Economics Bulletin

Volume 38, Issue 4

Evaluating the efficacy of regulatory and technological innovation on carbon dioxide emissions: An application of structural break analysis

Jennifer Hafer
University of Wisconsin

Logan Kelly
University of Wisconsin

Marina Onken
University of Wisconsin

Abstract

Starting as early as the 1950s, regulatory and technological innovations have played a co-causal role in the measurement and control of air pollution. "Technology-forcing" regulations, particularly early regulation in California, pushed the automobile industry to develop technology to mitigate carbon dioxide emissions, but as technology to measure carbon dioxide emissions was developed, more and better regulation was adopted. While the role of regulation in the development of new technology remains a topic of continued political debate, our analysis strongly supports the proposition that regulatory innovation played a significant role in the curtailment of carbon dioxide emissions since 1960.

The authors would like to thank the anonymous reviewers for their valuable and constructive comments.
Citation: Jennifer Hafer and Logan Kelly and Marina Onken, (2018) "Evaluating the efficacy of regulatory and technological innovation on carbon dioxide emissions: An application of structural break analysis", *Economics Bulletin*, Volume 38, Issue 4, pages 2399-2409
Contact: Jennifer Hafer - jennifer.hafer@uwrf.edu, Logan Kelly - lkelly@kellyecon.net, Marina Onken - marina.onken@uwrf.edu.
Submitted: July 21, 2018. **Published:** December 13, 2018.

1 Introduction

Starting as early as the 1950s, regulatory and technological innovations have played a co-causal role in the measurement and control of air pollution. California's early recognition of pollution and smog led to the adoption of automobile emissions regulation (see e.g. Willens 1970) and created a need for technological innovation. As a result, technology to measure CO_2 was developed, more and better regulation was adopted at the national level and by other states, and emissions technology, such as catalytic converters and fuel injected engines, became widely available. Technology was developed in conjunction with and even before regulations were enacted (J. Lee et al. 2010). After California led the way, the United States passed several regulations to create air quality standards and to reduce emissions in the 1960s. The passing of the 1970 Clean Air Act, however, was the most significant federal regulation (Gil-Alana and Solarin 2018) and it meant that the automobile manufacturing industry needed to rapidly innovate to meet the "technology forcing" regulations and lower emissions to meet air quality standards.

This paper examines the impact of regulatory and technological innovation on CO_2 emissions in the US. After a steep increase in CO_2 emissions per capita (hereafter referred to as CO_2) in the 1950s through the early 1970s (peaking in 1973), CO_2 decreased in the late 1970s and remains stable through the 1980s and 1990s. We use a Bai-Perron type structural break test (See e.g. Bai and Perron 2006, 2003b, 2003a, 1998) to detect innovations affecting CO_2.[1]

2 Data and Methodology

Data. Our sample is annual data spanning from 1960 -2016. CO_2 is metric tons of carbon dioxide per capita obtained from two sources: the World Bank for the period of 1960-1972 and the U.S. Energy Information Administration (EIA) for 1973-2016. GDPGAP is the log difference between Real GDP and Potential Real GDP multiplied by 100. OILPRICE is the log of the West Texas Intermediate Spot Crude oil price.

Methodology. We make use of a simple model of CO_2,

$$CO_2 = \beta_0 + \beta_1 \bullet Trend + \delta_0 \bullet \text{GDPGAP} + \delta_1 \bullet \text{D}\left(OILPRICE\right) , \qquad (1)$$

where $D\left(OILPRICE\right)$ is the first difference in log oil price and $Trend$ is a deterministic trend. The inclusion of a deterministic trend is consistent with the empirical findings of Lee and Chang (2009). We then utilize the Bai-Perron double maximum test for multiple unknown breakpoints to determine the existence of breakpoints in β_0 and β_1 to determine if an omitted factor, possibly a policy innovation, may be influencing the CO_2. Next utilize the Bai-Perron tests of *L+1* vs. *L*

---

[1] For a discussion of innovation, see, e.g. Gopalakrishnan and Damanpour (1997).

globally determined breaks to find the number and the timing of structural breakpoints (Bai and Perron 2003a, 1998).[2] Finally, we compare the timing of these breakpoints to historical events and policy innovations.

