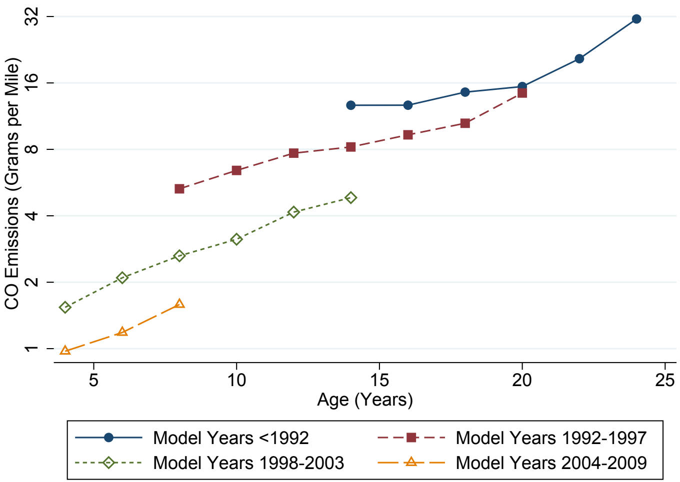
Emissions increase with vehicle age



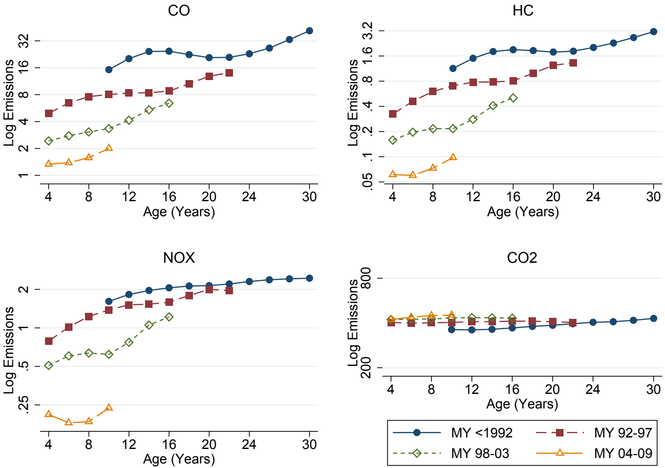
- Controls for odometer and VIN fixed effects

