REGULATING UNTAXABLE EXTERNALITIES: ARE VEHICLE AIR POLLUTION STANDARDS EFFECTIVE AND EFFICIENT?*

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The world has 1.4 billion passenger vehicles. How should governments regulate their air pollution emissions? A Pigouvian tax is technologically infeasible. Most countries instead rely on exhaust standards that limit air pollution emissions per mile for new vehicles. We assess the effectiveness and efficiency of these standards, which are the centerpiece of U.S. Clean Air Act regulation of transportation, and counterfactual policies. We show that the air pollution emissions per mile of new U.S. vehicles has fallen spectacularly, by over 99%, since standards began in 1967. Several research designs with a half century of data suggest that exhaust standards have caused most of this decline. Yet exhaust standards are not cost-effective in part because they fail to encourage scrap of older vehicles, which account for the majority of emissions. To study counterfactual policies, we develop an analytical and a quantitative model of the vehicle fleet. Analysis of these models suggests that tighter exhaust standards increase social welfare and increasing registration fees on dirty vehicles yields even larger gains by accelerating scrap, although both reforms have complex effects on inequality. *JEL Codes:* H21, H23, H70, Q50, R40.

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I. Introduction

The world has 1.4 billion passenger vehicles (IHS Markit 2022). How should governments regulate their air pollution? This article studies the effectiveness and efficiency of air pollution exhaust standards and counterfactual policies.

Vehicle transportation is one of the world's largest sources of air pollution. It accounts for 40% of total U.S. emissions of two major air pollutants, carbon monoxide and nitrogen oxides; creates $70 billion in annual pollution-related health and other damages; and causes 37,000 annual premature deaths (National Research Council 2010; Fann, Fulcher, and Baker 2013; U.S. EPA 2014b). Globally, air pollution from transportation causes 250,000 deaths each year (Chambliss et al. 2014; World Bank 2014).

Textbooks describe optimal policy to address pollution—a corrective or Pigouvian tax equal to the marginal external cost of emissions, or a comparable quantity mechanism (e.g., cap and trade). But taxing vehicle air pollution emissions is infeasible because direct measurement of pollution from individual vehicles is imperfect and prohibitively expensive (Venigalla 2013). We believe no government has ever directly taxed air pollution from vehicles.[1]

Instead, the United States, European Union, Japan, China, Russia, India, Brazil, and most other countries rely heavily on new-vehicle exhaust standards. Exhaust standards set a maximum emission rate per mile for every vehicle. Some standards impose fleet-wide average requirements.

Exhaust standards have been controversial for decades due to their large costs and ambiguous effectiveness. In the 1970s, Ford executive Lee Iacocca claimed these standards could stop U.S. vehicle production (Kaiser 2003). Congress has issued three requests to the National Academies of Science to provide advice involving exhaust standards (National Research Council 2001, 2004, 2006). Manufacturers have cheated on these standards, including the Volkswagen scandal that involved $22 billion in payments—the

1. Roadside pollution sensing via infrared beams has substantial measurement error for individual vehicles. Scheduled emissions tests (smog check) when paired with high-stakes incentives can lead to avoidance behaviors, making taxes based on such tests inaccurate (Stedman, Bishop, and Slott 1998; Merel et al. 2014; Oliva 2015). Gasoline taxes target greenhouse gas emissions but weakly proxy air pollution (Knittel and Sandler 2018).

largest auto settlement in U.S. history—leading to questions about standards' effectiveness (Yacobucci 2015).

Little economic research, however, scrutinizes exhaust standards. They are separate from fuel economy standards, which target gasoline consumption and have been the focus of much prior literature, reviewed below. We highlight the different patterns and challenges of air pollution and fuel economy. Thus, existing insights and methods from the fuel economy literature do not answer the questions we pose for vehicle air pollution.

This article helps fill this literature gap by investigating several questions. How have vehicle air pollution emission rates changed over time? To what extent have exhaust standards caused these declines? Are these standards cost-effective? Finally, how might reforms improve policy, either by targeting the stringency of exhaust standards or introducing complementary policies that accelerate vehicle scrap?

We find striking answers to each question. First, the air pollution emissions per mile of the U.S. new-vehicle fleet has fallen by more than 99% since regulation began in the 1960s. This spectacular decrease may exceed that of any other major sector. Used vehicles follow similar patterns. We conclude that these trends represent genuine, long-term, large declines in exhaust emission rates of U.S. vehicles. We find much smaller declines for carbon dioxide (CO_2) emissions that fuel economy regulations target.

Second, to assess the effect of exhaust standards on emission rates, we exploit variation in exhaust standards between California and federal standards and across classes of vehicles, model years, and pollutants. We find that exhaust standards have caused 50% to 100% of the time series declines in air pollution emission rates. Equivalently, we find an elasticity of vehicle emission rates with respect to exhaust standards of 0.5 to 1.0. Several pieces of evidence support these estimates' internal validity. Event study graphs show that changes in emissions align in time with changes in exhaust standards. We obtain qualitatively similar results when controlling for potential confounding policies—gasoline prices including taxes and standards for smog check ("inspection and maintenance"), fuel economy, gasoline hydrocarbons, gasoline sulfur content, and ethanol blending. We obtain similar results when separately analyzing each set of standards, generally called Tier 0 (model years 1968–93), Tier 1 (1994–2003), and Tier 2 (2004–16). Although we find that exhaust standards do not change basic vehicle attributes (horsepower, fuel economy, etc.), they do lead manufacturers to install cleaner engines. This statistical evidence echoes informal assertions by engineers and policy makers that exhaust standards, not secular technological innovation or other forces, account for most decreases in air pollution emission rates from U.S. vehicles.

Third, while the aforementioned regressions suggest exhaust standards are effective, stylized facts suggest that exhaust standards are not cost-effective.[2] They do not equate the marginal cost of abating pollution across vehicles, a necessary condition for cost-effectiveness, because they only weakly regulate pollution from older vehicles. Emission rates of air pollutants (but not CO_2) increase rapidly with age. A majority of air pollution emissions in a calendar year come from vehicles more than 10–15 years old, which are largely exempt from exhaust standards.[3] Registration fees on the oldest and dirtiest used vehicles could in principle discourage ownership of these vehicles. We build a database containing tax rates we collected from United States state and local governments describing vehicle registration fees, motor vehicle taxes, and vehicle property taxes (which we collectively refer to as "registration fees"). We find that registration fees are higher for newer, cleaner vehicles, and thus encourage ownership of older, dirtier vehicles, thereby exacerbating inefficiencies in fleet turnover. This echoes the broader idea that a commodity tax system that imposes higher tax rates on cleaner goods can cause important environmental damages (Shapiro 2021).

Fourth, we develop an analytical and a quantitative model to evaluate counterfactual policies. The early parts of the article show regressions analyzing differences in emission rates; the latter parts combine those data with formal theoretical models to clarify remedies for and implications of the patterns in emission rates. An analytical model makes minimal assumptions about the distribution of primitives, including scrap costs, and provides comparative statics on how counterfactual policies affect social

2. A cost-effective pollution policy minimizes the cost of achieving a given pollution reduction, or maximizes the pollution reduction for a given cost. A pollution policy may increase social welfare yet not be cost-effective—the social willingness to pay for its pollution reduction may exceed its costs, even though other policies could have achieved that pollution reduction at even lower cost.

3. Smog check programs regulate emissions of old dirty vehicles. Most of our data are from areas with smog check programs, suggesting that older vehicles could account for an even larger share of pollution in the absence of smog check programs.

welfare. We analyze the equilibrium of a continuum of agents who can buy new vehicles from competitive manufacturers or repair new vehicles to drive them as used. Equilibrium used-vehicle prices depend on exhaust standards and registration fees and also determine scrap rates. Our first result shows that tightening new-vehicle exhaust standards extends the lifetime of used vehicles, which exacerbates inefficiency from consumers scrapping used vehicles later than is socially optimal. This formalizes the "Gruenspecht effect," which has been informally noted for many environmental policies. Our second analytical result shows that increasing registration fees on used vehicles can improve social welfare and complement exhaust standards by correcting the low scrap rate for used vehicles.

The quantitative model estimates gains from counterfactual policies. The quantification has a similar basic structure as the analytical model but allows for substitution across over 500 vehicle types differentiated by manufacturer, age, class, and size. The quantitative model also accounts for the engineering cost of meeting exhaust standards and fuel economy standards, Bertrand competition among new-vehicle manufacturers, firm expectations, supply chain (life cycle) emissions from manufacturing vehicles, and transitional dynamics. We study counterfactual changes to exhaust standards or registration fees. For each, we determine the equilibrium that results, then calculate the change in pollution emissions, producer and consumer surplus, environmental damages, and social welfare. The quantification uses data and estimates from earlier parts of the article.

The quantitative model provides several results. Accelerating the rollout of tighter (Tier 2) exhaust standards by one year increases social welfare by \$20 to \$30 billion. Policy makers are debating the importance of delays in stringent global climate policy; although we study air pollution rather than climate change, we find large consequences of the timing of an environmental policy. In addition, we find that the benefits of Tier 2 exhaust standards (which operated in the 2000s and 2010s) are 10 to 15 times its costs, and that Tier 2's measured benefits due to avoided premature mortality are 35% larger than those of a prominent cap-and-trade market for industrial plants from the same period, the NO_x Budget Program (Deschenes, Greenstone, and Shapiro 2018). We find larger gains, around \$300 billion in present value, from reforming annual registration fees to reflect the environmental damage of a vehicle's age × type. Changing registration fees creates these benefits primarily by encouraging scrap of old and dirty vehicles. This counterfactual causes scrap of nearly all vehicles aged 25 years old or more. Echoing the Gruenspecht effect analytical result, levying such environmental registration fees only on new vehicles actually creates welfare losses because new-vehicle fees discourage scrap of old vehicles, extending their lifetimes and emissions.

These counterfactuals have complex effects on inequality. Because households in low-income communities drive older and dirtier vehicles, increasing registration fees for dirtier vehicles may trade off equity and efficiency. Exposure to aggregate vehicle emissions, for example, because of proximity to highways, is also greater for low-income communities, leading to a potentially progressive environmental incidence. Transportation is a large source of pollution in vulnerable communities (Carlson 2018; Apte et al. 2019). In addition, recycling revenues from automobile policy substantially influences its regressivity (Bento et al. 2009). We carefully discuss these channels and their political-economy implications.

Three ties connect the article's empirical and theoretical sections. First, they answer complementary parts of the research questions. The empirical analysis studies effectiveness, while the models analyze cost-effectiveness and efficiency. Second, the regressions guide model assumptions. For example, the empirical finding that exhaust standards are effective and (subject to overcompliance) binding motivates corresponding assumptions in the models and also motivates the counterfactual analysis of tightening standards. Similarly, the empirical finding that age plays a central role in explaining emissions and that existing registration fees exacerbate these patterns motivates the models' analyses of age-based registration fees and the models' overall focus on fleet composition and scrap. Third, the empirical parts help assess the properties of the emissions inspections data that the quantitative model uses extensively and that the analytical model uses in a back-of-the-envelope quantification.

This study uses the most comprehensive data on vehicle pollution emission rates ever constructed. It includes a half century of comparable pollution data using the same high-quality measurement method. These data cover nearly every new U.S. light-duty vehicle and light-duty truck sold between 1972 and 2020 and many over the period 1957–71. We believe this is the longest-lasting comparable microdata on pollution emission rates from any country or sector.[4] We supplement these new-vehicle records with 65 million used-vehicle test records from three types of tests—used-vehicle inspections, official regulatory "in-use" tests, and roadside remote sensing. Our new-vehicle data are national. Our main used-vehicle data are from the state with the most high-quality and extensive used-vehicle tests in the United States, Colorado, though we corroborate some patterns with additional data from 11 other states and six other countries. Finally, we use the Leontief inverse of the U.S. input-output table combined with plant-level industrial emissions data to account for the emissions embodied in the manufacturing of new vehicles and the associated supply chain.

This paper builds on several literatures. We provide the first comprehensive analysis of exhaust standards, which are the centerpiece of U.S. Clean Air Act regulation of transportation. Landmark papers study Clean Air Act regulation of industry (e.g., Henderson 1996; Carlson et al. 2000; Greenstone 2002; Walker 2013). Another important literature studies fuel economy standards, which are separate from exhaust standards (Goldberg 1998; West and Williams 2005; Goulder, Jacobsen, and van Benthem 2012; Jacobsen 2013; Anderson and Sallee 2016; Langer, Maheshri, and Winston 2017). Analysis of fuel economy standards has developed methods to use the R-squared from a regression to study imperfect targeting of environmental policy (Jacobsen et al. 2020), but the primary challenge we highlight for exhaust standards involves fleet composition and scrap. Existing work largely does not directly analyze exhaust standards' effects.[5]

4. For example, emissions data from U.S. manufacturing only have firm-level records generally available back to 1990, in many cases come from engineering predictions rather than direct measurement, and can fail data quality tests (Currie et al. 2015). Similarly, regular emissions monitoring from U.S. power plants began in 1980, is quinquennial through 1995, and in many years covers only the largest electricity-generating units.

5. Prior papers describe standards (Bishop and Stedman 2008) or abatement technologies (Bresnahan and Yao 1985); summarize engineering estimates of abatement costs (Fowlie, Knittel, and Wolfram 2012; Cropper et al. 2014); describe model-year trends from before versus after standards change using one cross section of vehicle tests (Kahn 1996a, 1996b), which does not separate effects of age, model year, and standards; undertake simulations of vehicle emissions with a few types of vehicles (Mills and White 1978; Innes 1996; Kohn 1996; Harrington 1997; Walls and Hanson 1999; Fullerton and West 2010; Feng, Fullerton, and Gan 2013); compare emissions from electric and gasoline vehicles (Holland et al. 2016); or study time series vehicle emissions and health effects without distinguishing contributions from standards versus other causes (Choma et al. 2021).

In addition, this article provides the first simple sufficient conditions for stricter environmental policy on new capital to create inefficiency by decreasing scrap. Known as the Gruenspecht effect (Gruenspecht 1982), this pattern has been informally lamented for decades. Many prominent environmental regulations differ by capital vintage, such as the U.S. Clean Air Act's New Source Review or energy efficiency construction codes (Gruenspecht and Stavins 2002; Stavins 2006). Existing work uses regressions to analyze effects of vintage-differentiated regulations (Bushnell and Wolfram 2012; Bai et al. 2021) or analyzes new-vehicle purchase fees proportional to CO_2 emissions (Adamou, Clerides, and Zachariadis 2013; D'Haultfoeuille, Givord, and Boutin 2013). Some papers evaluate programs that encourage retirement of polluting vehicles, including "Cash for Clunkers" (Busse et al. 2012; Sandler 2012; Li, Linn, and Spiller 2013; Hoekstra, Puller, and West 2017). More broadly, Barahona, Gallego, and Montero (2019) and Gillingham et al. (2022) find that policies spurring scrap of old vehicles substantially increase social welfare.

We also create the first national data on and economic analysis of vehicle property taxes. Research analyzes property taxes for real estate (e.g., Poterba and Sinai 2008; Cabral and Hoxby 2015), but many property taxes also apply to vehicles. We create a data set of vehicle property taxes and registration fees from U.S. states, cities, counties, and special districts.

In addition, this research provides the first equilibrium model of vehicle markets and scrap that accounts for air pollution abatement and emissions. Existing frameworks to analyze fuel economy, economy-wide greenhouse gas emissions, or polluting industrial activity do not apply directly to air pollution from vehicles (Goldberg 1998; Goulder, Jacobsen, and van Benthem 2012; Busse, Knittel, and Zettelmeyer 2013; Jacobsen and van Benthem 2015). The model relates to recent industrial organization papers studying equilibrium trade in used-car markets in settings with more general forms of market power and frictions (Biglaiser et al. 2020; Gillingham et al. 2022).

Several papers analyze used-vehicle emissions from smog check tests, primarily from California, which measure pollution emission rates from used vehicles and require repairs of the dirtiest vehicles, but those papers do not evaluate exhaust standards (Merel et al. 2014; Knittel and Sandler 2018; Sanders and Sandler 2020).

Finally, this research helps answer the question of why pollution in industrialized countries is declining. We describe a setting where a specific regulation accounts for most of a long-term national decrease in pollution emission rates.[6] Although many countries and sectors have had large decreases in pollution over time, and most of this decrease reflects cleaner production in an industry rather than reallocation across industries, studies have struggled to assess which economic forces or policies have caused that decline. The article proceeds as follows. Section II describes policy and technology. Section III discusses the data. Section IV describes emissions trends. Section V estimates effects of exhaust standards. Section VI establishes stylized facts on cost-effectiveness. Section VII describes the analytical model, Section VIII describes the quantitative model, and Section IX concludes.

II. Background on Exhaust Standards

II.A. *History of Exhaust Standards*

In 1952, chemist A. J. Haagen-Smit discovered that hydrocarbons (HC) and nitrogen oxides (NO_x) emissions from vehicles contribute to smog. By 1959, engineers had developed technology to abate emissions by running exhaust fumes over a catalyst.