The analysis in this paper differs from prior work in that it accounts for economic conditions as well as unknow omitted variable. See, e.g., Lee and Chang (2009), who employ a Bai-Perron structural break test to account for omitted factors, but they do not make explicit account of business cycle or oil price. See also Casler and Rose (1998) and Schmalensee, Stocker, and Judson (1998), who account for economic growth but not structural breaks.

3 Structural Break Analysis

Following Bai and Peron (1998, 2003a), we estimate

$$y_t = x_t'\beta_j + z_t'\delta + u_t \quad t = T_{j-1}+1,\ldots,T_j \quad j = 1,\ldots,m+1 \tag{2}$$

where x is a vector of independent variables whose coefficients, β, are allowed to break and z x is a vector of independent variables whose coefficients, δ, are held fixed over the entire sample. We use the Bai-Perron tests of *L+1* vs. *L* globally determined breaks for up to five breakpoints. Table 1 reports the results of the structural break tests. We find three break points at 1970, 1981 and 2005. Figure 1 plots emissions of CO_2 per capita with breakpoints overlaid.

---

[2] Note that Bai and Perron (2003b) provide critical values for this multiple structural break test. For a detailed treatment of structural break testing, see Perron (2006).

Table 1: Double maximum structural break analysis of the CO_2 model

Bai-Perron tests of 1 to M globally determined breaks

Number of Breaks	*F-statistic*	*Scaled F-statistic*	*Weighted F-statistic*	*Critical Value*
1 *	9283.7	18567.41	18567.41	11.47
2 *	122.71	245.41	288.71	9.75
3 *	787	1573.99	2159.53	8.36
4 *	247.2	494.39	788.69	7.19
5 *	182.86	365.72	717.05	5.85

Unweighted max F-stat *	1744.79	critical value**	11.70	No. of Breaks	1
Weighted max F-stat *	2393.87	critical value**	12.81	No. of Breaks	1

Bai-Perron tests of L+1 vs. L globally determined breaks

Break Test	*F-statistic*	*Scaled F-statistic*	*Critical Value*
0 vs. 1 *	9283.70	18567.41	11.47
1 vs. 2 *	81.51	163.03	12.95
2 vs. 3 *	**20.33**	**40.66**	**14.03**
3 vs. 4	2.15	4.30	14.85
4 vs. 5	0.65	1.29	15.29

Estimated break dates:

1: 1970
2: 1970, 2001
3: 1970, 1981, 2005
4: 1970, 1978, 1987, 2005
5: 1970, 1980, 1988, 1996, 2005

* Significant at the 0.05 level.

** Bai and Peron (2003b) critical values.

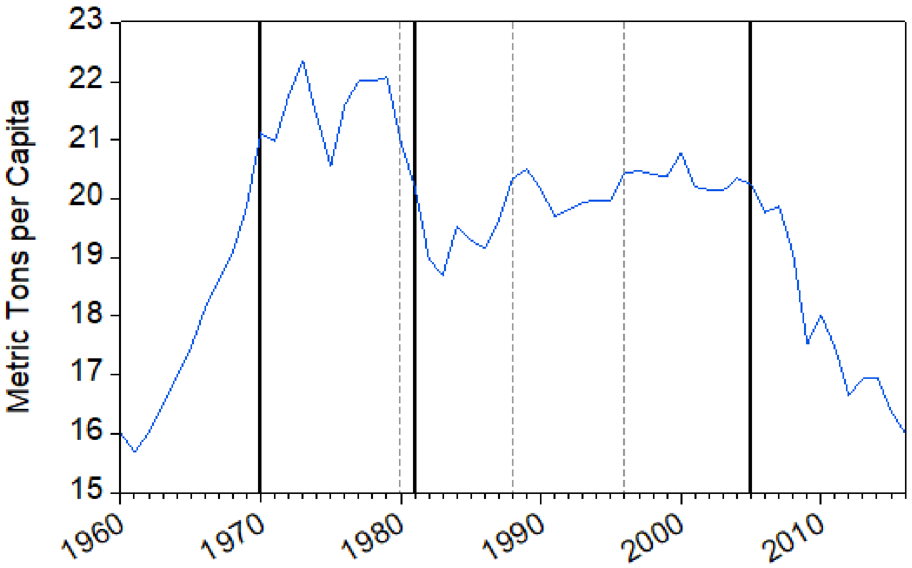

Figure 1: CO_2 *emissions per capita with breakpoint overlaid. Solid vertical lines indicate the three break points indicated by the unweighted maximum F-statistic and the dashed lines indicate additional breakpoints that are significant using the five-break model indicated by a sequential testing method. Note in the five-break model 1980 rather than 1981 is a significant break point.*

When we allow the CO_2 model, see equation (1), to take the form of the breaking regression, see equation (2), our analysis can be described as a breaks in trend model that controls for both oil price and business cycle fluctuations. Obviously, a simple deterministic trend is insufficient to describe the true data generating process of CO_2, but we make use of the parameter instability caused by this misspecification to find points where a latent explanatory variable is exerting significant influence. Table 2 presents the breaks in trend estimation for the three-break point model.