Age and Vintage Increase Emissions

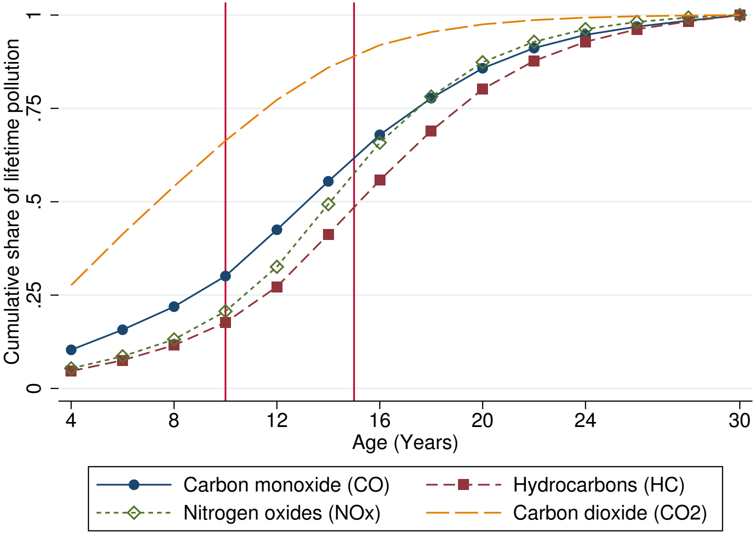


- Similar patterns for other air pollutants, little trend for CO2

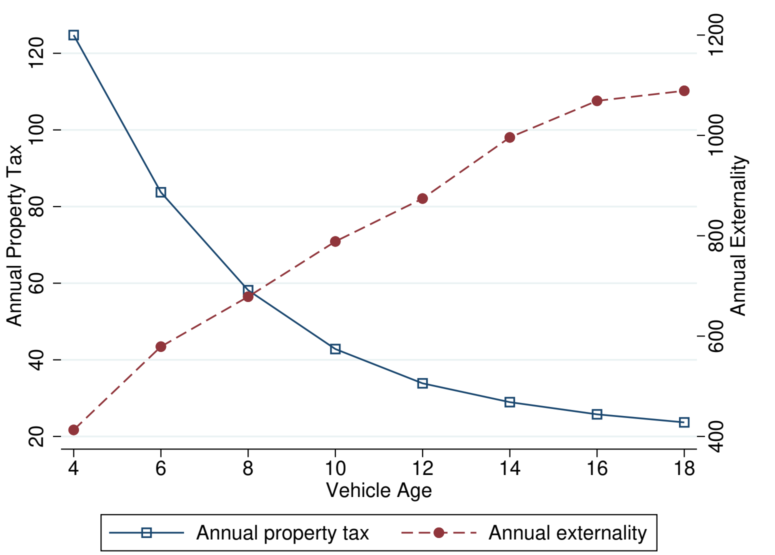
Age and Vintage Increase Emissions



Older Vehicles Account for Most Pollution



Dirtier Vehicles Face Lower Registration Fees



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Analytical Model: Setup

- **Goals**
  - Few/no functional forms
  - General results about exhaust standards, registration fees
- **Environment**
  - One vehicle type, two time periods
  - Vehicle: new (n) in first period, used (u) in next
  - Vehicle creates externality both periods
  - Study steady state
- **Vehicle market assumptions**
  - Measure one, risk neutral, $N + U = 1$
  - Each period, choose new or used vehicle
  - Utility from used: 0
  - Utility from new: $w \geq 0 \sim G(w)$

Analytical Model: Vehicle Supply

- **New vehicle supply**
  - New vehicle manufacturers: constant returns, competitive
  - New vehicle marginal cost ψ^s (exogenous)
  - New vehicle price $\psi = \psi^s + \tau$

- **Used vehicle supply**
  - New vehicle owner may scrap or repair
  - Value of scrap $= 0$
  - Repair cost $= k \sim H(k)$
  - Used vehicle price $= p$ (endogenous)

$$
\begin{aligned}
U^s(p) &= N * H(p) \\
&= (1 - U) * H(p) \\
&= \frac{H(p)}{1 + H(p)}
\end{aligned}
$$

Analytical Model: Vehicle Demand

- WTP for used vehicle: utility minus price:

$$0 - p$$

- WTP for new vehicle: utility minus price plus continuation value:

$$w - \psi + H(p)(p - \overline{k})$$

where expected repair cost is $\overline{k} = [1/H(p)] \int_{-\infty}^{p} k dH(k)$

- Prefer used vehicle if higher WTP, i.e.,

$$-p > w - \psi + H(p)(p - \overline{k})$$

- Used vehicle demand is share that buy used vehicle:

$$U^d(p) = G\Big(\psi - p - H(p)(p - \overline{k})\Big)$$

- (Recall notation): $w \sim G(\cdot)$ preference for new, ψ new vehicle price, $k \sim H(\cdot)$ repair cost, p used vehicle price = cutoff repair cost

Equilibrium

- **Key equilibrium condition**:

$$U^s(p) = U^d(p)$$

$$\frac{H(p)}{1+H(p)} = G\Big(\psi - p - H(p)(p - \overline{k})\Big) \tag{1}$$

Analytical Model: Pollution and Policy

- **Pollution**
  - Pollution from manufacturing Φ
  - Pollution from used exceeds new, due to depreciation or policy
  - New-used difference in externality: $\Delta_t = \Phi + \phi_t^n - \phi_t^u$
- **Policy**
  - Tax on new - used vehicles $\tau \equiv \tau_n - \tau_u$
  - Optimal tax: $\tau = (\Phi + \phi_t^n) - \phi_t^u$

Analytical Model: Results

Proposition (Gruenspecht)

A policy that increases ψ will decrease the scrap rate and increase the market share of used vehicles. Specifically, the derivative of the scrap rate with respect to the new vehicle price is

$$\frac{d(1 - H(p))}{d\psi} = -h(p)\left(\frac{1 + H(p)}{\frac{h(p)}{g(w^*)(1+H(p))} + (1 + H(p))^2}\right) < 0$$

where $w^* = \psi - p - H(p)(p - \overline{k})$ *is the type indifferent between used and new vehicles.*