Federal regulators have since imposed standards regulating these pollutants and carbon monoxide (CO). We call these regulations “exhaust standards.” Others sometimes call them tailpipe or emission standards. These standards limit the emissions per mile of these pollutants. We refer to the grams of pollution emitted per mile driven as a vehicle’s emission rate and the total grams of pollution emitted as emissions. We refer to CO, HC, and NO_x as air pollution, though they are sometimes also called local or criteria pollution, to distinguish them from global pollutants like CO_2. Table I summarizes the standards. Online Appendix A.1 discusses details of standards less directly relevant to this study.

6. Following Copeland and Taylor (1994) and Grossman and Krueger (1995), researchers have allocated economy-wide changes in pollution into changes in total output (scale); changes in the share of output from different industries (composition); and changes in pollution emitted per unit of output within a given industry (technique). In many regions, technique accounts for most decreases in pollution from manufacturing (Levinson 2009; Cherniwchan, Copeland, and Taylor 2017; Shapiro and Walker 2018; Copeland, Shapiro, and Taylor 2022).

TABLE I

FEDERAL EXHAUST STANDARDS

		Light-duty vehicles			Light-duty trucks			Mean	Mean
Policy	Model years (1)	CO (2)	HC (3)	NO_x (4)	CO (5)	HC (6)	NO_x (7)	Limit (8)	Pollutant (9)
Uncontrolled	−1967	90.0	8.200	3.40	90.0	8.200	3.40	—	—
Tier 0	1968–71	34.0	4.100	—	34.0	4.100	—	—	—
	1972–74	28.0	3.000	3.10	28.0	3.000	3.10	—	—
	1975–76	15.0	1.500	3.10	20.0	2.000	3.10	—	—
	1977–78	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	—	—
	1981–83	3.4	0.410	1.00	18.0	1.700	2.30	—	—
	1984–87	3.4	0.410	1.00	10.0	0.800	2.30	—	—
	1988–93	3.4	0.410	1.00	10.0	0.800	1.50	—	—
Tier 1	1994–96	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	2001–3	3.4	0.139	0.40	5.2	0.250	0.80	0.075	NMOG
Tier 2	2004–6	3.4	0.125	0.40	3.4	0.139	0.40	0.070	NO_x
	2007–16	3.4	0.100	0.14	3.4	0.100	0.14	0.070	NO_x
Tier 3	2017–25	4.2^+	0.16^+		4.2^+	0.16^+		0.030	NMOG+NO_x

Notes. CO is carbon monoxide, HC is hydrocarbons, NO_x is nitrogen oxides, NMOG is nonmethane organic gases. All numbers are for gasoline vehicles, measured in grams per mile by the federal test procedure. See Online Appendix A.1 for details. Columns (5) through (7) show mean standards across truck types, with weights equal to the proportion of each vehicle from model year 1993 in Colorado smog check data. For policies that impose a fleet-wide mean limit, columns (2) through (7) show the limit for the highest bin. $^+$Tier 3 standards apply at 150,000 miles, whereas earlier policies apply at lower mileage. Tier 3 has a combined NMOG+NO_x standard, which is phased in and reaches 0.030 in model year 2025. Uncontrolled emissions are calculated based on emission rates and estimates from vehicles before emissions controls.
Sources. National Commission on Air Quality (1981); Bresnahan and Yao (1985); Davis (1997); U.S. EPA (2016).

The 1965 Motor Vehicle Air Pollution Control Act created national standards, called Tier 0. The 1970 Clean Air Act Amendments substantially expanded them.[7] Standards began for CO and HC in 1968 and for NO_x in 1972.[8] Tier 0 standards periodically tightened through 1993. These standards essentially required every vehicle to have a catalytic converter by the mid-1970s, although catalytic converters were not broadly viable in the 1960s. Automakers developed and installed catalytic converters to comply with exhaust standards. We focus on federal exhaust standards, but the Clean Air Act lets California set its own, tighter exhaust standards. Other countries and U.S. standards have similar structure.

7. Corporate Average Fuel Economy Standards are enabled by the Energy Policy and Conservation Act of 1975, a separate law from the Clean Air Act.

8. All years in this section refer to vehicle model years.

The 1990 Clean Air Act Amendments required Tier 1 standards, which were phased in beginning in 1994 and became binding in 1996.[9] A few light-duty trucks could wait until 1997 to comply. Exhaust standards regulate “light-duty vehicles” and “light-duty trucks”; we refer to these as cars and trucks. Tier 1 decreased CO and HC standards more for categories of trucks than for cars, though required similar NO_x decreases in emission rates for cars and trucks. Thus, our analysis of Tier 1 does not focus on NO_x because we exploit differences in stringency between vehicle classes. Tier 2 standards phased in over the years 2004–9 and continued through 2016. Tier 3 is being phased in from 2017 through 2025.

These standards have the same general approach but different details. Tier 0 and Tier 1 define maximum standards. Each standard requires every vehicle in a class (e.g., trucks in a certain weight range) to emit less than the standard. Tier 2 and Tier 3 impose fleet-wide mean standards and tightened the maximum standards. The pollutant used for the fleet-wide average standard differs across regulations.

These standards use the same test to measure a vehicle’s emission rate, the federal test procedure. This test specifies the chemical composition of the fuel used in the test, the speed at every second of a 30-minute test, and is run on a dynamometer, a large treadmill-like device; Online Appendix A.2 discusses details.

Before a vehicle may legally be sold, the EPA must certify that the vehicle meets exhaust standards. In addition to conducting a test, the EPA or manufacturer estimates a “deterioration factor” predicting how emission rates will change during the vehicle’s useful life, which ranges from 50,000 miles and 5 years (whichever comes first) to 150,000 miles or 15 years, depending on the standard. The EPA regulates how manufacturers may determine deterioration factors. Exhaust standards apply to a new vehicle’s “certification level,” which equals the test result scaled up by the deterioration factor.

Several years after a vehicle is manufactured, the EPA assesses in-use compliance. Manufacturers conduct emissions tests on samples of vehicles at up to 150,000 miles and the EPA audits

9. Only 40% of vehicles had to comply with Tier 1 in the 1994 model year and 80% in 1995. Because many vehicles already met Tier 1 standards in 1993, Tier 1 was most binding for the dirtiest vehicles, which could remain at existing emission levels until model year 1996.

some. If these tests find emission rates above the standard, the vehicle is recalled and the emissions control system repaired or replaced. Between 1975 and 2008, 80 million vehicles, or about 16% of all vehicles sold, had recalls, though some of these involved minor reclassifications (U.S. EPA 2008; Department of Energy 2016). Accurately predicting a new vehicle's emission rate at 50,000 or 150,000 miles is challenging. In-use tests and the costs of recalls give manufacturers an incentive to overcomply with exhaust standards. Industry engineers and regulators we interviewed describe overcompliance, sometimes called headroom or a safety margin, as typical for this reason.

II.B. Pollution Abatement Technologies

Explaining technologies used to meet these standards helps interpret results; Online Appendix A.3 provides details. The approach has changed little since the 1970s: expose exhaust to precious metals inside a catalytic converter, which converts pollution into harmless gases. Because these metals are catalysts, pollution can react with them without consuming or changing them. The precious metal palladium primarily abates CO and HC, which have complementary abatement technologies; rhodium primarily abates NO_x; and platinum abates all three. Under ideal conditions, these reactions eliminate 100% of CO, HC, and NO_x.

Lead and sulfur render catalytic converters ineffective by coating the catalyst. Our used-vehicle data begin after model year 1975, when vehicles required unleaded gasoline (Mondt 2000). Nonetheless, catalytic converters decrease in effectiveness over time due to remaining low levels of sulfur in gasoline, wear of precious metals, or breakdown of complementary technologies like oxygen sensors.

Would emission rates decline without regulation, due to secular innovation? Engineers and regulators we interviewed argued that technologies that improve vehicle drivability do not affect pollution, so automakers would only decrease emission rates due to regulation. Crandall et al. (1986, 92) summarize this view: "There is little evidence to support the view that emission rates would have fallen significantly without the emissions standards program." Innovation may still decrease the marginal cost of controlling vehicle emission rates over time. Because emissions-related recalls are common and costly, even when policy is constant, decreasing marginal abatement costs over time give auto manufacturers an incentive to decrease emission rates even further (additional overcontrol), even without tightening standards, to decrease the rate of unexpected recalls.

One may also wonder whether trends in "green" or "warm glow" preferences for environmentally friendly goods could explain changing vehicle emission rates. We believe this is not a major contributor, in part due to limited consumer information. We have not found anecdotal or statistical evidence that consumers value or even know their vehicle's air pollution emissions, though consumers may have information on fuel economy. Unlike fuel economy, information on a vehicle's air pollution is not easy to find and interpret.[10]

Many environmental policies, including exhaust standards, encourage innovation in abatement technology (Vollebergh 2010; Rozendaal and Vollebergh 2021). The EPA calls exhaust standards "technology forcing" because they can require technologies that have been proven in focused settings but may not have had mass development or adoption. Innovation research finds that the announcement of Tier 0 and Tier 1 standards increased patenting and publishing of technical papers on relevant abatement technologies (Lee et al. 2010; Lee, Veloso, and Hounshell 2011).

II.C. Other Policies Relevant to Emission Rates

Other environmental policies are relevant to our analysis. Our regressions and quantitative model account for them. Corporate average fuel economy standards regulate the mean fuel economy of new vehicles. Fuel economy standards did not change in the periods we study most closely (Department of Transportation 2014). Federal gasoline excise taxes, state retail gasoline taxes, and gasoline prices could affect miles traveled or driving behavior. Around 10% of U.S. counties operate smog check programs, where registration requires used vehicles to pass emissions inspections. Our data mostly come from areas with smog check, so our findings that vehicle emission rates rise sharply with age and our estimates of the benefits of scrapping old dirty vehicles might be even larger without smog check. Some states and cities regulate the chemical content of gasoline

10. Air pollution emission rates are not shown on most leading consumer automotive websites. The EPA calculates a 1 to 10 "smog rating" for vehicles, which now appears in small font on a vehicle's fuel economy sticker. But this rating is not thoroughly explained and was absent for most of our sample period.

to decrease HC, but not other pollutants (Auffhammer and Kellogg 2011). Colorado, the source of our main data, has not used gasoline with regulated chemical content (U.S. EPA 2019). Ethanol accounts for an increasing share of fuel, in part due to policy. Evidence on how ethanol affects exhaust emission rates is mixed (Hubbard, Anderson, and Wallington 2014). Governments in 28 states, listed in Online Appendix F.1, have registration fees that vary with vehicle characteristics, especially value.

III. Data

III.A. New-Vehicle Pollution Data

We obtain test results for each new-vehicle type from the Annual Certification Test Results Report, also called the Federal Register Test Results Report.[11] We obtain electronic records for model years 1979 to 2019 from the EPA and keyed in records for 1972–78 from the Federal Register (1972–78); see Online Appendix B.2 for details. Although these data determine compliance with the Clean Air Act, we are not aware of any economics research using them.

For model years 1957–71, we obtain data on used vehicles tested in AES (1973), which applied the federal test procedure to about 1,000 vehicles aged 1 to 14 years old from five cities. The sample statistically represented the national distribution of vehicle characteristics. In model years before exhaust standards, emission rates of these vehicles do not appear to increase with age and are similar to estimates of uncontrolled emission rates. This is sensible because before exhaust standards, vehicles did not have emissions control systems that could break down. Hence, for these preregulation years, new and used vehicles likely had similar emission rates. We identify vehicles meeting California standards in AES (1973) as those in California and vehicles meeting federal standards as those in other states.

III.B. Used-Vehicle Pollution Data

Our main used-vehicle emission data come from smog check tests in Colorado, which we use for several reasons. Although many states test vehicle emissions, recently only Colorado has

11. We use “class” to denote cars versus trucks, or weight categories of trucks, and “type” to denote more detailed classification of vehicles such as manufacturer, size, trim, or engine specifications.

used the highest-quality test, called IM240 (the inspection and maintenance test that lasts 240 seconds). This test provides a short version of the federal test procedure and is considered the gold standard of smog check tests for its quality and comparability to the federal test procedure (Sierra Research 1997; Joy et al. 2004; U.S. EPA 2006); Online Appendix B.1 discusses this comparability.[12] Most other states only obtain a computer description of the status of a vehicle's emissions control system (an on-board diagnostic test) and do not measure exhaust emission rates for most vehicles. Colorado includes about 12 million tests and extensive remote sensing and registration data.[13] Online Appendix B.3 shows that the Colorado counties have similar driving and emissions patterns to other polluted urban U.S. counties.

The Colorado data cover calendar years 1997 through 2014. In these years, all Colorado gasoline vehicles model year 1982 or later are tested biennially, beginning at age four, so the data cover model year 1982 through 2010. Online Appendix B.3 describes additional sample restrictions, such as excluding observations missing key variables.

We take a few steps to limit concerns about avoidance and short-term evasion behavior. We restrict the Colorado sample to the first test in a sequence, which is less subject to short-term manipulation concerns. A sequence is a test series for a specific registration, ending in a vehicle passing (and then able to register) or being sold, traded, or driven unregistered. Manipulation is arguably more likely after a vehicle fails the first test. We include estimates that control for the stringency of the relevant smog check standard. In addition, we report sensitivity analyses using remote-sensing estimates from a Colorado database with over 50 million remote-sensing readings, from smaller samples taken in 11 states, from four other countries, and from heavy-duty trucks (e.g., 18 wheelers).

We show sensitivity analyses from remote sensing, which uses roadside infrared or ultraviolet beams connected to devices

12. The EPA describes the IM240 test as "the most accurate short test available for use in I/M programs" (U.S. EPA 1995). Colorado describes it as "arguably the most accurate emissions test currently in use for replicating the Federal Test Procedure (FTP) that is used to certify new model year vehicles" (AIR 2015).

13. Most economic research using data on U.S. used-vehicle emission rates uses data from California, but its data have lower quality; Online Appendix A.2 provides details.

that measure pollution concentrations in an exhaust plume. Remote sensing provides data that is believed to be impervious to manufacturer "defeat devices" and that is not generally used in economics publications.[14] Remote sensing, however, has substantial measurement error and imperfectly comparable units versus new- or used-vehicle tests (Borken-Kleefeld 2013). Online Appendix Table A1 compares remote-sensing and smog check readings from the same vehicle in essentially the same week. If remote-sensing and smog check data were perfectly comparable, Online Appendix Table A1 would obtain regression coefficients and elasticities of one. Although matched remote-sensing and smog check readings are strongly correlated, the magnitude of that regression coefficient ranges from 0.000015 to 435, and the magnitude of the elasticity ranges from 0.01 to 2.98, depending on the pollutant and specification. None of the 95% confidence regions includes zero or one. We interpret remote sensing as an important check on the sign and precision of changes in emission rates, but interpret magnitudes from remote sensing cautiously because of its differences in measurement.

Finally, we report sensitivity analyses from "in-use" tests in California (see Online Appendix B.5), which have no direct incentives for vehicle owners, so are unlikely to suffer from owner manipulation. In-use tests apply the federal test procedure to a sample of vehicles several years old to assess compliance with exhaust standards.

III.C. Other Data Notes

Online Appendix Table A2 summarizes the samples and coverage of the article's data sets. We use all years to describe emission rate trends and subsets of years to analyze Tiers 0, 1, and 2. In addition, we use vehicles from model year 1993 and calendar year 2000 to describe fleet-wide emissions, and test year 2000–2014 data to calibrate the quantitative model. Online Appendices B.6 and B.7 discuss details including concordances, use of the U.S. input-output table to measure the emissions from manufacturing vehicles, and the marginal damages of pollution.

Here we summarize emissions from manufacturing vehicles. We use the Leontief inverse of the U.S. input-output table, which

14. Defeat devices typically turn on parts of an emissions control system only when they detect that a vehicle is undergoing a laboratory driving test. Remote sensing observes vehicles during typical on-road driving.

helps measure the entire supply chain of all goods used to produce a vehicle. We measure emissions from each industry in the vehicle supply chain by using plant-level air pollution emissions data from the National Emissions Inventory. Aggregated, this calculation suggests that manufacturing a new car or truck creates about \$600 in environmental damages due to air pollution in the year 2000, including emissions from the entire supply chain, which is in the ballpark of numbers that engineers have estimated from life cycle analyses. These damages fall over time as manufacturing becomes cleaner.

IV. Trends in Emission Rates

We first quantify trends in new- and used-vehicle emission rates. Figure I plots mean emission rates in grams per mile from new U.S. vehicles over model years 1957–2020. The figure shows the three air pollutants that exhaust standards target—CO, HC, and NO_x. It also shows CO_2, which fuel economy standards target. The graphs show the mean certification level for 50,000 miles, that is, the emission rate of a new vehicle scaled up by an engineering calculation reflecting 50,000 miles. Each *y*-axis has a log scale. Vertical lines show the year before exhaust standards. The lines with blue squares show the unweighted mean across vehicle types. For model years 2000–2015, the lines with hollow red circles show means weighted by fleet size.

