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Environmental Policy as Social Policy? The Impact of Childhood Lead Exposure on Crime*

Jessica Wolpaw Reyes

Abstract

Childhood lead exposure can lead to psychological traits that are strongly associated with aggressive and criminal behavior. In the late 1970s in the United States, lead was removed from gasoline under the Clean Air Act. I use the state-specific reductions in lead exposure that resulted from this removal to identify the effect of childhood lead exposure on crime rates. The elasticity of violent crime with respect to childhood lead exposure is estimated to be 0.8, and this result is robust to numerous sensitivity tests. Mixed evidence supports an effect of lead exposure on murder rates, and little evidence indicates an effect of lead on property crime. Overall, I find that the reduction in childhood lead exposure in the late 1970s and early 1980s was responsible for significant declines in violent crime in the 1990s and may cause further declines in the future. Moreover, the social value of the reductions in violent crime far exceeds the cost of the removal of lead from gasoline.

KEYWORDS: crime, lead, environmental policy

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I. INTRODUCTION

In the 1990s, after decades of relatively steady increase, crime rates in the United States began a sharp and surprising decline. Researchers have investigated many possible explanations for this decline. Levitt (2004) argues that the decline in crime in the 1990s is primarily explained by increases in the number of police, the size of the prison population, the waning crack epidemic, and the legalization of abortion in the 1970s. This paper argues that the removal of lead from gasoline in the late 1970s under the Clean Air Act is an additional important factor in explaining the decline in crime in the 1990s. The main result of the paper is that changes in childhood lead exposure are responsible for a 56% drop in violent crime in the 1990s.

Substantial reasons suggest that a person's lead exposure as a child could affect whether he commits a crime as an adult. Childhood lead exposure increases the likelihood of behavioral and cognitive traits such as impulsivity, aggressivity, and low IQ that are strongly associated with criminal behavior. Under the 1970 Clean Air Act, lead was almost entirely removed from gasoline between 1975 and 1985. Children exposed to significant lead in the early 1970s may have been more likely to grow up to be impulsive or aggressive adults who committed crimes in the late 1980s and early 1990s. On the other hand, children born in the 1980s, who experienced drastically lower lead exposure after the phase-out of lead from gasoline, may have been much less likely to commit crimes when they became adults in the late 1990s and early 2000s. As each cohort approaches adulthood, the sharp declines in lead exposure that occurred between 1975 and 1985 could be revealed in their behavior as adults. By the year 2020, all adults in their 20s and 30s will have grown up without any direct exposure to gasoline lead during childhood, and their crime rates could be correspondingly lower.

This paper uses state-level observations to identify this connection between lead exposure and crime. I construct a panel of state-year observations by linking crime rates in a state in a given year to childhood lead exposure in that state 20 or 30 years earlier.[1] I evaluate this link for all 50 states and the District of Columbia for crime in the years 1985 to 2002. The link between lead and crime is thus identified from the variation of lead exposure and crime over time within each state. Lead exposure is measured both as lead in gasoline and lead in the air, and these lead exposure measures are tested against individual-level blood data. I test the robustness of the crime results to sample restrictions, alternate specifications, and alternate measures of childhood lead exposure.

The elasticity of violent crime with respect to childhood lead exposure is estimated to be approximately 0.8. This implies that, between 1992 and 2002, the

[1] This methodology is similar to that of Donohue and Levitt (2001).

phase-out of lead from gasoline was responsible for approximately a 56% decline in violent crime. Sensitivity testing confirms the strength of these results. Results for murder are not robust if New York and the District of Columbia are included, but suggest a substantial elasticity as well. No significant effects are found for property crime. The effect of legalized abortion reported by Donohue and Levitt (2001) is largely unaffected, so that abortion accounts for a 29% decline in violent crime (elasticity 0.23), and similar declines in murder and property crime. Overall, the phase-out of lead and the legalization of abortion appear to have been responsible for significant reductions in violent crime rates.

This paper shows that childhood lead exposure can increase the likelihood of violent criminal behavior, and that this effect is large enough to have significantly affected national crime trends. It provides a new explanation for rising and declining crime rates, and predicts continuing declines in the future. More broadly, this paper shows that environmental regulations such as the Clean Air Act can have large and unexpected social benefits.

The paper is organized as follows. Section II discusses lead, and Section III explains the association between childhood lead exposure and criminal behavior. Section IV outlines the empirical framework, discusses the measurement of lead exposure, and introduces the data. Section V presents the empirical results, Section VI provides interpretation, and Section VII concludes.

II. LEAD

Lead is an extremely useful metal but unfortunately has also proved to be a dangerous toxin. Lead exposure is particularly dangerous to young children because they absorb more lead from their environment and are at a critical and sensitive stage of their neurobehavioral development.[2] Not until after 1950 was it widely accepted that the neurological effects of lead persist beyond the stage of acute poisoning and that lead exposure is dangerous even at low levels.[3] The two primary environmental sources of lead exposure for the average child are leaded gasoline and lead-based paint.[4]

Lead was first added to gasoline in the late 1920s to boost engine power, and the lead content of gasoline rose throughout the middle part of the century

[2] Hammond (1988) reports that children absorb up to 50% of lead they ingest, compared with 8% for adults. Bellinger (2004) surveys differences in lead absorption between children and adults.

[3] Lead exposure is simply exposure to some level of lead, whereas lead poisoning encompasses a certain set of symptoms and occurs at particularly high levels of exposure (traditionally blood lead levels in excess of 25 µg/dL). This paper is primarily concerned with lead exposure.