Analytical Model: Results

Proposition (Gruenspecht)

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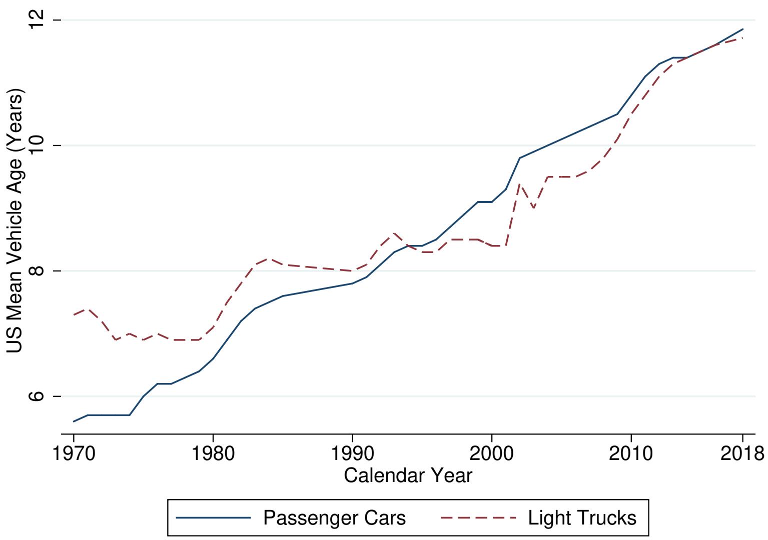
- Proof: totally differentiate (1), sign each part
- Intuition: standards for new durable goods extend life of used durable goods
- Relevance:
  - Buiding codes (commercial/industrial/residential)
  - Coal-fired power plants (US, China, ...)
  - Efficiency requirements (light bulbs, furnaces, ...)

Analytical Model: Results



Analytical Model: Results

Proposition (Welfare)

Welfare in period t is maximized when $\tau = \Delta_t$. If $\tau > \Delta_t$, decreasing τ increases welfare. If $\tau < \Delta_t$, increasing τ increases welfare.

Analytical Model: Results

Proposition (Welfare)

Welfare in period t is maximized when $\tau = \Delta_t$. If $\tau > \Delta_t$, decreasing τ increases welfare. If $\tau < \Delta_t$, increasing τ increases welfare.

- Proof: find cutoff w, differentiate welfare w.r.t. that w, simplify
- Intuition: moving tax rate closer to optimum increases welfare
- Implication: since current ownership fees are higher for new (clean) vehicles than for used, flatting or reversing this sign can increase welfare
- But, requires manufacturing emissions to be 'small'

Outline

- Background
- Data
- Trends
- Causes
- Stylized facts
- Analytical model
- **Quantitative model**
    - Theory
    - Choice of counterfactuals
    - Data and parameters
    - Results
    - Inequality
- Conclusions

Quantitative Model: Consumers

- **Representative agent**:

$$\max_{v,x} U(v,x) = (\alpha_v v^{\rho_u} + \alpha_x x^{\rho_u})^{\frac{1}{\rho_u}} - \Omega \quad (2)$$

$$s.t.\ e_v v + e_x x \leq M \quad (3)$$

- **Operating cost**:

$$e_{csam} = r_{csam} + \tau_{csam} + \sigma_{csam}$$

- **Notation**
  - Vehicles v, outside good x, substitution elasticity ρ_u, prices e_v, e_x, income M, pollution externality Ω
  - Vehicle rental price r, registration fees τ, operating costs σ
  - Vehicle class c, size s, age a, manufacturer m

Quantitative Model: Vehicle Manufacturers

- **Firms**:

$$\max_{p_{cst},\phi_{cst},f_{cst}} \quad \sum_{c,s}\left[\left(p_{cst} - C^{b}_{cs} - C^{\phi}_{cst}(\phi_{cst}) - C^{f}_{cst}(f_{cst})\right) * q^{d}_{cst}\right] \tag{4}$$

$$C^{\phi}_{cst}(\phi_{cst}) = \chi^{t}\zeta_{cs}\left(\frac{\phi_{cs0}}{\phi_{cst}} - 1\right) + \xi_{cst} \tag{5}$$

$$\phi_{cst} \leq \bar{\phi}_{cst} \tag{6}$$

$$\frac{\sum_s q^{d}_{cst}}{\sum_s (q^{d}_{cst}/f_{cst})} \geq \overline{f}_{ct} \tag{7}$$