Figure I shows that the emissions per mile for each air pollutant have fallen by more than 99% since regulation began. CO has fallen by 99.4%, HC by 99.7%, and NO_x by 99.5%. For example, the mean CO emission rate of new U.S. vehicles fell from 83 g per mile in the 1960s to 0.5 g per mile in 2020. Even between 1990 and 2018, these emission rates fell by 75% to 95%. Unweighted trends and trends weighted by fleet size are similar.[15] We do not believe previous research has directly used these new-vehicle test results to measure long-term pollution trends.[16] The long

15. Online Appendix C.1 discusses data limitations but shows qualitatively similar results for weighted trends before 2000.

16. Existing evidence does not definitively show these trends. The EPA uses a simulation model, the Motor Vehicle Emission Simulator (MOVES), to calculate annual vehicle emissions. Dividing predicted national emissions from MOVES by national vehicle-miles traveled shows that air pollution emissions per mile have fallen by 98%–99% since the 1970s (U.S. EPA 2022). MOVES, however, relies on numerous parameters, data sources, and calculation modules; its design changes

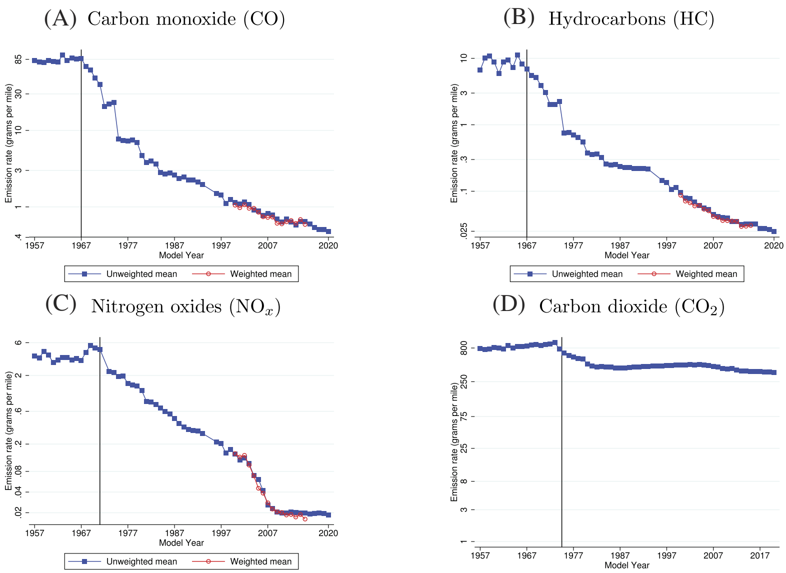


FIGURE I

Mean Pollution Emission Rates of New U.S. Vehicles, 1957–2020

The y-axes have logarithmic scales. Graphs use the full sample of new-vehicle test data and AES (1973). For Panels A–C, model years 1957–1971 are means of a sample of used vehicles given an FTP test. Model years 1972–2020 are from certification test records for 50,000 miles. Model years 1972–74 received an earlier version of the FTP test (FTP72). We concord FTP72 to FTP values, separately by pollutant, using ratios for all vehicles in AES (1973). The vertical line depicts the year before exhaust standards began. CO_2 data are sales-weighted fleet-wide averages. CO_2 data are converted from mile per gallon data, from U.S. EPA (1973) for 1957–75 and U.S. EPA (2021) for 1975–2020. We splice the two CO_2 series to have the same mean in 1975. Weights for CO, HC, and NO_x in the red lines with circles are the frequency of each vehicle in Colorado remote-sensing data.

lifetime of vehicles in a setting where emissions are rapidly declining implies that at any given moment, older vehicles are operated alongside newer, cleaner vehicles. This motivates our consideration of policies targeted to accelerate scrap in Section VII. The changes in emission rates between model years we document here underpin the quantitative model of Section VIII.

frequently; and its internal processing can be somewhat nontransparent. Kahn (1996a, 1996b) uses a cross section of smog check data to calculate decreases in emission rates of 50%–90% between the early 1970s and late 1980s, though it is difficult to separate age and model year effects in the cross section.

For context, between 1990 and 2018, ambient pollution levels (which depend on emissions from all sources) of CO, NO_2, and ozone fell by 20% to 75% (U.S. EPA 2018), suggesting that new vehicles cleaned up faster than other pollution sources. The decrease in emission rates from new vehicles is more rapid than declines in manufacturing emissions or ambient water pollution over this period (Shapiro and Walker 2018; Keiser and Shapiro 2019).

Comparing emission rates in Figure I and standards in Table I shows that emission rates fall particularly in years when policy tightens. Emission rates are flat before standards begin. Rates then decline rapidly. Figure I reflects the large decreases that standards required in 1975. The CO and HC graphs show flatter lines between 1984 and 1993, when standards were flat. Emission rates and standards were also flatter between 2007 and 2017.

Figure I also shows that CO_2 fell less than air pollution. CO_2 only fell by 55% between 1957 and 2017 and by 25% between 1990 and 2017. The changes in CO_2 rates largely occurred in the late 1970s and 2010s, when fuel economy standards tightened. Between 1982 and 2007, the CO_2 line and fuel economy standards were flat.

Used-vehicle emission rates have similar patterns, although they are available for fewer years and are subject to the challenge of disentangling model year, test year, and age effects. Online Appendix C.2 explains how we analyze Colorado smog check data. Online Appendix Figure A2 shows that mean used-vehicle emission rates for each air pollutant fell by roughly 90% between 1982 and 2010; new-vehicle emission rates from Figure I fell by similar amounts. Mean CO_2 emission rates of the used-vehicle fleet actually increased between model years 1990 and 2005, partly due to the increasing market share of light-duty trucks.

V. Effects of Exhaust Standards on Emission Rates

This section describes effects of Tier 0, 1, and 2 exhaust standards on emission rates. We use different approaches for each tier, reflecting relevant regulations and data. One goal is to understand the extent to which exhaust standards caused the trends documented in Section IV. We focus on estimates in logs, though also report estimates in levels, to facilitate comparisons across pollutants and data sets, address outliers, and help interpretation even when manufacturers overcomply with standards. Online Appendix D discusses sensitivity analyses.

V.A. *Econometrics: Effects of Exhaust Standards on Emission Rates*

1. *Tier 0*. The following equation analyzes how Tier 0 affected emission rates:

$$lnE_{pry} = \beta_1 lnS_{pry} + \eta_{pr} + \lambda_y + \epsilon_{pry}. \tag{1}$$

We analyze model years 1957–71. Each observation represents the mean emission rate of vehicles for pollutant p (CO, HC, NO_x, or CO_2), in region r (California or federal), from model year y. CO and HC faced regulation in the 1960s; NO_x and CO_2 did not. The variables E and S represent emission rates and standards. The term β_1 represents the elasticity of emission rates with respect to exhaust standards. The pollutant × region fixed effects, η_{pr}, address potential confounding from time-invariant differences between vehicles facing California's standards versus those facing federal standards, separately by pollutant. Model year fixed effects, λ_y, address time-varying emission rates common to vehicles nationally.

2. *Tier 1*. For Tier 1, we estimate the following equation:

$$lnE_{picy} = \beta_2 lnS_{picy} + X'_{picy}\pi + \mu_{pc} + \nu_{py} + \xi_{pa} + \epsilon_{picy}. \tag{2}$$

We analyze model years 1982–2000. We report separate estimates where E represents new- or used-vehicle emission rates. An observation represents a reading of pollutant p for vehicle i in model year y. The main estimates distinguish vehicle class $c \in$ *car*, *truck*, which are the most comparable measures of standards. Sensitivity analyses explore more detailed subclasses. For estimates of used-vehicle emission rates, we include controls X for age fixed effects, odometer, and other environmental policies that could affect emission rates—fuel economy, fuel content, or smog check standards. The regression includes fixed effects for pollutant × vehicle class, pollutant × model year, and pollutant × age (μ_{pc}, ν_{py}, and ξ_{pa}). The coefficient β_2 represents the elasticity of emission rates with respect to exhaust standards. We cluster standard errors by model year × truck type.

3. *Tier 2*. After model year 2000, regulations imposed fleet-wide average standards. Hence, instead of using difference-in-differences across vehicle classes, we analyze the extent to

which new-vehicle emission rates predict used-vehicle emission rates of the same vehicle:

$$(3) \qquad lnE^{u}_{picy} = \beta_3 lnE^{n}_{picy} + X^{'}_{picy}\zeta + \nu_{py} + \xi_{pa} + \epsilon_{picy}.$$

We analyze model years 2000–2010 because the concordance file linking new-vehicle engine families and used-vehicle Vehicle Identification Number prefixes begins in model year 2000 and our Colorado smog check data conclude in model year 2010. Here E^u is the used-vehicle test result of vehicle i, E^n is the new-vehicle emissions test result corresponding to used vehicle i, and c, y, and X are defined above. The coefficient β_3 represents the elasticity of used-vehicle emission rates with respect to new-vehicle emission rates. The regression includes age and model year fixed effects (μ_{pa}, ν_{py}), which vary by pollutant.

V.B. Results: Effects of Exhaust Standards on Emission Rates

We start by graphing raw trend data by class. Figure II shows the national time series of exhaust standards (Panels A, C, and E) and new-vehicle emissions (Panels B, D, and F). They cover model years 1982–2010. In each graph, the blue solid line describes cars and the dashed red line describes trucks. The vertical dashed lines show when car standards changed; the vertical solid lines show when car and truck standards changed. Each panel shows a different pollutant. Values are measured in grams of pollution emitted per mile.

Figure II reveals a close correspondence between standards and emissions, which shows that exhaust standards cause large decreases in emission rates. For example, in 1984, truck standards for CO and HC fall abruptly and emission rates do also. In 1996, when Tier 1 rolled out, standards and emissions again move in tandem. A similar pattern occurs for Tier 2 in the mid-2000s.

The main exception here is the decline in NO_x truck emissions in model years 1982–87 which Panel F shows. California gradually tightened truck standards in these years, while the EPA tightened standards only in 1987. The 1980s new-vehicle data do not distinguish California from federal vehicles, so the 1980 trend in NO_x emission rates for trucks may reflect compliance with California's standards.

These graphs also show overcompliance. New-vehicle emissions are about half of exhaust standards. The y-axis scale in Panels D–F is nearly half the scale in Panels A–C. For example,

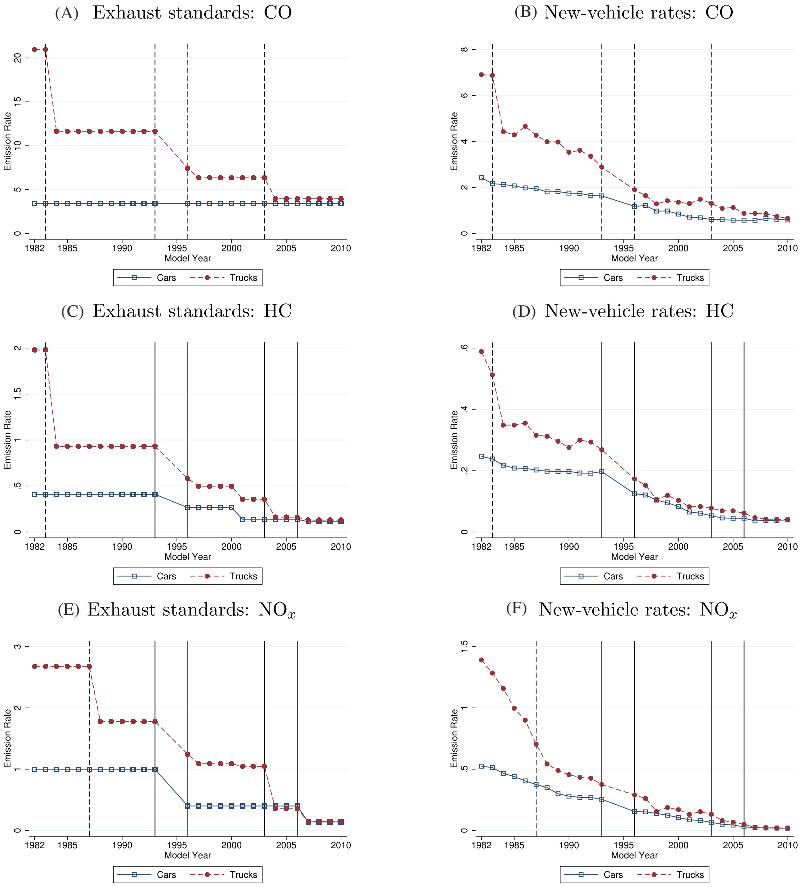


FIGURE II

Exhaust Standards and Emission Rates, Cars versus Trucks

Dashed vertical lines show years when standards change for cars only; solid vertical lines show years when standards change for both cars and trucks. Each panel uses the full sample, restricted to model years 1982–2010. Panels D–F show certification levels, equal to raw test results scaled up by deterioration factors for 50,000 miles. Online Appendix A.1 explains details. Beginning in 1988 for NO_x and 1994 for other pollutants, standards distinguish subgroups of trucks based on weight; graphs show weighted means of standards across these groups, with weights equal to the proportion of each vehicle from model year 1993 in Colorado smog check test data.

in 1990, cars and trucks faced CO standards of 10 and 4, but emission rates for these groups were around 4 and 2. As discussed in Section II.A, manufacturers overcomply because compliance is ultimately assessed against used vehicles 5 to 10 years later.

We turn to regressions focused on each Tier of exhaust standards separately.

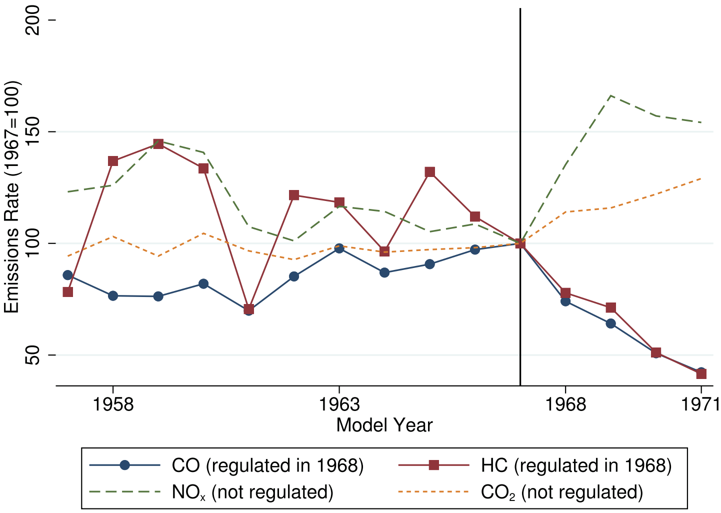
1. *Effects of Tier 0 Exhaust Standards (Model Years 1957–71).* Figure III shows annual emission rates over model years 1957–71. Panel A shows vehicles facing federal standards, and Panel B shows vehicles facing California standards. Each line shows a different pollutant. Federal standards regulated CO and HC in 1968. California standards regulated CO and HC in 1966. Standards only regulated NO_x or CO_2 in 1972 and 1978, respectively. The vertical line in each graph shows the year before regulation began.

Figure III suggests that exhaust standards decreased emission rates of regulated pollutants. Before regulation, emission rates of all pollutants were fairly flat. This is consistent with a limited effect of productivity growth on emission rates. When California's exhaust standards began in 1966, CO and HC from California vehicles fell. CO and HC emission rates from federal vehicles only decreased in 1968, when federal regulation began. The other pollutants, CO_2 and NO_x, did not fall when CO and HC standards began and slightly increased. These other pollutants may have increased because catalytic converters were not viable in the 1960s, so manufacturers responded to exhaust standards with technologies like combustion modification that can increase NO_x and CO_2 (National Research Council 1988, 2006).

Table II shows regressions corresponding to equation (1). Panel A pools pollutants. Panels B and C show one pollutant each. Column (1) is a time series estimate comparing across model years and within each pollutant and region. Columns (2) through (7) provide difference-in-differences estimates comparing across regions and model years.

Table II shows that Tier 0 exhaust standards decreased emission rates. The time series estimate in column (1) obtains an elasticity of emission rates with respect to exhaust standards of 0.61 (0.07). Our preferred elasticity estimate is 0.80 (0.08), from the difference-in-differences estimate of column (2). Other estimates in levels or restricted to California or federal vehicles are qualitatively similar (columns (3) through (6)).