Table 2: Breaks in Trend: Three Break Model

Variable	*Coefficient*		*Std. Error*	*t-Statistic*
1961 - 1969				
Constant	15.28	***	0.25	60.38
Trend	0.41	***	0.05	8.44
1970 - 1980				
Constant	21.07	***	0.34	62.18
Trend	0.04		0.02	1.42
1981 - 2004				
Constant	19.24	***	0.48	40.32
Trend	0.03	**	0.01	2.51
2005 - 2016				
Constant	36.44	***	0.39	94.62
Trend	-0.36	***	0.01	-48.27
No Non-Breaking Variables				
GDPGAP	0.17	***	0.02	7.29
D(OILPRICE)	0.006	**	0.002	2.54

****, **, * indicates significance at the 1%, 5% and 10% levels*

4 Historical Event Analysis

Table 3 summarizes major policy changes from 1963 through 2005 and cross-references those changes with breakpoints found via the breaks in trend analysis. The remainder of section four reconciles policy innovations with breaks in trend of CO_2 per capita (three break model).

Table 3: Break in trends vs. historical event analysis

Year	*Breakpoints*		*Event Description*
	3 Breaks	*5 Breaks*	
1963			The Federal Clean Air Act passed
1965			The Federal Clean Air Act amended Motor Vehicle Air Pollutions Control Act California cars comply with stringent state regulation
1967			The Air Quality Act of 1967 passed
1970	X	X	The Clean Air Act of 1970 passed The Environmental Protection Agency (EPA) formed
1975			Clean Air Act in effect Corporate Average Fuel Economy (CAFE) program passed
1977			Clean Air Act amended
1980		X	
1981	X		All new vehicles meet the amended Federal Clean Air Act standards New vehicles emissions technology becomes available
1983			1977 mandated standards for all gasoline-powered cars in effect Fuel injection technology becomes more common
1988		X	
1990			The Clean Air Act of 1990 passed
1996		X	
2005	X	X	Stringent emission standards for nonroad diesel engines developed by EPA Natural gas becomes predominate fuel for electricity production

4.1 Pre-1970

California, starting in the 1950s, lead the nation in its development of technology to measure air pollution in Los Angeles, as well as the development of regulation of the domestic automobile industry. As the public began to search for solutions to the problem of smog, scientists needed to define the extent of the problem by measuring air pollution. However, the technology did not exist and had to be created (Willens 1970). In addition, "technology-forcing" regulations pushed the automobile industry to develop innovations to mitigate emissions from automobiles (J. Lee et al. 2010).[3] These regulations created a need for technological innovation. Automobile manufacturers entered into cross-licensing agreements to encourage the free exchange of information of technology in the emissions field. As technology was developed to measure air pollution and to reduce automobile emissions, California developed a regulatory structure in coordination with domestic automobile manufacturers to adopt standards for vehicle emissions in the 1960s (Willens 1970). On the other hand, Lee et al. (2010) argued that regulation forced innovation because of the

---

[3] A "technology-forcing" regulations occurs when a regulator specifies a standard that cannot be met with existing technology, or at least not at an acceptable cost (Gerard and Lave 2005).

very short time frame. Regardless of the exact causal structure, all new vehicles sold in the fall of 1965 complied with the state's requirements for motor vehicle emissions (Willens 1970).

The Federal Clean Air Act in 1963 and its amendment in 1965 authorized the issuance of federal standards to regulate motor vehicle emissions, as well as research into techniques to minimize air pollution (Gil-Alana and Solarin 2018). The U.S. Department of Health, Education, and Welfare was given the authority to regulate motor vehicle emissions and adopted the California limitations on hydrocarbons and carbon monoxide for all new vehicles (Willens 1970; White 1982).