- **Notes**
  - Perfect or Bertrand competition; exhaust, fuel economy standards
  - Price p, quantity q, emission rate ϕ, fuel economy f
  - Marginal cost: baseline C^{b}; exhaust C^{Φ}; fuel control C^{f}
  - Fleet $c \in$ (passenger car, light duty truck) and vehicle size $s \in$ (small,large)
  - Pollution control: χ innovation rate; ζ variation by class$\times$size; ξ residual

Quantitative Model: Competitive Vehicle Renters

- **Timing within period**
  1. Inherit used vehicles
  2. Draw repair cost $k_{a,t}$ from distribution $H(k_{a,t})$
  3. If $k \geq p$, scrap the vehicle
  4. If $k < p$, repair the vehicle and rent out at price r
  5. Vehicles not scrapped survive to the next period.

- **Assumption: rental price expectations**

$$\mathbb{E}[r_{csam,t+1}] = r_{csam,t} \tag{8}$$

- **Result: rental price dynamics**

$$p_{a,t} = r_{a,t} + (1 - y_{a+1,t})\left(\frac{p_{a+1,t} - \bar{k}_{a+1,t}}{1+\delta}\right)$$

- Rental rate r, repair cost draw k, repair cost cutoff, i.e., vehicle asset value p, scrap rate y, expected repair cost $\overline{k}$, discount rate δ, oldest age bin a_{max}

Quantitative Model: Competitive Vehicle Renters

- **Assumption: repair cost shock CDF is CES**

$$H(k_{a,t}) = 1 - b_a (k_{a,t})^{\gamma_a}$$

- **Result: expected repair cost**

$$\begin{aligned} \bar{k}_{a,t} &\equiv \mathbb{E}(k_{a,t} | k_{a,t} < p_{a,t}) \\ &= \frac{b_a^{-1/\gamma_a} \gamma_a - b_a \gamma_a p_{a,t}^{1+\gamma_a}}{(1+\gamma_a)\left(1 - b_a p_{a,t}^{\gamma_a}\right)} \end{aligned} \tag{9}$$

- **Result: scrap and used vehicle supply**

$$\begin{aligned} y_{a,t} &= b_a (p_{a,t})^{\gamma_a} \\ q^s_{a,t} &= q_{a-1,t-1} * (1 - y_{a,t}) \end{aligned} \tag{10}$$

Quantitative Model: Equilibrium

- **Competitive equilibrium**: Prices and pollution ($p_{csam}, \phi_{cs}, f_{cs}$) so
  - Representative agent maximizes utility (2) s.t. budget constraint (3)
  - Vehicle manufacturers maximize profits (4) s.t. pollution standards (6), (7)
  - Rental price expectations follow (8)
  - Vehicle renters choose repair (9), scrap (10) to maximize profits
  - New and used vehicle markets clear

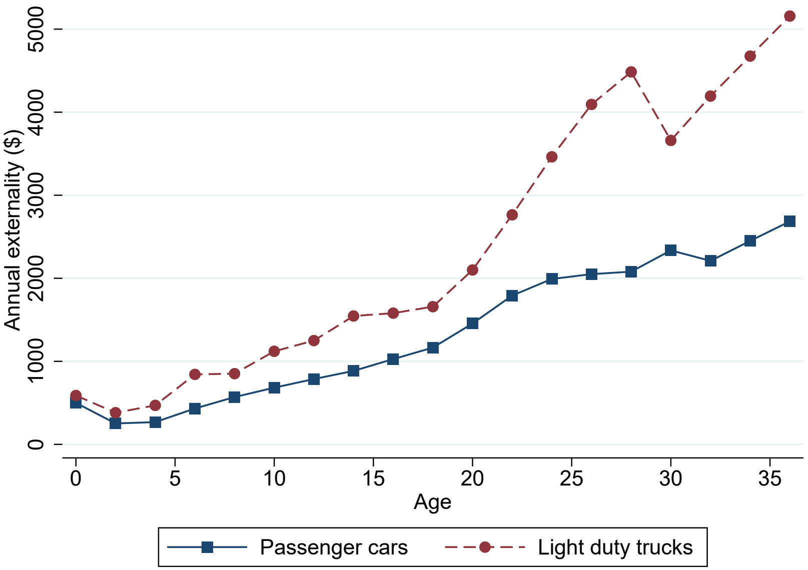
- **Social Welfare**: combines
  - Consumer surplus (equivalent variation)
  - Producer surplus (manufacturer profits)
  - Environmental externalities