(A) Vehicles outside California, model years 1957–1971



(B) Vehicles in California, model years 1957–1971

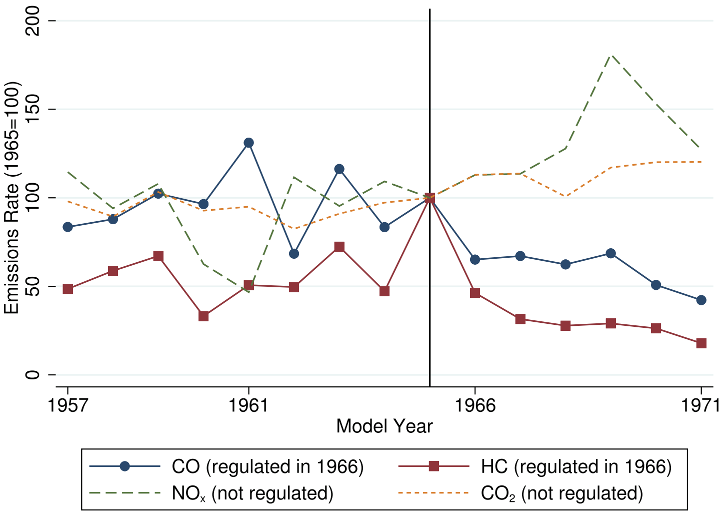


FIGURE III

Event Study Graphs for Tier 0 Exhaust Standards, 1957–1971

Graphs use the full sample from AES (1973). All emission rates are in grams per mile, scaled to equal 100 in 1967 (Panel A) or 1965 (Panel B).

TABLE II
EFFECTS OF TIER 0 EXHAUST STANDARDS ON VEHICLE EMISSIONS

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Carbon monoxide and hydrocarbons (CO and HC)							
Exhaust standard	0.61***	0.80***	0.97***	0.62***	0.90***	0.59***	0.82***
	(0.07)	(0.08)	(0.18)	(0.08)	(0.09)	(0.12)	(0.18)
N	105	105	105	60	60	45	45
Panel B: Carbon monoxide (CO)							
Exhaust standard	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 standard	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	—
Fixed effects:							
Pollutant × region	X	X	X	X	X	X	X
Model year	—	X	X	—	X	—	X
Levels	—	—	X	—	—	—	—
California only	—	—	—	X	X	—	—
Federal only	—	—	—	—	—	X	X

Notes: The dependent variable is the emission rate in grams/mile from AES (1973). Regressions are in logs except where otherwise noted. Robust standard errors are in parentheses. Before standards began, "exhaust standards" are defined to equal the unconstrained emission rate from Table 1. * $p < .10$, ** $p < .05$, *** $p < .01$.

2. *Effects of Tier 1 Exhaust Standards (Model Years 1982–2000).* Figure IV shows event study graphs analyzing the roll out of Tier 1 standards between model years 1990 and 2000. Panels A and B show the change in exhaust standards, Panels C and D show the change in new-vehicle emission rates, and Panels E and F show the change in used-vehicle emission rates. All these graphs plot differences between trucks and cars by model year, with values for 1993 normalized to zero.

Figure IV shows that Tier 1 exhaust standards decreased new- and used-vehicle emission rates. Panels A, B, E, and F show that used-vehicle emission rates and standards change by similar amounts. Panels C and D show that new-vehicle emission rates change less, consistent with initial firm overcompliance. The new-vehicle graphs show some differences between cars and trucks in model years 1990–92. This pattern does not appear for used-vehicle emission rates, which matters because used-vehicle rates are likely closer to actual on-road emissions.

Table III reports regressions corresponding to equation (2). The pooled time series estimate in column (1) compares across

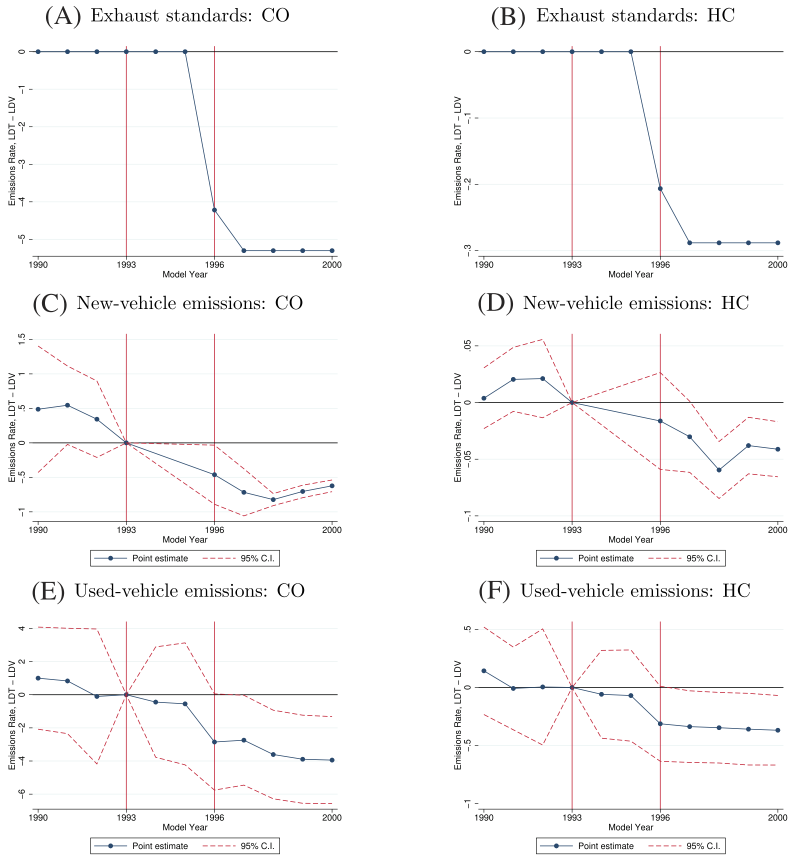


FIGURE IV

Event Study Graphs for Tier 1 Exhaust Standards, 1990–2000

Graphs use model years 1990–2000 from new-vehicle tests (Panels C and D) or Colorado smog check data (Panels E and F). Emissions are measured in grams per mile. In Panels A and B, each class × model year is weighted by its share in the 1993 Colorado smog check test data. Panels C and D show certification levels for 50,000 miles. New-vehicle emission rate data are unusable for 1994–95 (see Online Appendix B.2). The reference year is 1993. Standard errors are clustered by model year × truck type.

model years and within categories of cars and trucks. The difference-in-differences estimate in column (2) adds model year controls, so exploits changes within class and across model years. Column (3) controls for other policies—fuel economy standards, smog check standards, each vehicle's gasoline cost per mile (equal to the relevant tax-inclusive retail gasoline price divided by the vehicle's fuel economy), the ethanol fuel share, and the fuel sulfur content. Column (4) adds model year × truck linear trends. Column (5) limits the sample to vehicles aged four to six years. Column (6) restricts the sample to begin in model year 1990. Column (7) estimates the regression in levels rather than logs. Panels A through C analyze used vehicles; Panels D through F analyze new vehicles.

Table III shows that Tier 1 exhaust standards decrease used- and new-vehicle emission rates. The basic difference-in-differences estimate in column (2) is 0.86 (0.08) for used vehicles and 0.54 (0.05) for new vehicles. Controlling for other environmental policies in column (3) does not change the estimate.[17] The other specifications in columns (4) through (7) obtain broadly comparable results, though some point estimates are smaller. Most estimates are precise. Online Appendix D discusses sensitivity analyses, which obtain qualitatively similar results.

3. *Effects of Tier 2 Exhaust Standards (2000–2010).* Table IV evaluates the effects of Tier 2 standards on emission rates, using regressions corresponding to equation (3). Columns (1) through (6) repeat the specifications of Table III. Columns (7) and (8) add back the abbreviated tests.

Table IV shows that new-vehicle emission rates strongly predict used-vehicle emission rates. The pooled elasticities in Panel A are generally around 0.5. Most estimates reject elasticities of both zero and one with 99% confidence. Rejecting the null hypothesis of zero implies that new-vehicle emissions tests predict a vehicle's actual emission rate. This suggests that even if defeat devices or short-term manipulation occur, enforcement is imperfect, or abatement technologies deteriorate unexpectedly, new-vehicle emissions tests strongly predict used-vehicle emission rates.

Why are many elasticity estimates below one? Table IV, Panel E for CO_2 suggests that measurement provides an important

17. One interpretation of these estimates is that even if CAFE standards had not been implemented, tightening exhaust standards would have decreased emission rates per mile substantially. But because a vehicle's air pollution emission rates change almost one-for-one with its gasoline consumption, if exhaust standards had not been implemented, tightening CAFE standards would have decreased emissions per mile to some extent. In this sense, each policy alone would have been sufficient to decrease emission rates, though the decrease due to exhaust standards is larger and would have occurred even without CAFE standards.

TABLE III
EFFECTS OF TIER 1 EXHAUST STANDARDS ON USED- AND NEW-VEHICLE EMISSION RATES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Carbon monoxide and hydrocarbons (CO and HC), used vehicles							
Exhaust standard	2.02***	0.86***	1.01***	0.39***	1.15***	0.88***	1.34***
	(0.12)	(0.08)	(0.09)	(0.13)	(0.13)	(0.11)	(0.13)
N	17,165,695	17,165,695	16,874,083	17,165,695	3,352,360	13,379,341	17,165,695
Panel B: Carbon monoxide (CO), used vehicles							
Exhaust standard	2.03***	0.81***	0.77***	0.45***	1.02***	0.77***	1.34***
	(0.14)	(0.07)	(0.09)	(0.17)	(0.12)	(0.09)	(0.13)
N	8,568,269	8,568,269	8,422,458	8,568,269	1,670,269	6,675,107	8,568,269
Panel C: Hydrocarbons (HC), used vehicles							
Exhaust standard	2.02***	1.09***	2.20***	0.23	2.44***	1.97***	1.47***
	(0.14)	(0.22)	(0.25)	(0.22)	(0.35)	(0.33)	(0.13)
N	8,597,426	8,597,426	8,451,625	8,597,426	1,682,091	6,704,234	8,597,426
Panel D: Carbon monoxide and hydrocarbons (CO and HC), new vehicles							
Exhaust standard	1.29***	0.54***	0.52***	0.36***	—	0.35***	0.29***
	(0.10)	(0.05)	(0.06)	(0.07)	—	(0.12)	(0.01)
N	17,039	17,039	17,039	17,039	—	11,111	17,039
Panel E: Carbon monoxide (CO), new vehicles							
Exhaust standard	1.36***	0.54***	0.54***	0.33**	—	0.35***	0.29***
	(0.09)	(0.06)	(0.07)	(0.14)	—	(0.12)	(0.01)
N	8,522	8,522	8,522	8,522	—	5,557	8,522

TABLE III
CONTINUED

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel F: Hydrocarbons (HC), new vehicles							
Exhaust standard	1.25***	0.53***	0.49***	0.34***	—	0.35	0.22***
	(0.11)	(0.05)	(0.05)	(0.07)	—	(0.30)	(0.01)
N	8,517	8,517	8,517	8,517	—	5,554	8,517
Fixed effects:							
Truck × pollutant	X	X	X	X	X	X	X
Model yr. × 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. 1990–2000	—	—	—	—	—	X	—
Levels	—	—	—	—	—	—	X

Notes. The dependent variable is the emission rate in grams/mile. Independent and dependent variables are in logs except where otherwise noted. Estimates use model years 1982–2000, except for column (6). Panels A–C use the Colorado inspection data; Panels D–F use the new vehicle inspection data. Odometer includes linear and squared odometer terms. New-vehicle data in Panels D–F lacks age, odometer, and controls for other policies besides CAFE. Standard errors are clustered by model year × truck type. * $p < .10$, ** $p < .05$, *** $p < .01$.

TABLE IV

ASSESSMENT OF TIER 2 EXHAUST STANDARDS: DO NEW- PREDICT USED-VEHICLE EMISSION RATES?

	(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	0.67***	0.50***	0.49***	0.49***	0.48***	0.74***	0.21***	0.39***
	(0.01)	(0.02)	(0.02)	(0.02)	(0.02)	(0.06)	(0.01)	(0.05)
N	216,933	216,918	216,918	216,918	106,965	216,918	9,757,515	9,757,515
Panel B: Carbon monoxide (CO)								
New-vehicle emission rate	0.59***	0.58***	0.60***	0.58***	0.58***	0.76***	0.16***	0.51***
	(0.02)	(0.02)	(0.02)	(0.02)	(0.03)	(0.06)	(0.01)	(0.06)
N	72,311	72,306	72,306	72,306	35,655	72,306	3,252,505	3,252,505
Panel C: Hydrocarbons (HC)								
New-vehicle emission rate	0.81***	0.61***	0.51***	0.60***	0.49***	0.96***	0.35***	1.25***
	(0.03)	(0.03)	(0.03)	(0.03)	(0.03)	(0.08)	(0.01)	(0.06)
N	72,311	72,306	72,306	72,306	35,655	72,306	3,252,505	3,252,505
Panel D: Nitrogen oxides (NO_x)								
New-vehicle emission rate	0.67***	0.34***	0.36***	0.34***	0.33***	1.16***	0.20***	1.36***
	(0.02)	(0.03)	(0.03)	(0.03)	(0.03)	(0.10)	(0.01)	(0.09)
N	72,311	72,306	72,306	72,306	35,655	72,306	3,252,505	3,252,505
Panel E: Carbon dioxide (CO_2)								
New-vehicle emission rate	0.95***	0.87***	0.84***	0.87***	0.84***	0.79***	0.77***	0.72***
	(0.01)	(0.01)	(0.02)	(0.01)	(0.01)	(0.01)	(0.01)	(0.01)
N	72,311	72,306	72,306	72,306	35,655	72,306	3,252,505	3,252,505

TABLE IV
CONTINUED

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
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

Notes. Dependent variable is the used-vehicle emission rate in grams/mile. Regressions are in logs except where otherwise noted. Regressions use model years 1982–2000 of new-vehicle tests and Colorado smog check data. Columns (1) through (7) use the observations which completed all 240 seconds of the smog check test (Online Appendix B.3 describes details). The new-vehicle emission rate is the certification level for 50,000 miles. Estimates correspond to the specification of Table III, column (1), except where otherwise noted. Smog check standard is not defined for CO_2. Standard errors are clustered by VIN prefix. * $p < .10$, ** $p < .05$, *** $p < .01$.

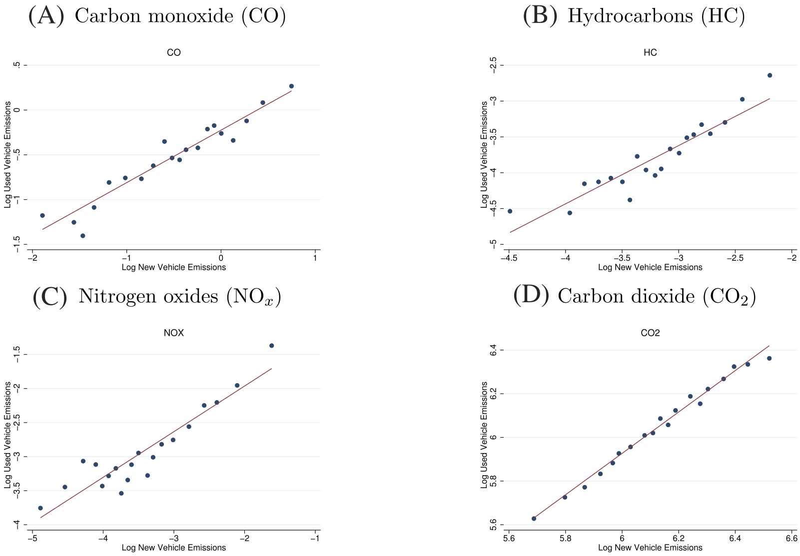


FIGURE V

Used- versus New-Vehicle Emission Rates for Tier 2 Exhaust Standards, 2000–2010

Graphs show binned scatter plots. Graphs use new-vehicle tests and Colorado smog check data. Graphs exclude a small share of observations with zero-pollution readings.

answer. A vehicle's fuel economy and associated CO_2 emission rate, unlike its air pollution emission rate, does not typically depreciate with age. Hence, the primary reason the elasticities in Panel E are below one is measurement error within and between new- and used-vehicle tests. The CO_2 elasticities in Panel E range from 0.72 to 0.95; all these estimates are significantly less than one, but most are larger than the estimates for air pollution in Panels A through D. Because air pollution emission rates depend on fuel economy and emissions control systems, measurement error may be more important for air pollution than for CO_2.

Binned scatterplot comparisons of new- and used-vehicle emission rates in Figure V show the tight relationship between new- and used-emission rates of a vehicle type. Each graph groups all new vehicles into 20 equal-sized bins, then plots the mean used-vehicle emission rate for each bin plus the linear trend. For all three air pollutants and for CO_2, the points have linear slope, suggesting a constant elasticity of used- to new-vehicle emissions.

V.C. Discussion: Effects of Exhaust Standards on Emission Rates

This section has described different approaches which find elasticities of emission rates with respect to standards generally between 0.5 and 1.0, suggesting that exhaust standards have caused between half and all of the time series decline measured in Section IV. In this sense, exhaust standards are effective.

How would regulation-induced innovation in abatement technology, discussed in Section II.B, affect interpretation of our estimates? We interpret our regressions as externally valid to exhaust standards that are not too far beyond the technology frontier. We study cases where technology developed or proved to be sufficient for compliance. Our estimates have some external validity to counterfactual delays in the standards that were implemented, because technology developed to meet these standards. Our estimates may be less externally valid for substantially more rapid tightening of standards. If standards had tightened by 99.5% in 1970, for example, the elasticity of emissions with respect to standards would likely have been lower than we estimated.