However, the Federal standards did not develop air quality criteria or standards for control techniques. Other states were also developing separate and sometimes conflicting standards of vehicle emission regulation. The automobile manufacturing industry urged developing a national standard, which lead to the Air Quality Act of 1967, but gave an exemption to California so that it could enact its own, more stringent, standard (Willens 1970). The Clean Air Act of 1970 became the most significant piece of legislation because it established standards for air quality and created regulations to control emissions. Although it has been called a “technology forcing” regulation (Gerard and Lave 2005; J. Lee et al. 2010), the automobile manufacturing industry was already developing technology in advance of Congress passing the regulations and had already invested in significant research and development. The number of patents increased as the automobile industry sought to develop new technologies rather than exploit existing technology (J. Lee et al. 2010). Thus, though a great deal of technological and regulatory innovation had occurred, we do not see a break in trend of CO_2 emissions until 1970.

4.2 1970 -1981

The Environmental Protection Agency (EPA) was created in 1970 (Willens 1970) and given broad authority to regulate motor vehicle pollution. The Clean Air Act was further amended in 1970 to require comprehensive federal and state regulations for both stationary and mobile pollution sources (U.S. EPA 2016). In 1973, the EPA published fuel economy and emission data for the first time, and in 1975 the first fuel economy goals were established by the Energy Policy Conservation Act.

4.3 1981 - 2005

In 1981, new vehicles met the amended (1977) Clean Air Act standards for the first time. Hence, while considerable regulatory changes occur between 1970 and 1981, the impact of those changes is consistent with a breakpoint occurring in 1981. In the 1980s, other technologies and policies had some impact upon CO_2 emissions, such as new vehicles sold with three-way catalysts, onboard computers, and oxygen sensors (U.S. EPA 2016), the establishment of the Corporate Average Fuel Economy (CAFE) program with more stringent fuel economy standards, and all gasoline-powered cars meeting more stringent standards by 1983 (Bertelsen 2001).

4.4 2005 forward

While coal-fired electric power plants are the largest source of carbon dioxide (Magill 2016) in the United States, the amount of electricity generated with coal has decreased to levels not seen since the early 1970s, and electricity generation using natural gas has been increasing since 1988. This substitution of fuel and its resulting reduction of CO_2 emissions was anticipated by the results of Casler and Rose (1998). This increase, since 2005, has been due in part to the increased use of fracking in the United States contributing to declining natural gas prices starting in 2008 (Lu, Salovaara, and McElroy 2012). Also, stricter emissions standards set by the Clean Air Act of 1990 have increased the operating cost of coal-fired power plants (Popp 2003). According to the U.S. Energy Information Administration, increased natural gas use has helped reduce power sector CO_2 emissions by 30 percent.

4.5 Policy Effectiveness Lag

In the 1950s, the problems with air pollution observed in California brought the problem of emissions to the public's attention (Willens 1970) and eventually lead to the Federal Clean Air Act in 1963, its amendment in 1965, and the Air Quality Act of 1967. Thus, from the passage of the Federal Clean Air Act we see about a seven-year policy lag until the positive trend in CO_2 emissions is arrested in 1970; though, a ten-year lag is probably a more accurate estimate given that there were state-level regulatory innovations that predated federal legislation.

The Clean Air Act of 1970 has a similar policy lag of 11 years until we see a reduction in CO_2 emissions. The policy lag of the Clean Air Act was shortened by the automobile manufacturing industry beginning to adopt new technology in anticipation of the act's passage and lengthened delays in the implementation of air quality standards written into the act, i.e., all new vehicles Clean Air Act standards until 1981.

Determining the policy lag of the Clean Air Act of 1990 is more complicated. While we do not see a breakpoint in trend CO_2 emissions for 15 years, we can observe one nearly immediate effect: very few coal-fired power plants are constructed after 1990 (Popp 2003). Still, much of the switch from coal to cleaner-burning natural gas is likely due to relative fuel prices with the price of coal beginning a steady increase in 2001 and the natural gas price beginning to decrease in 2008.