Quantitative Model: Solution Algorithm

1. Used vehicle rental rates r (Broyden's method)
    - Take candidate new vehicle prices p and fuel economy f
    - Iterate over demand system and scrap v. repair
2. New vehicle sale prices p
    - From manufacturer profit maximization
3. Update which fuel economy constraints bind

- 532 vehicle prices, 28 fuel economy levels, 28 exhaust emission rates

Quantitative Model: Annual Externality



Quantitative Model: Counterfactual Policies

- **Change exhaust standards**
  - Tier 2 (2004-2016) standards: accelerate or delay 4/8 years
  - Tighten all exhaust standards by 10 percent

- **Change registration fees**
  - Fees proportional to environmental damages
  - Revenue-neutral environmental registration fees
  - New vehicle registration fees
  - Flat registration fees

Quantitative Model: Data

Data input	Variable	Source
Vehicle miles traveled	$vmt_{c,s,a}$	Colorado Dept. Public Health and Environment
Vehicle prices	$p_{c,s,a,m,t}$	National Automobile Dealers Association
		Kelley Blue Book
Vehicle quantities	$q_{c,s,a,m,t}$	Wards Intelligence
		Federal Reserve Bank of St. Louis
Inflation	—	U.S. Bureau of Labor Statistics
Scrap rates	$y_{c,s,a,m,t}$	R.L. Polk & Company
Fuel economy	$f_{c,s,0,m,t}$	U.S. Department of Energy
		National Highway Traffic Safety Administration
		U.S. Environmental Protection Agency
Pollution per mile	$\phi_{c,s,a,m,t}$	Colorado Dept. Public Health and Environment
		U.S. Environmental Protection Agency
Pollution from manufacturing	$\Phi_{c,s,m,t}$	U.S. Bureau of Economic Analysis
		National Emissions Inventory
Vehicle registration fees	$\tau_{c,s,a,m,t}$	Jacobsen et al. (2021)
Household vehicle characteristics	—	U.S. Federal Highway Administration
GDP (2000)	M	U.S. Bureau of Economic Analysis
Gasoline price (2000)	p_{gas}	U.S. Energy Information Administration

Quantitative Model: Parameters

Parameter input	Sources	Value(s)
Scrap elasticities	Jacobsen & van Benthem (2015)	(-0.50, -1.02)
Pollution damages/ton	Tschofen et al. (2019)	\$1,045 (CO)
	Knittel and Sandler (2015)	\$15,047 (HC)
		\$35,566 (NO_x)
Discount rate	USEPA	3.0% per year
GDP growth rate	USEPA	0.5% per year
Autonomous fuel economy improvement rate	Knittel (2011)	1.8% per year
Vehicle demand elasticities	Jacobsen & van Benthem (2015)	Paper Section D.8
Pollution reduction cost parameters	USEPA	Paper Section G.4
Fuel economy cost parameters	NRC (2002)	Paper Section G.4

Counterfactual Exhaust Standards: Model-Based Estimates

TABLE 5: Model-Based Estimates: Effects of Counterfactual Exhaust Standards and Registration Fees