Regulation-induced innovation does not change the causal interpretation of our estimates. One reason is the evidence from Section II.A that regulation is the main incentive to clean up air pollution. Another reason comes from Tier 0. Figure III shows that when Tier 0 begins in the 1960s, California regulated CO and HC in 1966, two years before the federal government did. California vehicles decreased emission rates in 1966, but vehicles outside California only decreased emission rates in 1968. California's regulation shows that technology was available for vehicles outside California in 1966, but auto manufacturers waited to install this technology for vehicles outside California until standards required it.

A similar point across vehicle classes applies to subsequent years. Figure II, for example, shows that in 1984, CO standards tightened sharply for trucks but not cars, and emission rates fell sharply for trucks but not cars. If technology alone drove the 1984 improvements in emission rates, both cars and trucks would have installed it. The 1984 CO truck standards may have led to innovation in pollution control technology, but auto manufacturers installed it because standards required it. Finally, California had more stringent standards during the Tier 2 era, which we study using our quantitative model. For example, the California HC standard for light-duty vehicles was 25%–40%

below the federal standard, and the NO_x standard was 64%–88% lower, suggesting that tighter federal standards would have been technologically feasible.

The rest of the article builds on these results. Section VI uses the data to describe stylized facts. The analytical and quantitative models of Sections VII and VIII take from this section that exhaust standards are effective, assess their efficiency, and analyze counterfactuals.

VI. Stylized Facts on Cost-Effectiveness and Age

VI.A. Emission Rates Increase with Age

Figure VI plots mean emission rates and annual driving by model year and age. Panels A through C show air pollution, Panel D shows CO_2, and Panel E shows annual miles traveled. The *y*-axes have logarithmic scales. These visually show the extent to which deterioration of emissions control systems has changed across model years.

The upward-sloping lines in Figure VI, Panels A–C demonstrate that emission rates for vehicles from a given model year increase with age. This is unsurprising because emissions control systems deteriorate with age. The upward shift of the lines for earlier model years in Panels A through C implies that earlier model years have higher emission rates. The age-emissions profile is similar for most groups of model years, though NO_x controls may be deteriorating more gradually. The *y*-axis scale implies that these effects are proportional to age. Panel D shows that none of these patterns occur for CO_2. The downward slopes in Panel E imply that older vehicles drive fewer annual miles. This may occur because most households prefer to drive the newer of two vehicles (Archsmith et al. 2020) or because the households that own older vehicles have lower driving demand.

Several additional analyses in the Online Appendix show similar conclusions but with different contexts or methods. Online Appendix Figure A4 shows similar patterns in other states and countries and for heavy-duty trucks. Online Appendix Figure A5 shows similar patterns but from regressions including age fixed effects, odometer readings, and vehicle identification number fixed effects. It shows that a vehicle's CO_2 rates and associated fuel economy do not change with age, but a vehicle's air pollution exhaust emission rate increases rapidly with vehicle age. This

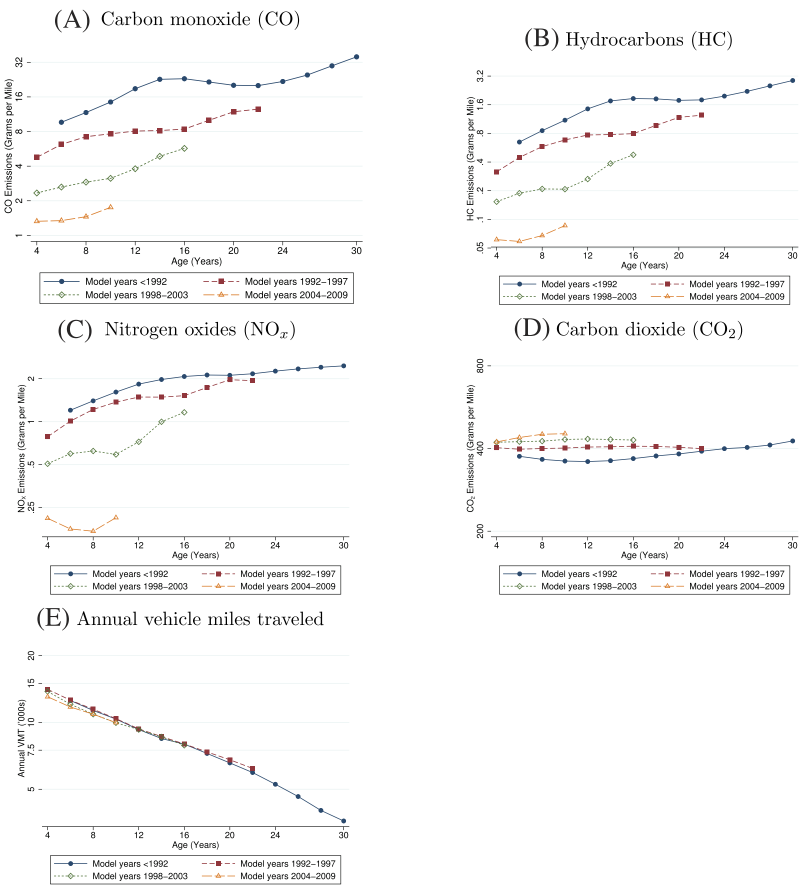


FIGURE VI

Used-Vehicle Emission Rates and Miles Traveled, by Model Year and Age

Figures use the full sample from Colorado smog check data. Points represent mean emission rates in a given model year × age cell, averaged across all vehicles in the data. The *y*-axes have logarithmic scales.

difference makes sense—as vehicles age, catalytic converters and other pollution abatement technologies break down, increasing emissions. But because end-of-pipe pollution control technologies are not commercially viable for CO_2, vehicles have no CO_2 control systems that would break down with age, so a vehicle's CO_2 emission rate does not change with age.

Does age or odometer account for these patterns? Online Appendix Figure A5 controls for odometer and finds that age independently increases deterioration. Online Appendix Table A6 shows regression analogues to these graphs, suggesting that both age and odometer readings independently increase emissions. Deterioration due to mileage occurs in part because even the low sulfur content in fuel decreases catalytic converter effectiveness. Age may independently cause deterioration because variable weather, aging seals and electronics, and failure of complementary technologies like oxygen sensors and direct injection can decrease catalyst efficiency. We focus on age since existing registration fees already depend on it. We are not aware of U.S. fees that directly depend on odometer readings; because age, unlike odometer, is not susceptible to manipulation; and because taxes that vary only with vehicle age and type simplify modeling the intensive margin of driving choice.

VI.B. Older Vehicles Account for a Large Share of Emissions

Exhaust standards limit used-vehicle emission rates through in-use testing, but in-use tests only apply to vehicles up to 10–15 years old. Exhaust standards are therefore unlikely to equalize abatement costs across vehicles of different ages, which is a necessary condition for cost-effectiveness (the equimarginal principle). Intuitively if older vehicles cause a large share of emissions, exhaust standards will be less cost-effective.

Figure VII plots the cumulative distribution of emissions versus vehicle age. The graph shows a cross section of vehicles in calendar year 2014 from Colorado smog check data. Online Appendix Figure A6 shows similar patterns from a cohort of model year 1993 vehicles and from Colorado and multistate remote-sensing data.[18] This graph shows a smaller emissions share for the old vehicles in the 1993 cohort, consistent with the idea that model year rather than aging accounts for the majority of this pattern. The vertical red lines show ages 10 and 15. Each graph shows separate curves for each pollutant.

Figure VII shows that a large share of air pollution emissions come from vehicles older than 10 to 15 years. In these data, 70%

18. We show cross-sectional data for 2014 because it is the most recent year when Colorado required smog check test of vehicles aged four and older. The Online Appendix shows cohort data from 1993 because this is the earliest model year where we observe tests of four-year-old vehicles.

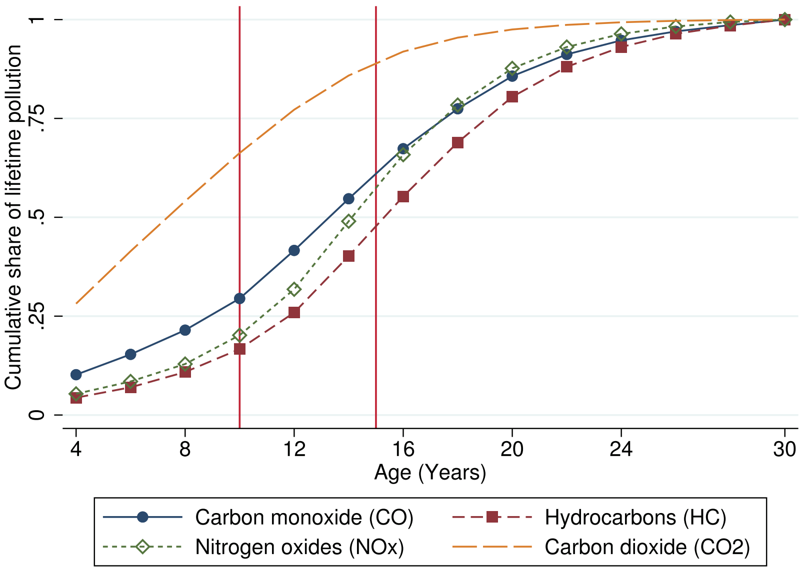


FIGURE VII

Cumulative Share of Fleet Emissions from Each Vehicle Age

Each line shows the cumulative distribution for total pollution emissions from each age. Vertical lines at ages 10 and 15 show when exhaust standards stop applying. Pollution for a vehicle equals the emission rate times miles driven. Miles equals the change in a vehicle's odometer since the previous test, divided by years since the previous test. For a vehicle's first test, decimal years equal age. Data are from 2014 Colorado inspections.

to 80% of air pollution emissions come from vehicles older than 10 years. Vehicles older than 15 years account for 30% to 50% of air pollution emission but only 10% of CO_2 emissions. Less CO_2 comes from older vehicles because fuel economy, unlike air pollution, does not change with vehicle age and because fuel economy standards have changed less than exhaust standards across model years. Although older vehicles are driven fewer miles per year and are more likely to be scrapped, their air pollution emission rates are high enough to offset the lower mileage.

Secular trends in vehicle longevity in the U.S. fleet amplify these pollution differences. Online Appendix Figure A7 shows large linear trends in the mean age of U.S. vehicles over the last half century. In 1970, the mean U.S. vehicle was 6 years old; in 2018, mean vehicle age had doubled to 12 years. This aging likely

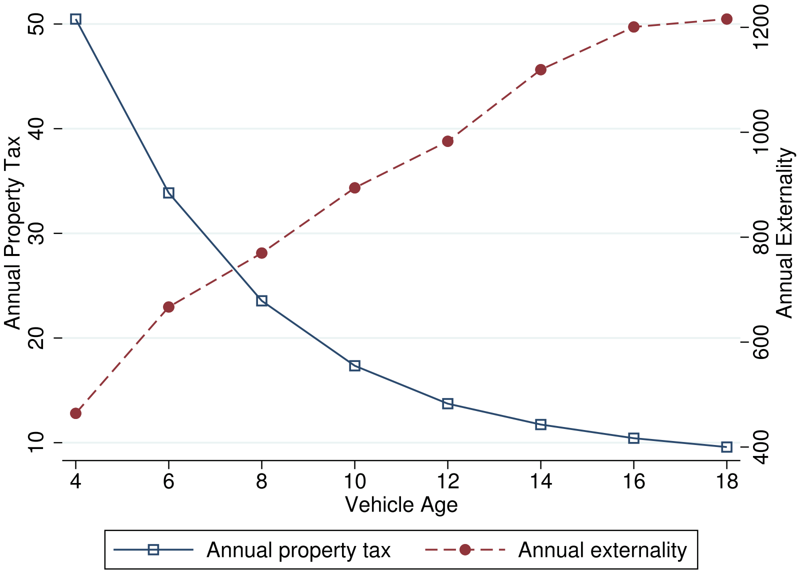


FIGURE VIII

Annual Pollution Externalities, Property Taxes, and Vehicle Age

The graph measures market shares of VIN prefixes using calendar year 2000 Colorado inspections to calculate the mean externality and tax by age. Vehicle values are from the National Automobile Dealers Association used retail prices. Currency is in 2019$. Property taxes are weighted across regions by population.

reflects both improved durability technology for automakers and increasing new-vehicle prices via the Gruenspecht effect.

VI.C. Annual Registration Fees are Higher on Cleaner Vehicles

Exhaust standards mandate clean new vehicles. They do not give consumers an incentive to scrap dirty old vehicles and do not give manufacturers an incentive to decrease pollution from aging vehicles. Annual ownership fees that increase with the pollution from a vehicle would give drivers and auto manufacturers incentives to decrease pollution.

Many states and local governments already impose annual registration fees for vehicles that vary with a vehicle's attributes. How do these existing fees vary with emissions?

Figure VIII plots the national mean annual registration fee in dollars for vehicles aged 4 to 18 years. The solid blue line shows the mean annual registration fee; the dashed red line shows the annual air pollution externality from vehicles on the road in calendar year 2000, all in 2019 dollars.

Figure VIII shows that dirtier vehicles face lower registration fees. In other words, these registration fees implicitly subsidize rather than tax emissions. Owners of 18-year-old vehicles pay $40 less in annual registration fees than the owners of 4-year-old vehicles do. But 18-year-old vehicles create about $700 more in air pollution damages than 4-year-old vehicles do. Registration fees decrease in age, while annual externalities increase in age. Modifying this incentive is a key consideration of the next two sections.

VII. Analytical Model

The previous sections show that exhaust standards decrease emission rates and that registration fees are higher on cleaner vehicles. We now develop a model with minimal parametric assumptions on the distribution of primitives to clarify how these standards and fees affect scrap and welfare.

Motivated by the trends, regressions, and stylized facts of Sections IV–VI, we focus on differences in policy and emissions between vehicles of different ages and model years. The quantitative model in Section VIII has heterogeneity within vehicle ages and transition dynamics, which we abstract from in the analytical model. These models seek to clarify mechanisms by which exhaust standards affect emissions and to address questions that the previous sections cannot, such as how different types of exhaust standards and registration fees affect social welfare.

VII.A. Analytical Model Setup

We consider a single vehicle type that can last up to two time periods t. A vehicle is initially new (n) and becomes used (u) in the next period. Driving new and used vehicles emits pollution. Manufacturing new vehicles also emits pollution. A measure one continuum of risk-neutral consumers demands vehicles. Pollution is a pure externality, so consumers ignore it in making expenditure decisions. Denote the size of the new- and used-vehicle market as N and U, respectively, where $N + U = 1$ in a period, so that there is no outside good.[19]

19. Online Appendix E.2 derives results allowing for an outside good. The key insights of the model derived here carry over to that model, with the exception

Demand reflects consumers' different taste for new versus used vehicles. We normalize the value of a used vehicle to zero and let w denote willingness to pay for a new vehicle, distributed $G(w)$, which we assume is nondegenerate and continuous with no mass points. All w are weakly positive, that is, no consumer prefers a used over a new vehicle at the same price. We assume the distribution $G(\cdot)$ is the same for all consumers and time periods and thus abstract from income effects.

New- and used-vehicle supply have different properties. New-vehicle supply comes from competitive, constant-returns manufacturing with marginal cost and thus producer price ψ^s. We write the final price to consumers of a new vehicle as $\psi = \psi^s + \tau$, where τ is any tax on new vehicles, explained below. The supply of used vehicles reflects consumer scrap, as follows. A consumer who buys a new vehicle receives a repair cost draw k from the distribution $H(k)$, which we assume is nondegenerate and continuous with no mass points. We assume this distribution is the same for all consumers and time periods. In the next period, this consumer either scraps the vehicle or resells it as used in a competitive, frictionless resale market at price p. We assume the value of scrap is zero.[20]

VII.B. *Analytical Model Equilibrium*

A competitive equilibrium is a used-vehicle price p in all time periods such that consumers choose new- versus used-vehicle purchases and scrap versus repair to maximize utility, and supply equals demand for both new and used vehicles. Utility maximization lets us describe used-vehicle supply in more detail. A consumer who purchases a new vehicle in one period will repair it in the next period if the used-vehicle price exceeds the owner's repair cost draw (i.e., if $p > k$) and will scrap it otherwise. Hence, the share of new vehicles that are repaired and survive as used vehicles equals the cumulative distribution of repair costs, evaluated at the used-vehicle price: $H(p)$. Correspondingly, the number of used vehicles supplied equals $U^s = H(p)N$. In equilibrium, $N = 1 - U$, so we can write used vehicle supply as $U^s = \frac{H(p)}{1+H(p)}$.

of one comparative static related to the size of the used-vehicle market, which is ambiguous in the case with an outside good.