5 Discussion and Future Work

While the role that regulation has played and will continue to play in the development of new technology remains a topic of continued political debate, there is certainly an argument to be made that "technology-forcing" regulation played a significant role in the curtailment of the pre-1971 increase in CO_2 emissions (See e.g. Willens 1970; Gerard and Lave 2005; J. Lee et al. 2010). Figure 2 presents CO_2 emissions per capita vs. the natural logarithm of total U.S. Patent applications with the breakpoints from our 3-breaks model overlaid. Notice that though the breakpoints are estimated with a model that does not include patent applications, the breakpoints from the 3-breaks appear to line up with changes in trend of patent applications. Hence, we find circumstantial evidence supporting the argument that regulation has the potential to stimulate innovation; and thus, we plan to examine environmental technology related patent application data (see e.g. Hascic et al. 2009).

Willens (1970) points out, as technology to measure CO_2 was developed, more and better regulation was adopted. Thus, there may well be an endogeneity problem that has not been accounted for in the literature (see e.g. Parry, Pizer, and Fischer 2003). So future work will include an examination of regulation on technological innovation and CO_2 emissions, the time lag in policy effectiveness, and the possible endogeneity problem between innovation and regulation.

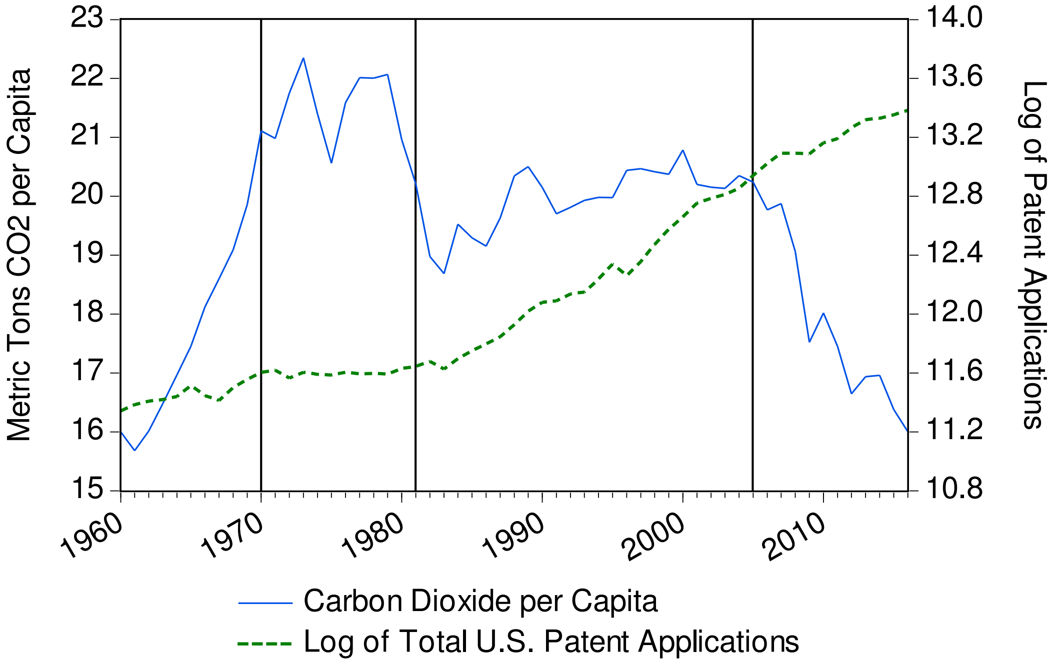

Figure 2: CO_2 emissions per capita vs. log of total U.S. Patent applications with breakpoint overlaid. Solid vertical lines indicate the three break points indicated by the unweighted maximum F-statistic

6 Conclusion

In this paper, we provide an analysis of the effectiveness of regulatory innovation on U.S. CO_2 emissions per capita. Breakpoints at 1970, 1981, and 2005 correspond to both regulatory and technological innovations. While we cannot know how technology would have developed in the absence of observed regulatory innovation, our analysis strongly supports the proposition that regulatory innovation, particularly in California, created a need for the development of new emissions technology. It is difficult to envision a solely market-driven development of technology, such as the catalytic converter, happening at the pace observed. This technological development lead to significant reductions in per capita CO_2. Moreover, this study demonstrates the usefulness of structural break testing in the evaluation of regulatory policy and technological innovation events.

References

Bai, Jushan, and Pierre Perron. 1998. "Estimating and Testing Linear Models with Multiple Structural Changes." *Econometrica* 66 (1): 47–78.

———. 2003a. "Computation and Analysis of Multiple Structural Change Models." *Journal of Applied Econometrics* 18 (1): 1–22.