	Change in market surplus	Change in pollution damages	Total change in social welfare = (1) - (2)	New tax revenue	Percent change in cumulative emissions		
					CO	HC	NOx
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A. Counterfactual Exhaust Standards							
1. Delay Tier 2 by four years	8.4	120.6	-112.3	0.0	8.0	4.8	10.7
2. Delay Tier 2 by eight years	13.6	207.0	-193.4	0.0	15.6	8.3	18.4
3. Accelerate Tier 2 by four years	-10.5	-127.7	117.2	0.0	-6.3	-4.9	-11.1
4. Accelerate Tier 2 by eight years	-22.4	-202.5	180.1	0.0	-9.7	-7.7	-17.5
5. Tighten standards 10 percent	-2.4	-27.9	25.5	0.0	-1.4	-1.1	-2.4

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Counterfactual Exhaust Standards: Model-Based Estimates

- **Synopsis of Tier 2 exhaust standards**
  - $30 billion in annual environmental benefits
  - Like preventing 3,000 deaths/year (at VSL=10mn)
  - Benefit/cost ratio of 10 to 15

Counterfactual Registration Fees: Model-Based Estimates

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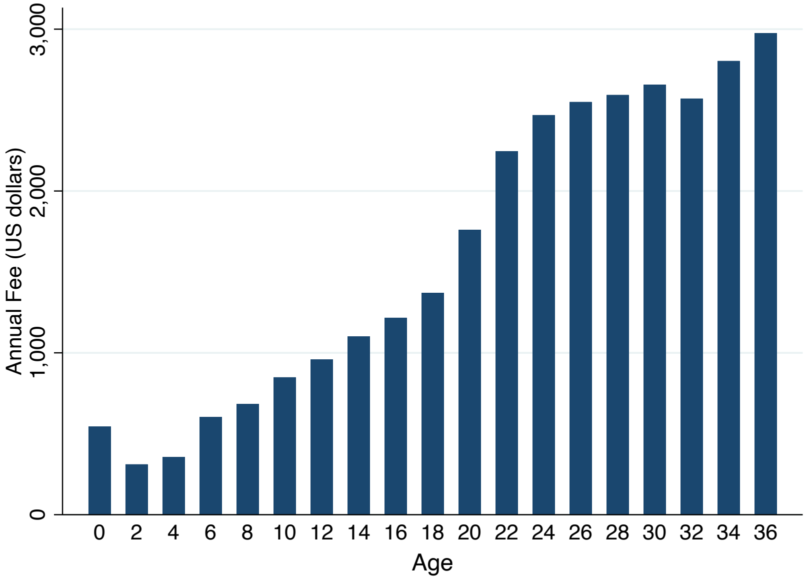
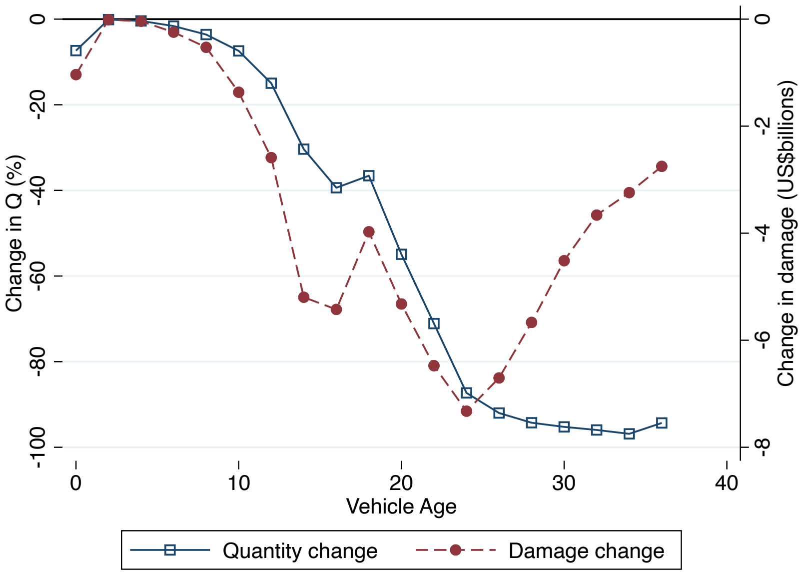
Panel B. Counterfactual Registration Fees							
6. Age×type fee	-176.4	-509.7	333.2	1,181.2	-43.4	-43.2	-24.8
7. Age×type fee, revenue neutral	-115.4	-350.8	235.4	0.0	-34.0	-33.6	-15.3
8. New vehicle fee	-19.7	1.4	-21.1	407.1	1.7	1.8	-0.5
9. Flat registration fee	-3.7	-21.9	18.2	0.0	-1.9	-1.9	-1.2