20. A uniform scrap value would be capitalized into used-vehicle prices, which would shift up the price of all used vehicles in equilibrium, but this would not affect the sign of our comparative statics. Adding a scrap value would be equivalent to shifting the distribution of w by a constant, as the scrap value is folded into the normalized value of a used vehicle.

We can also describe used-vehicle demand in more detail. The value of a new vehicle to a consumer is its benefit minus its price, $w - \psi$ plus its expected resale value net of repair costs. When deciding whether to scrap or repair a vehicle, the owner receives a repair cost draw. They will repair the vehicle as long as the repair cost k is less than the used-vehicle price; otherwise the vehicle is scrapped. Anticipating this, the ex ante expected resale value net of costs is $H(p)$ (the probability that a vehicle will be repaired) times $(p - \bar{k})$, where $\bar{k}$ is the expected cost of repair, conditional on repair being optimal.[21] Thus, a consumer will buy a new vehicle at the start of the period if and only if the surplus from a new vehicle exceeds that of a used vehicle, that is, $w - \psi + H(p)(p - \bar{k}) > -p$. Equivalently, the demand for used vehicles is the probability a consumer does not buy a new vehicle, which is $U^d = G(\psi - p - H(p)(p - \bar{k}))$.

Equating supply and demand for used vehicles provides the key equilibrium condition, where p denotes the equilibrium price:

$$\frac{H(p^*)}{1 + H(p^*)} = G(\psi - p^* - H(p^*)(p^* - \bar{k})). \tag{4}$$

The left-hand side of equation (4) describes used vehicles supplied as a function of used-vehicle prices p; the right-hand side describes used vehicles demanded as a function of p. Our main results are comparative statics that describe changes in this equilibrium that result from changing primitives. Because supply $\frac{H(p)}{1+H(p)}$ is increasing in p and demand $(G(\psi - p - H(p)(p - \bar{k})))$ is decreasing in p, there will be a unique equilibrium p^*.[22]

VII.C. Analytical Model: Pollution and Policy

We assume the following about pollution, echoing empirical findings from Sections V and VI. A new vehicle creates pollution Φ from production and ϕ^n from exhaust. A used vehicle creates

21. The truncated mean $\bar{k}$ of the repair cost distribution is a function of p: $\bar{k} = \frac{1}{H(p)} \times \int_{-\infty}^{p} k dH(k)$.

22. Uniqueness follows from our assumption that the H and G distributions have no mass points, so there are no flat portions of the supply or demand curve. One exception is if the primitives imply a corner solution where all vehicles are new. This would occur, for example, if the minimum repair costs are sufficiently high. These extremes seem to have little practical interest, so we focus on interior solutions.

exhaust emissions ϕ^u. The difference in externalities between a new and a used vehicle is $\Delta \equiv \Phi + \phi^n - \phi^u$. Exhaust emissions for a used vehicle exceed exhaust emissions for a new vehicle at a given time ($\phi^u > \phi^n$), because tightening exhaust standards cleaned up new vehicles over time or because emissions control systems deteriorate. If $\Delta > 0$, a new vehicle emits more than a used vehicle, after accounting for production and retirement emissions.

We consider two policies. Exhaust standards ω constrain new-vehicle exhaust emissions: $\phi^n \leqslant \omega$. Tighter exhaust standards increase manufacturing costs, so $\psi^{s'}(\omega) \leqslant 0$.[23] Registration fees for new or used vehicles are τ_n and τ_u. Revenues are recycled lump sum to consumers. With no outside good, only the new-used difference in tax rates $\tau \equiv \tau_n - \tau_u$ is needed for our analysis. We can write the consumer's price of a new vehicle as $\psi = \psi^s(\omega) + \tau$.

Welfare in the model is private consumer welfare minus costs minus the externality. Costs include used-vehicle repair and new-vehicle production. As is standard, the potential for welfare improvement from policy comes from correcting the market choice (in this case the share of new vehicles) that prevails when agents ignore externalities. Online Appendix E.2 shows the model with an outside good, where the outside good share also influences welfare. Our baseline empirical model assumes perfect competition; Online Appendix F.9 shows results under imperfect (Bertrand) competition, where welfare also reflects profits.

VII.D. Analytical Model Results

PROPOSITION 1. A policy that increases ψ will decrease the scrap rate and increase the market share of used vehicles. The derivative of scrap with respect to new-vehicle prices is

(5)
$$\frac{d(1-H(p^*))}{d\psi} = -h(p^*)\left(\frac{1+H(p^*)}{\frac{h(p^*)}{g(w^*)(1+H(p^*))} + (1+H(p^*))^2}\right) < 0,$$

23. Because we describe a competitive equilibrium that involves a constant p^*, we focus on exhaust standards that cause a constant shift in vehicle manufacturing costs. If the industry learns over time how to reduce emissions at lower cost, then a standard is tightening over time such that the marginal cost remains constant.

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

Online Appendix E.1 shows proofs. On the left-hand side of equation (5), the numerator of the derivative is the scrap rate and the denominator is the new-vehicle price. The right-hand side of equation (5) evaluates this derivative. Proposition 1 shows that tighter exhaust standards extend vehicle lifetimes by decreasing scrap. Tighter exhaust standards—a lower ω—increase production costs ψ. The negative sign of equation (5) shows that higher production costs decrease equilibrium scrap and thus extend vehicle lifetimes. The mechanism is intuitive. Increasing new-vehicle prices causes higher demand for and thus price p^* of used vehicles. For any repair cost draw k, higher used-vehicle prices make a consumer less likely to scrap vehicles.

A simple example may clarify. Imagine a driver who crashes an old car, has it towed to a repair shop, and must decide whether to repair or scrap it. If exhaust standards are weak, vehicle production costs and used-vehicle values will be relatively low. The cost of repairing the crashed vehicle is more likely to exceed the vehicle's value, so the driver is more likely to scrap the vehicle. If exhaust standards are stringent so that production costs and used-vehicle prices are high, the driver is more likely to find that the vehicle's value exceeds the repair cost, and thus more likely to repair the vehicle, extending its lifetime.

Proposition 1 also shows that making registration fees higher for new than used vehicles, as Figure VIII shows happens on average in the United States, extends vehicle lifetimes. The same holds for any new-vehicle tax—higher relative registration fees on new vehicles are equivalent to a higher τ. The negative sign on the right-hand side of equation (5) shows that this increase in new-vehicle purchase prices decreases scrap and extends vehicle lifetimes.

The Gruenspecht effect posits that policies increasing the prices of new durable goods will extend the life of used durables, which often pollute more. We believe Proposition 1 provides the first formal derivation of it. Gruenspecht (1982) originally considered policy exempting old power plants from pollution standards imposed on new plants, but the Gruenspecht effect is cited more broadly in discussions of policies affecting power plants, vehicles, home and building construction, and other durables (Keohane, Revesz, and Stavins 1998; Stavins 2006; Bushnell and Wolfram 2012; Jacobsen and van Benthem 2015; Anderson and Sallee 2016).

Proposition 1 also implies that vehicles survive longer than is socially optimal if and only if $\tau > \Delta$. In other words, the market share of used vehicles is larger than is optimal if new vehicles are taxed more than their relative pollution damages. The reason is that if consumers internalized pollution externalities, they would perceive a price difference between new and used vehicles equal to $(\psi + \Delta) - (p - H(p)(p - \bar{k}))$. Because we abstract from outside goods here, this is equivalent to treating the new vehicle price as $\psi + \Delta$.[24] This leads to the second result.

PROPOSITION 2. Welfare in a time period is maximized when $\tau = \Delta$. If $\tau > \Delta$, then moving to τ' where $\tau > \tau' \geqslant \Delta$ will increase welfare; if $\tau < \Delta$, then moving to τ' where $\tau < \tau' \leqslant \Delta$ will increase welfare.

This result is intuitive. In this model, registration fees that differ between new and used vehicles by $\tau = (\Phi + \phi^n) - \phi^u$ can fully correct the pollution externality.[25] Welfare in a time period is improved if we move the tax rate closer to the fully corrected benchmark.

Figure VIII shows that existing registration fees are higher for newer and cleaner vehicles. Section VI shows that used vehicles have higher emission rates than new vehicles. If emissions from manufacturing new vehicles are not too large, Proposition 2 implies that flattening registration fees or changing the sign of the correlation between registration fees and age would increase welfare.

Intuitively, exhaust standards and registration fees are complementary. If a counterfactual policy makes exhaust standards tighten more rapidly across model years, the gap Δ between emissions of used and new vehicles grows, and the scrap rate deviates further from the optimum. Registration fees correcting the scrap rate then remedy a larger distortion, implying a greater return to taxing the emissions of used versus new vehicles.

24. With an outside good, the same results carry over with one exception. Raising the relative price of new vehicles induces a Gruenspecht effect in the same way. The only difference is that, while used vehicles represent a larger share of the total vehicle market (i.e., the fleet is older), the total number of used vehicles may rise or fall because the total vehicle market contracts.

25. In this model, this is the optimal fee policy for a given exhaust standard. In a more detailed setting, miles driven and maintenance could respond to policy, so registration fees would not restore the first best.

To roughly quantify how pollution rates differ by age, we divide the year 2000 fleet into two categories, new through 9 years old ("new"), and 10 years or older ("used"). Vehicles 9 years and younger accounted for 57% of the fleet and 65% of miles driven. Including estimated production emissions, the typical "new" vehicle causes \$486 of damages per year, while "used" vehicles cause \$1,364 of damages per year. The difference in damages between used and new vehicles, δ, is then \$878. These calculations are affected by age and model year because they come from a 2000 cross section of the fleet, and they take as given the mileage by model year and empirical scrap rates. Thus, despite being driven less, the typical used vehicle produces 2.8 times as much pollution as new vehicles. An efficient relative tax rate would tax used vehicles, whereas existing policy puts a relative tax on new vehicles. This binary division of the fleet hides variation in damages and taxes through a vehicle's life, which the next section explores in detail.

VIII. Quantitative Model

This quantitative model connects to the article's other sections in several ways—its analysis of cost-effectiveness and efficiency complements the regressions' analysis of effectiveness; its assumptions and choice of counterfactuals reflect empirical findings that exhaust standards are effective and that emissions rates increase with age; the Colorado smog check pollution data described in Section III provide key model inputs; and Propositions 1 and 2 help guide the discussion of counterfactuals. Some key elasticities here come from existing evidence—for example, the scrap elasticity comes from our prior work (Jacobsen and van Benthem 2015) and the pollution control cost function comes from engineering estimates (U.S. EPA 1999, 2014a).

VIII.A. Quantitative Model Details

The model setup is as follows. A representative agent serves several roles. She demands purchase of new vehicles and rental of used vehicles. She also chooses whether to scrap or repair used vehicles available from the previous time period, and therefore she serves as a competitive "supplier" of used vehicles.[26] Firms produce new vehicles and engage in Bertrand or perfect

26. We would obtain analytically equivalent results, at the cost of additional notation, from modeling a representative consumer and used-vehicle supplier as separate agents.

competition. Motivated by the differences in exhaust standards and emission rates between vehicle classes and ages found in Sections V and VI, we allow vehicles to be differentiated by over 500 combinations of class, size, age, and manufacturer. The model accounts for evolution of the vehicle fleet over time.[27]

1. *Agent Utility and Demand.* Demand for vehicles (new and used) is derived by assuming that the representative agent maximizes a constant elasticity of substitution (CES) utility function $U(v, x)$ in period t (t subscript suppressed) over a composite vehicle v and other goods x, given income M:

$$\max_{v,x} U(v, x) = (\alpha_v v^{\rho_u} + \alpha_x x^{\rho_u})^{\frac{1}{\rho_u}} - \Omega, \tag{6}$$

$$s.t. \quad e_v v + e_x x \leqslant M. \tag{7}$$

Here α_v and α_x are scale parameters that determine demand at baseline prices, and ρ_u represents the elasticity of substitution between vehicles and other goods. Pollution damages Ω are a pure externality, which the agent takes as given. The agent does not have "green preferences" leading her to buy cleaner vehicles out of environmental concern. The per period prices of the composite vehicle and the composite good are e_v and e_x.

Demand for the composite vehicle v comes from five sequential CES utility nests: vehicles versus other goods, class c, size s, age a, and manufacturer m. In a nest, demand depends on the per period cost $e_{c,s,a,m}$ of a differentiated vehicle:

$$e_{c,s,a,m} = r_{c,s,a,m} + \tau_{c,s,a,m} + \sigma_{c,s,a,m}. \tag{8}$$

This cost includes a vehicle rental rate r, which reflects depreciation and repair; vehicle registration fees τ, with revenues rebated lump sum; and fuel, insurance, and other operating costs σ. In equilibrium, rental rates, taxes and other ownership costs are capitalized in vehicle values. This is a "rental" model of vehicles, so the consumer problem can be solved in isolation each period. Beliefs about next-period vehicle prices influence rental costs r, which we discuss further when describing scrap decisions.

27. For tractability and data availability, we leave spatial modeling across U.S. counties for future research.

Optimizing this problem implies a standard CES demand system where $q^d_{c,s,a,m}$ denotes demand for each vehicle type conditional on prices. When policy changes per period costs, the agent reoptimizes vehicle quantities in each nest. Online Appendix F.3 details this derivation.

We allow miles driven to vary by vehicle class and age based on data but treat mileage within vehicle type × age as exogenous. Our counterfactual policies change the cost of owning a vehicle but not the per mile operating cost, so we expect their main effect to be on changes in fleet composition rather than miles traveled.

2. *New-Vehicle Manufacturers.* We present results for both where new-vehicle manufacturers engage in either Bertrand or perfect competition. For each class × size, manufacturer m chooses prices p, emissions ϕ, and fuel economy f to maximize profits in time period t, subject to exhaust and fuel economy standards (subscripts m, $a = 0$ suppressed):

$$\max_{p_{c,s,t},\phi_{c,s,t},f_{c,s,t}} \sum_{c,s=1,2} \Big[\big(p_{c,s,t} - C^b_{c,s} - C^{\phi}_{c,s,t}(\phi_{c,s,t}) - C^f_{c,s,t}(f_{c,s,t})\big) \times q^d_{c,s,t}(\mathbf{p},\mathbf{f})\Big] \tag{9}$$

$$C^{\phi}_{c,s,t}(\phi_{c,s,t}) = \chi^t \zeta_{c,s}\left(\frac{\phi_{c,s,0}}{\phi_{c,s,t}} - 1\right) + \xi_{c,s,t}, \tag{10}$$

$$s.t. \quad \phi_{c,s,t} \leqslant \bar{\phi}_{c,s,t}, \tag{11}$$

$$s.t. \quad \frac{\sum_s q^d_{c,s,t}(\mathbf{p},\mathbf{f})}{\sum_s \left(\frac{q^d_{c,s,t}(\mathbf{p},\mathbf{f})}{f_{c,s,t}}\right)} \geqslant \overline{f}_{c,t}, c \in 1, 2. \tag{12}$$

In the profit equation (9), $C^b_{c,s}$ represents per vehicle production cost at time period $t = 0$ with emissions and fuel economy levels as observed in the baseline, $C^{\phi}_{c,s,t}$ is the per vehicle cost of controlling exhaust emissions away from the baseline, and $C^f_{c,s,t}$ is the per vehicle cost of improving fuel economy relative to the baseline.

Demand $q^d_{c,s,t}$ depends on the vector of prices and fuel economies for all vehicles (**p, f**). Any profits are rebated lump sum to consumers. We model perfect competition using the limit as $\frac{\partial q^d_{c,s,t}(\mathbf{p},\mathbf{f})}{\partial p_{c,s,t}}$ and $\frac{\partial q^d_{c,s,t}(\mathbf{p},\mathbf{f})}{\partial f_{c,s,t}}$ go to infinity. In this case the first-order conditions in equation (9) reduce to zero-profit conditions that also satisfy the exhaust emissions and fuel economy constraints in equations (11) and (12).[28] In equilibrium, competitive new-vehicle prices translate into per period costs r and fuel economy translates into per period operating costs σ.

Equation (10) describes the cost function for controlling exhaust emissions, in 2002 and beyond, above a baseline level of control applied to vehicles in model year 2000. It builds on the general convex form in Bovenberg, Goulder, and Jacobsen (2008). Online Appendix A.3 discusses why we model pollution control as affecting marginal rather than fixed costs. The term $\chi < 1$ describes the rate of innovation in pollution control technology. The term $\zeta_{c,s}$ varies the relative control cost by vehicle class and size. The residual $\xi_{c,s,t}$ comes from the least squares calibration of χ and $\zeta_{c,s}$ to match the EPA's engineering cost estimates for Tier 2 and Tier 3 exhaust standards (Online Appendix F.6 provides details). This form and calibration has useful properties—adding no control above that in the 2000 model year adds no cost beyond that in the 2000 model year; a given level of emissions control becomes cheaper over time; marginal pollution control costs rise smoothly; it exactly matches the EPA's projected costs in a world where emissions standards are introduced at the historical rate; and it adapts engineering data from the EPA's analyses when applying arbitrary counterfactual exhaust standards. Sensitivity analyses examine alternative control costs. Motivated by the regressions in Section V and the idea that manufacturers primarily or only change exhaust rates due to standards, we assume that exhaust standards bind for all manufacturers.