———. 2003b. "Critical Values for Multiple Structural Change Tests." *Econometrics Journal* 6 (1): 72–78.

———. 2006. "Multiple Structural Change Models: A Simulation Analysis." *Econometric Theory and Practice: Frontiers of Analysis and Applied Research*, 212–237.

Bertelsen, Bruce I. 2001. "The U.S. Motor Vehicle Emission Control Program." *Platinum Metals Review* 45 (2): 50–59.

Casler, Stephen D., and Adam Rose. 1998. "Carbon Dioxide Emissions in the U.S. Economy: A Structural Decomposition Analysis." *Environmental and Resource Economics* 11 (3): 349–63. https://doi.org/10.1023/A:1008224101980.

Gerard, David, and Lester B. Lave. 2005. "Implementing Technology-Forcing Policies: The 1970 Clean Air Act Amendments and the Introduction of Advanced Automotive Emissions Controls in the United States." *Technological Forecasting and Social Change* 72 (7): 761–78. https://doi.org/10.1016/j.techfore.2004.08.003.

Gil-Alana, Luis A., and Sakiru Adebola Solarin. 2018. "Have U.S. Environmental Policies Been Effective in the Reduction of U.S. Emissions? A New Approach Using Fractional Integration." *Atmospheric Pollution Research* 9 (1): 53–60. https://doi.org/10.1016/j.apr.2017.06.008.

Gopalakrishnan, S., and F. Damanpour. 1997. "A Review of Innovation Research in Economics, Sociology and Technology Management." *Omega* 25 (1): 15–28.

Hascic, Ivan, Frans de Vries, Nick Johnstone, Neelakshi Medhi, and Hélène Dernis. 2009. "Effects of Environmental Policy on the Type of Innovation: The Case of Automotive Emission-Control Technologies."

Lee, Chien-Chiang, and Chun-Ping Chang. 2009. "Stochastic Convergence of per Capita Carbon Dioxide Emissions and Multiple Structural Breaks in OECD Countries." *Economic Modelling* 26 (6): 1375–81. https://doi.org/10.1016/j.econmod.2009.07.003.

Lee, Jaegul, Francisco M. Veloso, David A. Hounshell, and Edward S. Rubin. 2010. "Forcing Technological Change: A Case of Automobile Emissions Control Technology Development in the US." *Technovation* 30 (4): 249–64. https://doi.org/10.1016/j.technovation.2009.12.003.

Lu, Xi, Jackson Salovaara, and Michael B. McElroy. 2012. "Implications of the Recent Reductions in Natural Gas Prices for Emissions of CO2 from the US Power Sector." *Environmental Science & Technology* 46 (5): 3014–21.

Magill, Bobby. 2016. "Coal for Electricity Hits a 45-Year Low." Scientific American. January 29, 2016. https://www.scientificamerican.com/article/coal-for-electricity-hits-a-45-year-low/.

Parry, Ian W. H., William A. Pizer, and Carolyn Fischer. 2003. "How Large Are the Welfare Gains from Technological Innovation Induced by Environmental Policies?" *Journal of Regulatory Economics* 23 (3): 237–55. https://doi.org/10.1023/A:1023321309988.

Perron, Pierre. 2006. "Dealing with Structural Breaks." In *Palgrave Handbook of Econometrics*, 1:278–352.

https://www.researchgate.net/profile/Pierre_Perron/publication/4998524_Dealing_with_Structural_Breaks/links/0deec528ab21d602ce000000.pdf.

Popp, David. 2003. “Pollution Control Innovations and the Clean Air Act of 1990.” *Journal of Policy Analysis and Management* 22 (4): 641–60. https://doi.org/10.1002/pam.10159.

Schmalensee, Richard, Thomas M. Stoker, and Ruth A. Judson. 1998. “World Carbon Dioxide Emissions: 1950–2050.” *The Review of Economics and Statistics* 80 (1): 15–27. https://doi.org/10.1162/003465398557294.

U.S. EPA, OAR. 2016. “Timeline of Major Accomplishments in Transportation, Air Pollution, and Climate Change.” Collections and Lists. US EPA. June 27, 2016. https://www.epa.gov/air-pollution-transportation/timeline-major-accomplishments-transportation-air-pollution-and-climate.

Willens, Howard P. 1970. “The Regulation of Motor Vehicle Emissions.” *Natural Resources Lawyer* 3 (1): 120–30.