Counterfactual Registration Fees: Model-Based Estimates



Counterfactual Registration Fees: Model-Based Estimates



Counterfactual Registration Fees: Model-Based Estimates

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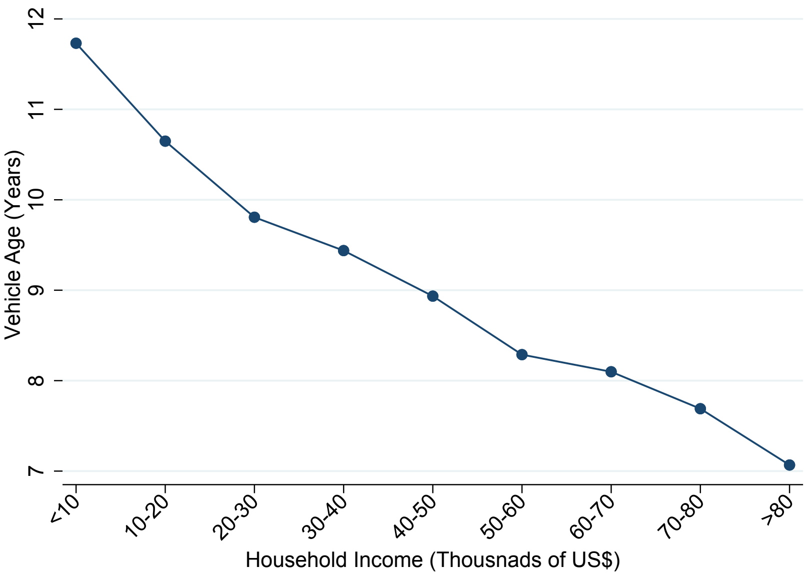
Counterfactual Registration Fees: Inequality



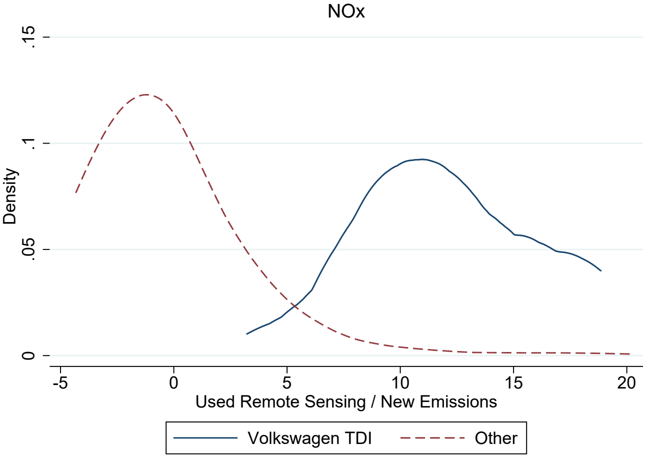
Counterfactual Registration Fees: Inequality

- **Regressive tax incidence?**
  - Low-income households drive dirtier vehicles
  - Vehicle prices adjust, offset some of fees
  - Revenue recycling affects incidence
- **Progressive environmental incidence?**
  - Dirtier vehicles registered/driven in poorer communities
  - Transportation main pollution source in low-income communities

Conclusions

- **World has 1.4 billion cars**
  - How should governments regulate their pollution?
- **US: surprising findings**
  - Pollution/mile has fallen 99%
  - Exhaust standards effective
  - Air pollution increases with age
  - Most emissions from old vehicles
  - Registration fees are higher on cleaner vehicles
  - Gruenspecht Effect important in general setting
  - Large gains, distributional consequences from reforming standards, fees
- **Broader comments**
  - Gasoline $\rightarrow$ electric
  - Equity: dirtier cars in low-income communities, communities of color
  - How generalize to China/India/Mexico/etc.?

Volkswagen Cheating in Our Data



- Ratio of used-to-new emissions is disproportionately high for Volkswagen (remote sensing data)

Return to Tier 2 results