Exhaust standards $\overline{\phi}$ in equation (11) cap exhaust emissions per vehicle, separately by vehicle class. We calibrate $\overline{\phi}$ to historical data, which already include any overcompliance. We assume the same overcompliance persists in counterfactuals. Fuel economy (CAFE) standards require that the harmonic average of fuel

28. Under perfect competition, vehicles are priced so $p_{c,s,t} = C^b_{c,s} + C^{\phi}_{c,s,t}(\phi_{c,s,t}) + C^f_{c,s,t}(f_{c,s,t})$ plus the shadow cost of vehicle c, s with respect to the fuel economy constraint in time t, and so $\phi_{c,s,t} \leqslant \bar{\phi}_{c,s,t}$ for each vehicle.

economies in a class $c \in$ (car, truck) must exceed $\overline{f}_{c,t}$, which is the form of CAFE relevant over most years this model analyzes. Because fuel economy standards average in a manufacturer × class, firms equalize marginal compliance costs across vehicles in each class.

3. *Vehicle Scrap Decisions.* We refer to the representative agent's capacity as a competitive supplier of used vehicles as "vehicle rental suppliers." Vehicle rental suppliers begin each period with a stock of used vehicles from the previous period and take as given rental rates $r_{a,t}$ for used vehicles (subscripts c, s, and m suppressed). At the period's start, each vehicle receives a repair cost draw $k_{a,t}$ that must be paid to survive, or the vehicle is scrapped. To generate a constant elasticity scrap decision, we assume the cumulative distribution of repair cost shocks is $H(k_{a,t}) = 1 - b_a(k_{a,t})^{\gamma_a}$, where b_a is a scale parameter (which we calibrate) and γ_a (which we take from the literature) controls the elasticity of the scrap rate with respect to vehicle value. This cumulative density corresponds to a probability density $h(k_{a,t}) = -b_a\gamma_a(k_{a,t})^{\gamma_a - 1}$ defined over the support $k_{a,t} \geqslant (\frac{1}{b_a})^{\frac{1}{\gamma_a}}$. Vehicle rental suppliers maximize current and expected rental receipts minus the cost of repairs and new-vehicle purchases.

Vehicle rental suppliers expect that rental rates follow $\mathbb{E}[r_{c,s,a,m,t+1}] = r_{c,s,a,m,t}$.[29] With these expectations, the sequence of used-vehicle resale values is (derived in Online Appendix F.4):

$$p_{a_{max},t} = r_{a_{max},t}$$
$$p_{a,t} = r_{a,t} + (1 - y_{a+1,t})\left(\frac{p_{a+1,t} - \bar{k}_{a+1,t}}{1+\delta}\right), \quad a = 1, \ldots, a_{max} - 1. \tag{13}$$

Here δ is the per period discount rate, $y_{a,t}$ is the scrap rate, and $\bar{k}_{a,t}$ is expected expenditure on repair per vehicle of a given age,

29. We do not assume rational expectations about future vehicle rental rates but we do adjust expectations based on upcoming changes in fuel economy and registration fees. This adjustment happens at a slower rate than if suppliers had fully forward-looking expectations; see Online Appendix F.7. "Surprises" are possible along transitions after a policy shock, but once the system reaches a new steady state, this form of naive expectations will, by definition of the steady state, match fully forward-looking expectations.

which follows from the repair cost density $h(k_{a,t})$:

$$\bar{k}_{a,t} \equiv \mathbb{E}(k_{a,t}|k_{a,t} < p_{a,t})$$

$$= \frac{b_a^{-\frac{1}{\gamma_a}}\gamma_a - b_a\gamma_a p_{a,t}^{1+\gamma_a}}{(1+\gamma_a)\left(1 - b_a p_{a,t}^{\gamma_a}\right)}. \tag{14}$$

Applying the used-vehicle values from equation (13), vehicle rental suppliers choose the following set of scrap rates and thus used-vehicle supply:

$$y_{a,t} = b_a(p_{a,t})^{\gamma_a}$$

$$q^s_{a,t} = q_{a-1,t-1} \times (1 - y_{a,t}). \tag{15}$$

We let γ_a vary with class and size and choose b_a to match scrap rates in the baseline data.

Vehicle rental suppliers also choose how many new vehicles to purchase. Vehicle manufacturers sell new vehicles at price $p_{0,t}$ (0 refers to age; t to the time period). Because vehicle rental suppliers earn zero expected and realized profits in steady state, they purchase new vehicles until their profits are zero; $r_{0,t}$ equals depreciation between new and one-period-old vehicles adjusted for repair and scrap:[30]

$$r_{0,t} = p_{0,t} - (1 - y_{1,t})\left(\frac{p_{1,t} - \bar{k}_{1,t}}{1+\delta}\right). \tag{16}$$

Because equation (13) shows that $p_{1,t}$ is a function of rental prices and the repair cost density, new-vehicle rental price becomes a function of new-vehicle purchase price, used-vehicle rental prices, and the repair cost density.

4. *Equilibrium and Welfare.* A competitive equilibrium of this model is a series of vectors of new-vehicle prices, used-vehicle rental rates, new-vehicle emission rates, and new-vehicle fuel

30. Along transition paths additional accounting flows need to be tracked. In particular, the supplier can experience rental flows that are greater or less than the depreciation it assigns in any given year along a transition. The timing of changes in accounting profits depends on the depreciation method the supplier uses to value its capital. Online Appendix F.9 finds that over the long run, welfare does not depend importantly on this choice; the depreciation method influences only the timing of perceived gains and losses.

economy levels ($p_{c,s,0,m,t}$, $r_{c,s,a,m,t}$, $\phi_{c,s,0,m,t}$, $f_{c,s,0,m,t}$) such that the representative agent maximizes utility equation (6) subject to the budget constraint (7); scrap decisions follow equation (15); vehicle manufacturers maximize profits as in equation (9) subject to exhaust and fuel economy standards in equations (11) and (12); and supply of each vehicle equals demand ($q^s_{c,s,a,m,t} = q^d_{c,s,a,m,t}$). New-vehicle manufacturers take pollution control in period 0 as given and treat it as a starting value. We solve for equilibrium in each time period in sequence by iteratively applying the exhaust and fuel economy constraints, and using a globally convergent quasi-Newton algorithm (Broyden's method; Online Appendix F.5 provides details).

Our general strategy here has important features in common with Barahona, Gallego, and Montero (2019), who use the same approach to specifying vehicle suppliers and rental rates. The equilibrium setting in our model differs primarily on the demand side and in that Barahona, Gallego, and Montero (2019) consider rational expectations so the full path of vehicle prices is known throughout. Our approach of solving each time period in sequence leaves future prices as expectations from the perspective of suppliers in any given time period. This is important for computational tractability in the present model given the variety of vehicle classes and brands we consider and to allow consideration of imperfect competition. As discussed in the previous subsection, the "no change" expectations we assign to vehicle suppliers converge to rational expectations over time as the fleet evolves to a new steady state.[31]

We measure the effect of counterfactual policy on social welfare from the equivalent variation of utility. Exhaust standards and registration fees affect social welfare by changing vehicle manufacturing, demand decisions, and environmental externalities.

VIII.B. Data and Parameters

This model analyzes 2 vehicle classes (car and truck), 2 sizes (small or large), 19 age categories (ages 0 to 37, grouped in two-year bins to reduce the computation), and 7 manufacturers (Ford, General Motors, Chrysler, Toyota, Honda, other Asian,

31. The steady state we have in mind is a setting where the policy changes have worked their way through the fleet, so the age profile and vehicle prices stabilize. The forecast of no change in prices becomes correct.

and European). There are thus 28 vehicle types per age and 532 (= 28 × 19) vehicle types.

We summarize data and parameters for the quantitative model here; Online Appendix F.1 and Online Appendix Table A7 provide details. We calibrate the model to leading industry data on vehicle prices and composition for the 2000 U.S. vehicle fleet and follow vehicles through 2020;[32] Online Appendix F.2 discusses how baseline model outputs compare with the data. This period lets us observe the evolution of emission rates over the following 20 years. We use our life cycle measure of the emissions from the supply chain of manufacturing a new vehicle. The model also incorporates age, class, and size-specific averages for vehicle miles traveled. We take the elasticity of the scrap rate with respect to vehicle value from Jacobsen and van Benthem (2015). We calculate the value of external damages Ω outside the equilibrium algorithm since it is additively separable.[33] We measure pollution damages from the AP3 model (Tschofen, Azevedo, and Muller 2019), which accounts for emissions from each U.S. county, atmospheric transport (i.e., wind speed and direction), functions relating ambient pollution concentrations to outcomes like mortality, and the value of a statistical life. Our baseline quantification analyzes perfect competition among new-vehicle manufacturers, though a sensitivity analysis accounts for market power.[34] We discuss sensitivity analyses varying many of these parameters.

VIII.C. Counterfactual Policies

We evaluate two classes of policy.[35] The first changes exhaust standards. Actual Tier 2 exhaust standards rolled out over the

32. We begin in the year 2000 because it lets us follow vehicle types as they age. This primarily encompasses the roll out of Tier 2 exhaust standards.

33. It is $\Omega_t = \sum_{c,s,a,m} \phi_{c,s,a,m,t}\ vmt_{c,s,a}\ \theta\ q_{c,s,a,m,t} + \sum_{c,s,m} \Phi_{c,s,m,t} q_{c,a,0,m,t}$, where $\phi_{c,s,a,m,t}$ indicates per mile exhaust emissions, $vmt_{c,s,a}$ denotes vehicle miles traveled, θ are damages per ton of emissions, and $\Phi_{c,s,m,t}$ reflects damages from emissions associated with the manufacturing of a new vehicle.

34. The baseline quantification assumes perfectly competitive manufacturers because then pollution externalities provide the only distortion, letting us focus on the welfare effects of alternative policies that are second best along a single dimension.

35. The quantitative model is flexible enough to analyze many other possible types of policies, such as a tax on vehicle miles traveled (VMT). We have chosen to save VMT taxes and other classes of counterfactuals for future work for several reasons. Focusing on counterfactual registration fees and property taxes maximizes coherence and consistency with the rest of this article. These counterfactuals change vehicle purchase prices but not per mile driving costs, which lets us focus the model accordingly. In addition, vehicle registration fees and exhaust standards are common and vary substantially across space, time, and vehicle

period 2004 through 2006, then applied through model year 2016. Data from Section V indicate that annual damages from new vehicles decreased by 77% during the roll out of Tier 2 standards. We consider counterfactual policies that delay or accelerate these improvements by four or eight years. We also consider a uniform tightening of exhaust standards by 10%. We implement these counterfactuals by changing exhaust standards $\overline{\phi}_{c,s,t}$.

We choose these exhaust standard counterfactuals for several reasons. Tier 2 is the main set of exhaust standards that changed over the years 2000–2020, where we have best data coverage. Studying acceleration or delay of these standards lets us measure the annual value of Tier 2. Policy makers also frequently debate the timing of important environmental policies. Studying a 10% change in exhaust standards helps us think about broad general changes in exhaust standards. We analyze four- and eight-year delays and accelerations for a few reasons—four years is the gap between the beginning of the Tier 2 rollout and our baseline period (2004 versus 2000); comparing four versus eight years lets us examine doubling the duration of delay; and four and eight years correspond to presidential-term durations, which are relevant since standards are federally chosen and enforced.

One could think of accelerating Tier 2 as encouraging earlier adoption of abatement technologies in a scenario where they were available. Some evidence suggests this scenario is plausible. Increasing catalyst mass (precious metals—palladium, platinum, and rhodium) is available in any year at additional cost and represents a large component of abatement costs (U.S. EPA 2014a). Online Appendix Table A8 shows that 70%–90% of new vehicles met Tier 2 standards four years early, and 50% met Tier 2 standards eight years early. The share emitting less than half of Tier 2 standards early (i.e., that overcomplied) was lower. Pinning down the precise technological feasibility of implementing standards four to eight years early is beyond the scope of this article, but we believe these counterfactuals are realistic enough to be relevant.

The second class of counterfactuals covers four possible changes to annual registration fees. The first adds fees equal to the annual pollution damages of each age × vehicle type. The second scales these fees to be revenue neutral. The third imposes fees on new vehicles only, reflecting lifetime environmental damages.

type/attributes, which suggests that reforms of these policies in the direction of an externality-based fee system may be politically feasible.

The fourth makes registration fees flat. We implement these counterfactuals by changing registration fees τ in equation (8). These counterfactuals hold the path of exhaust standards fixed at their actual, historical value, and recycle registration fee revenue to the representative agent. Welfare gains mirror those in Proposition 2 in the analytical model.

We study these registration fee counterfactuals for several reasons. Our empirical results show strong age deterioration, so we focus on a policy targeting vehicle age. State and local governments charge registration fees that vary with vehicle attributes. The technical, and perhaps political, ability to consider such policies makes reforms in the direction of externality-based fees interesting and plausible. A full damage-based type × age fee is the natural baseline to evaluate even if states are more likely to implement partial versions. Adding revenue neutrality to the fee system may further improve political feasibility. Finally, many existing policies target new vehicles, so restricting fees to those vehicles may be politically feasible.

VIII.D. Results

Table V shows how counterfactual policies affect several outcomes. Column (1) describes market surplus, equal to consumer surplus under perfect competition. Column (2) shows the change in pollution damages. Column (3) shows the change in social welfare, and column (4) shows the change in tax revenues, all in cumulative billions of 2019 dollars. Columns (5) through (7) show the percent change in cumulative pollution emissions over the same 20-year horizon, relative to baseline. Each row considers one counterfactual. Panel A examines changes in exhaust standards and Panel B examines changes in registration fees.

1. *Counterfactual Exhaust Standards.* Table V, row 1, shows that delaying implementation of Tier 2 exhaust standards by four years decreases social welfare by \$107 billion, or \$27 billion a year. Delaying standards slightly increases market surplus and massively increases pollution damages. A four-year delay in Tier 2 increases total pollution emissions by 5%–10%. Exhaust standards generate no tax revenue. Row 2 shows slightly smaller per year effects for an eight-year delay in Tier 2. Columns (5) through (7) show that an eight-year delay produces nearly double the total pollution increase as a four-year delay. Rows 3 and 4

TABLE V

MODEL-BASED ESTIMATES: EFFECTS OF COUNTERFACTUAL EXHAUST STANDARDS AND REGISTRATION FEES

	Change in market surplus	Change in pollution damages	Total change in social welfare	New tax revenue	Percent change in cumulative emissions		
			= (1) − (2)		CO	HC	NO_x
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
Panel A: Counterfactual Exhaust Standards							
1. Delay Tier 2 by four years	8.2	115.3	−107.2	0.0	8.1	4.6	10.3
2. Delay Tier 2 by eight years	13.3	198.2	−184.9	0.0	15.8	8.1	17.8
3. Accelerate Tier 2 by four years	−9.9	−122.8	112.9	0.0	−6.3	−4.7	−10.8
4. Accelerate Tier 2 by eight years	−20.7	−195.2	174.5	0.0	−9.7	−7.5	−17.1
5. Tighten standards 10%	−2.3	−27.0	24.7	0.0	−1.4	−1.0	−2.4
Panel B: Counterfactual Registration Fees							
6. Age × type fee	−170.6	−492.5	321.9	1,167.5	−42.3	−42.7	−24.6
7. Age × type fee, revenue neutral	−113.9	−343.7	229.7	0.0	−33.2	−33.5	−15.7
8. New vehicle fee	−16.5	3.2	−19.7	399.6	1.7	1.8	−0.3
9. Flat registration fee	−3.2	−20.7	17.5	0.0	−1.9	−1.9	−1.1

Notes. Policies start in calendar year 2000 and effects are calculated over 20 years. Values in columns (1) through (4) are in billions of 2019$. Values in columns (5) through (7) are percent changes. Social welfare is defined as consumer + producer surplus – pollution damages, which equals welfare for a social-welfare function that abstracts from distribution. As we assume perfect competition among vehicle manufacturers, market surplus equals consumer surplus. The main text describes each counterfactual policy.

show that accelerating Tier 2 by four or eight years increases social welfare by \$113 billion or \$175 billion in present value. While accelerating Tier 2 decreases surplus in the vehicle market somewhat, it decreases pollution damages by far more. Row 5 describes a more modest 10% improvement in standards relative to the baseline. This increases welfare by \$25 billion over 20 years.

We do not observe a monotone relationship between the duration of delay and the per year consequences of delay. In column (1) of Table V, for example, an eight-year delay causes moderately less than double the impact on market surplus of a four-year delay; but an eight-year acceleration causes moderately more than double the impact on market surplus of a four-year acceleration. In general, the per year effect of different duration of delay or acceleration depends on the baseline time profile of pollution and market outcomes. It also depends on how discounting affects the present value of reforms in different years. For example, due to discounting, a reform with a certain impact on nominal surplus 10 years in the future will have smaller present value than a reform with identical effect on nominal surplus 5 years in the future.

Several benchmarks suggest these magnitudes are economically important. If the benefits of Tier 2 were measured against a value of a statistical life of \$10 million, they would represent around 2,700 fewer deaths per year. This is an appropriate benchmark because almost all the monetized benefits of decreasing NO_x and VOC emissions are due to avoided premature mortality (Tschofen, Azevedo, and Muller 2019). Another benchmark is other recent environmental policies. An important cap-and-trade market for industrial NO_x implemented over this period, the NO_x Budget Program (NBP), prevented an estimated 2,000 premature deaths per year (Deschenes, Greenstone, and Shapiro 2018). Thus, Tier 2 exhaust standards create about 35 percent larger annual health benefits due to avoided premature mortality than this prominent cap-and-trade market. Comparing columns (1) and (2) of Table V suggests Tier 2 has a benefit/cost ratio of ten to fifteen; this ratio is in line with those of other recent federal air quality regulations (Keiser, Kling, and Shapiro 2019). If one took the pollution changes documented for Tier 0 and Tier 1 in Section V and extrapolated the types of numbers estimated here for Tier 2, they would likely imply welfare gains from Tier 0 and Tier 1 exhaust standards in the trillions of dollars.

2. *Counterfactual Registration Fees.* We also consider counterfactuals that vary registration fees. Table V, row 6, shows that making registration fees proportional to environmental damages produces a present-value social welfare gain of $322 billion and produces $1.2 trillion in additional revenue over 20 years, or $60 billion annually. These counterfactual registration fees have double the welfare gains from accelerating counterfactual Tier 2 exhaust standards. The environmental registration fees decrease cumulative vehicle emissions by one-third.

This reform heavily taxes the oldest vehicles. Figure IX, Panel A, shows the fee that this counterfactual imposes for vehicles of each age. These graphs average across vehicle types within an age. The fee for zero-year-old vehicles reflects both exhaust emissions and air pollution damages from vehicle manufacturing. Vehicles more than 20 years old face an annual registration fee of over $2,000, which exceeds the resale value of these vehicles.[36]

The solid line in Figure IX, Panel B, shows that this policy leads households to scrap one-third of 15-year-old vehicles, half of 20-year-old vehicles, and 90% of 25-year-old vehicles. This is an extraordinary change in the fleet of older vehicles. Put another way, most vehicles aged over 25 and older here have environmental damages exceeding their annual ownership cost. The dashed line in Panel B shows the environmental gains due to vehicles of each age, which has a hump shape that peaks at vehicles of age 24. Younger vehicles have lower emissions rates. Vehicles age 25 and older pollute more per mile, but there are few such vehicles in the baseline and they are driven few miles per year.

Table V, row 7 shows a revenue-neutral version of the age × vehicle type registration fee, which taxes dirty vehicles and subsidizes clean vehicles (a "feebate"). It increases welfare somewhat less, about $230 billion, because it produces composition changes but not a downsizing of the entire fleet, as vehicles remain

36. Such reforms might affect unregistered driving, though we conjecture that such effects would be modest. The only estimate of unregistered driving rates we could find describes California (U.S. Bureau of Transportation Statistics 2011). Only 1% of all vehicles were unregistered more than three months after the registration deadline, and practically none (0.03%) after more than two years. For comparison, estimates suggest that over 10% of U.S. drivers are uninsured; thus, most uninsured drivers' vehicles are registered. While unregistered driving may increase in response to higher registration fees, regulators can also increase enforcement of vehicle registration requirements, which only requires observing a vehicle's license plate.

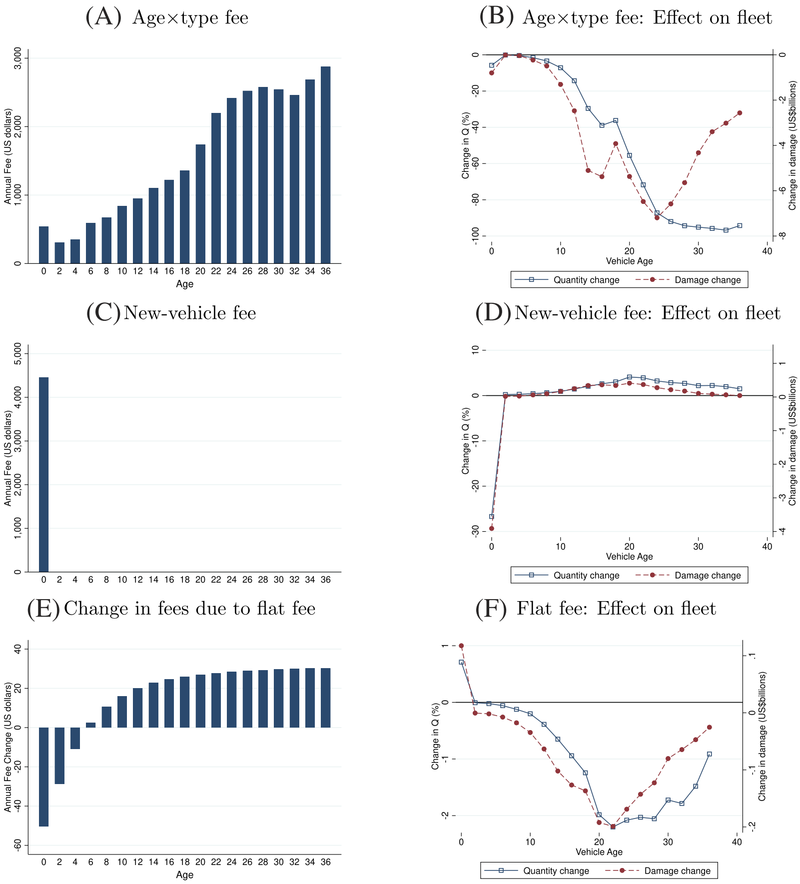


FIGURE IX

Model-Based Estimates: Levels of Counterfactual Registration Fees and Effects on Fleet Composition and Pollution Damages

Panels B, D, and F show the model-based estimates of the effect of counterfactual policies on the calendar year 2000 fleet and environmental damages. Currency values are in 2019$, deflated using the Consumer Price Index for urban consumers.

underpriced on average. Rows 6 and 7 shed light on the role of composition versus scale effects. Roughly, the revenue-neutral fee system creates welfare gains through improved composition. The externality tax improves composition and also reduces the scale of the market in line with the externality.

Table V, row 8, shows that charging registration fees for new vehicles only, with the fee equal to lifetime external damages from the vehicle, modestly decrease social welfare, by $20 billion in present value. This perverse result reflects the power of the Gruenspecht effect highlighted in Proposition 1. Although these fees encourage new vehicle buyers to choose cleaner vehicles, they also increase the price of all vehicles, which decreases scrap and keeps dirty used vehicles on the road longer. This phenomenon also underscores why the difference-in-differences regressions of Section V imply a mixed review of exhaust standards. While Section V shows exhaust standards decrease emission rates, this model quantification implies exhaust standards also extend the lifetime of dirtier used vehicles.

Figure IX shows this example of the Gruenspecht effect in action. Panel C shows that the average new vehicle has lifetime pollution damages of about $4,500, though new-vehicle registration fees in this counterfactual vary by vehicle type, and this graph shows the average across types. Charging that externality only to new vehicles decreases purchase of new vehicles, by over 25%.[37] Panel D shows that the number of surviving used vehicles increases, especially vehicles 15–30 years old. The new-vehicle fee substantially extends used-vehicle lifetimes, for precisely the dirtiest vehicles.

Table V, row 9, shows the effect of changing current registration fees to be identical for all vehicle ages and types. Figure IX, Panel E, shows that this counterfactual decreases registration fees by up to $50 for vehicles younger than five years old and increases them by up to $30 for older vehicles. This reform increases social welfare by $18 billion in present value and decreases pollution emissions by around 2%. The smaller effect for this counterfactual versus the externality-based fee in rows 6 and 7 reflects the idea that the inefficiency of current registration fees is less due to an implicit subsidy to pollution (which row 9 remedies) and more due to the failure to price externalities (which rows 5 and 6 address).

Online Appendix F.9 discusses variations in parameters, data, and assumptions about market power, which produce qualitatively similar results. It also describes how spatially varying emissions rates boost the benefit-cost ratio of age-based

37. This relatively elastic response in the first year of policy diminishes in later years as used vintages become in shorter supply.

fees in MSAs, and that bans on vehicles become cost-effective at age 14 in MSAs but only at age 26 in non-MSA areas.

VIII.E. Inequality, Environmental Justice, and Political Economy

This analysis provides a menu describing the consequences of different policies' effects on pollution, surplus, and social welfare. A full analysis should also consider these policies' effects on different socioeconomic groups. Incidence is important directly and for assessing political feasibility. Concern about an equal distribution of environmental quality is a top priority in some jurisdictions.

The counterfactuals we study affect inequality through several channels. Lower-income households tend to own older and more polluting vehicles, so increasing registration fees on dirtier used vehicles could have regressive initial incidence. Online Appendix Figure A11, Panel A uses data from the National Highway Travel Survey (U.S. Federal Highway Administration 2001) to show that vehicle owners with household income below \$10,000 have a mean vehicle age close to 12 years, whereas owners with income above \$80,000 have a mean vehicle age of 7 years. Similarly, Panel B shows that vehicle owners with less than a high school degree have a mean vehicle age of 10.5 years, whereas owners with a graduate degree have a mean vehicle age of 7 years. Panel C displays the distribution of vehicle ages for high and low incomes in more detail.

Online Appendix Table A9 shows the change in discounted annualized fees paid across the income distribution for our various policy counterfactuals, accounting for scrap of the oldest vehicles.[38] Under age $\times$ type vehicle registration fees, fees go up somewhat more for higher-income households—they own newer cars so the per car fee is less, but they own more cars in total. Overall, however, this fee system is still regressive in that lower-income households pay more as a fraction of income. A revenue-neutral age $\times$ type fee system that returns revenues on a per vehicle basis becomes even more regressive, again because higher-income households own more cars. New-vehicle fees, in contrast, place much of the burden on wealthier groups but, as shown in Table V, fail to produce pollution improvements.

38. Our main simulation uses a representative consumer. To account for differential scrap rates by income group, we augment the model. Details are provided in Online Appendix F.8.

Several other factors determine the full incidence of emissions policies. First, reforming registration fees and exhaust standards affects the resale value of used vehicles. Making registration fees more proportional to pollution will decrease the value of older polluting vehicles that lower-income households disproportionately own. In the longer run, the lower rental or ownership costs of older and dirtier vehicles will offset some of the effect of changed registration fees.

Second, as shown in Table V, registration fees raise substantial revenue. Overall incidence depends on how those revenues are redistributed. Registration fees proportional to environmental damages generate $60 billion in annual revenues. Dispersing revenue equally to each household or through the income tax system could produce progressive outcomes. This is not relevant for the revenue-neutral registration fees or exhaust standards.

Third, the health effects of vehicle pollution reduction may disproportionately benefit low-income households. Similar patterns occur with other corrective taxes (Allcott, Lockwood, and Taubinsky 2019). Older and dirtier vehicles are disproportionately owned by households that reside in low-income communities. If these vehicles are disproportionately driven near those communities or pollute them, increasing registration fees on dirty used vehicles could create outsize environmental benefits to those communities. Transportation is a leading source of pollution in vulnerable communities, some of which border major roads (Stuart, Mudhasakul, and Sriwatanapongse 2009; Rowangould 2013; Carlson 2018; Apte et al. 2019). Quantifying where vehicles are driven, separately by demographic of owner and vehicle attribute, is a complex task we leave for future research. The net effect of the regressive fee channel and the possibly progressive pollution channel is ambiguous and may vary with the specific counterfactual.

One other effect on political feasibility is worth noting. The registration fee policies we analyze increase the cost of owning used vehicles, which can increase new vehicle demand. Hence, auto manufacturers, a powerful interest group, may support such reforms, particularly if they are revenue neutral. At the same time, exhaust standards increase new-vehicle prices and encourage substitution to used vehicles and may be expected to receive less support from auto manufacturers.

What is the broad political feasibility of reforming vehicle registration fees? Only some states impose registration fees that vary with vehicle value or age. The pattern of these states does not obviously reflect geography or politics. Although it is hard to generalize globally, Japan does have a national "shaken" registration fee that increases with vehicle age. In general, we believe that mass increases to registration fees are politically sensitive, but moderate reforms to fee patterns, particularly revenue-neutral reforms, have political feasibility in some areas. Our goal is related to that of the optimal taxation literature—to identify the efficiency and equity of potential reforms, while recognizing that the political feasibility of these reforms varies.

IX. Conclusions

Vehicle air pollution exhaust standards are arguably among the world's most important environmental policies, particularly for transportation. They have been the subject of limited economics research. This contrasts with fuel economy standards, a separate set of regulations that economics research has studied carefully. It likewise contrasts with the influential research on the U.S. Clean Air Act's regulation of industry.

This article examines U.S. exhaust standards over the last half century. We first document vast declines of over 99% in air pollution emissions per mile from new U.S. vehicles since exhaust standards began in the 1960s. Panel data regressions using various time periods, data sets, and research designs find that exhaust standards have caused most of that downward emissions trend. Several stylized facts, however, suggest that these standards are not cost-effective because they do not tightly regulate emissions from older vehicles. In addition, registration fees and property taxes are lower on older and dirtier used vehicles. An analytical model highlights the Gruenspecht effect, which policy debates have informally mentioned for decades but has not been rigorously derived before—environmental standards and other policies raising the price of new, clean capital counterproductively extend the lifetime of used, dirty capital. The analytical model also suggests potential efficiency gains from increasing registration fees on old dirty vehicles. A quantitative model finds present-value net benefits in the hundreds of billions of dollars from setting annual registration fees equal to the pollution damages of a vehicle age $\times$ type. Using externality-based registration fees appears to have larger benefits than further tightening standards, although both produce substantial gains. In sum, we conclude that vehicle exhaust standards have been remarkably effective, but they have left room for improvement in cost-effectiveness, and feasible policy reforms can thus generate large welfare gains.

Given the enormous decreases in pollution from passenger transportation that this study documents, do additional reforms have economically important magnitudes? Although pollution used to be an even worse problem, the 37,000 annual U.S. deaths mentioned at the beginning highlight that pollution is still costly.

We conclude with several areas which we believe are important for future work. First, how important are issues in this article for ongoing fleet composition trends? Although electric vehicles represent less than 1% of the U.S. fleet today, industry forecasts suggest they may constitute half the fleet in 2050 (Cage 2022). Thus, while the transition to electric vehicles will require most of the twenty-first century, policy makers in regions with a clean electric grid will face a trade-off between clean new electric vehicles and polluting older gasoline vehicles. The question of how policy should deal with legacy pollution at that stage will mirror the questions we analyze here. Anticipating that transition may inform policy for electric vehicles today. In addition, this articles shows steady downward trends in emission rates even for gasoline vehicles. While we quantify effects of varying past policy reforms, what are potential welfare gains from current or future additional reforms? Continuing deterioration of emissions control systems with age suggests that in the future when vehicles are cleaner, older used gasoline vehicles may continue emitting the majority of pollution. Such analysis would require projection or imputation of many of the data used in the quantitative model, but are relevant to future policy.

Second, to what extent should the kinds of policies we study differ across space? Driving in exurbs, suburbs, and city centers creates different levels of externalities, including congestion and pollution damages. Many European cities have addressed these issues with low-emission zones that restrict driving to relatively clean vehicles. Online Appendix F.9 highlights these policies in a simple framework, but studying such questions in more detail requires models emphasizing spatial differentiation.

Third, what are the magnitude, environmental, and welfare consequences of "leakage" due to policies encouraging scrap of polluting old vehicles? For example, suppose the United States implemented some reforms we analyze; how would these reforms affect exports of old U.S. vehicles to Mexico, and how would such exports affect welfare in both countries? If Mexico implemented such reforms, one could ask a similar question for Mexico's used-vehicle exports to Central America. Davis and Kahn (2010) study these questions for NAFTA and California's smog check policies but one could ask similar questions for exhaust standards and registration fees in broader settings.

Finally, how externally valid are our findings to other types of environmental policy? For example, we find that pollution emission rates have declined precipitously and that environmental policy is the leading cause. Aspects of those findings also appear to apply to electricity generation, industrial air pollution, and municipal water pollution (Shapiro 2022). The Gruenspecht Effect is relevant for drinking-water treatment, coal-fired electricity generation, and industrial water pollution regulation (Stavins 2006). Our quantitative model finds that while tightening pollution standards can produce welfare gains, revising tax instruments to reflect environmental damages can produce larger welfare gains; this broad conclusion of the relative efficiency of taxes over standards is a common theme in environmental economics.

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Supplementary Material

An Online Appendix for this article can be found at *The Quarterly Journal of Economics* online.

Data Availability

The data underlying this article are available in the Harvard Dataverse, https://doi.org/10.7910/DVN/MISSZQ (Jacobsen et al. 2023).

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