[4] Troesken (2006) makes a compelling argument that water pipes have historically represented a third important source of lead exposure. However, exposure from water pipes did not experience sharp changes during the time period under consideration, so its omission from the analysis is not expected to cause a problem.

and remained high until the 1970s. According to the Environmental Protection Agency (EPA), in 1973 gasoline represented "the most ubiquitous source of lead found in the air, dust, and dirt in urban areas."[5] In 1974, under the authorization of the Clean Air Act, the EPA mandated a timetable for the reduction of lead in gasoline, requiring petroleum companies to meet targets of maximum grams of lead per gallon of gasoline. The average lead content of the gasoline produced by each refinery was to be reduced from 2.0 grams per total gallon to a maximum of 0.5 grams per total gallon by 1979. Over the next few years, the timetable was delayed slightly, and further reductions were implemented. This phase-out was extremely successful: gasoline lead dropped by 99% between 1975 and 1990.[6]

Lead from gasoline can be absorbed into the body directly from breathing gasoline exhaust from the air and also indirectly from contact with lead deposits that have accumulated in soil. From the 1950s to the 1980s, leaded gasoline was the major source of lead exposure for the general population.[7] The National Health and Nutrition Examination Survey (NHANES) also confirmed that the massive reduction of lead emissions from gasoline between 1975 and 1990 was closely associated with corresponding large reductions in the blood lead levels of Americans.[8] For the entire population, the mean dropped from 16 micrograms per deciliter of blood (μg/dL) in 1976 to only 3 μg/dL in 1991; among children under age 6, levels declined from 18 μg/dL in 1976 to 2.8 μg/dL in 1991. These declines occurred across all demographic groups, including age, race, income, and urban vs. non-urban residence: the entire distribution shifted downward.

Lead in paint is the second major source of environmental lead exposure, but it is not as readily absorbed as lead from gasoline. Gasoline lead is spewed into the air whereas paint lead mostly sits inertly on houses. Moreover, paint lead did not experience such drastic changes. The lead content of paint declined relatively smoothly from 1920 on, with breaks in 1950 when new lead-based paint was banned for interior use and in 1978 when it was banned for all residential uses. The primary danger since 1970 stems from older housing with deteriorating paint. Children absorb lead from paint sources directly when they eat paint chips or indirectly when deteriorating paint creates lead dust.

Thus, lead exposure was significant throughout this century, until federal legislation in the 1970s essentially eliminated first-hand exposure.[9] The

[5] U.S. Environmental Protection Agency, 1973.
[6] U.S. Environmental Protection Agency, 1998.
[7] Schwartz and Pitcher (1989) show that, when gasoline was leaded in the U.S., blood lead levels of individuals were highly correlated with gasoline lead consumption in the previous two months.
[8] U.S. Environmental Protection Agency, 1991; Brody, Pirkle, 1994.
[9] Between 1975 and 1990, all lead measures (on-road vehicle emissions, other emissions, air lead, gasoline lead, and blood lead) declined drastically and in concert with one another. Total lead emissions declined by 97%, and gasoline lead went from the dominant source of lead (80% of emissions) to a minor source (8% of emissions). Although first-hand exposure is currently low, dust, dirt, and old paint still represent significant sources of lead in our environment.

substantial decline in lead exposure from gasoline sources between 1975 and 1985, resulting from the Clean Air Act, will be the main source of identification for the current analysis.

III. LEAD AND CRIME

The association between low-level lead exposure during early childhood development and subsequent deficits in cognitive development and behavior is widely accepted. A large and diverse literature in epidemiology, psychology, and neuroscience reaches the consensus that early childhood lead exposure negatively affects cognitive development and behavior in ways that increase the likelihood of aggressive and antisocial acts.[10] While the majority of these studies make reasonable attempts to control for confounding factors (such as age, race, parents' education, socioeconomic status, and home environment), it is important to keep in mind that establishing causality is a difficult task.[11]

A. Lead, Behavior, and Crime

Cellular and animal studies indicate that lead affects neurological function in two ways: it has irreversible effects on the development of the central nervous system, as well as possibly reversible effects on the day-to-day operation of the nervous system. Most importantly, lead exposure during critical stages of development appears to impair brain development by disrupting the orderly formation of networks of neurons, a process that is important for normal behavior.[12] Lead can also disrupt neurotransmitter function in ways that impair cognition and reduce impulse control. Results from animal studies show that lead exposure disrupts social behavior in ways that would impair inhibitory processes and produce hyperactivity, impulsivity, and attention disorders in humans. Exposure early in life appears to have more severe and persistent effects on cognition and behavior than exposure later in life.[13]

Higher lead levels have been associated with aggressive behavior, impulsivity, hyperactivity, attention impairment, "minimal brain damage," and attention deficit and hyperactivity disorder (ADHD).[14] These effects pertain to varying degrees for all lead levels, for exposure from the prenatal period through early childhood, and for cognitive and behavioral performance of age groups from

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[10] Banks *et al.*, 1997.

[11] In light of the numerous disciplines spanned by the literature on the effects of lead, the literature review in this paper endeavors to discuss primarily those articles that meet high standards for identification. Some articles merely establish a correlation, or rather claim to establish causality.

[12] Needleman *et al.* (1996) report that lead exposure peaks between the ages of two and three, which is also when neuronal fibers are pruned.

[13] Banks *et al.*, 1997.

[14] Wilson and Petersilia, 1995; Needleman, 1990; Needleman, 1991; Banks *et al.*, 1997.

infants to teenagers. It is generally agreed that early childhood exposure (before age 6) is most harmful to psychological development, and that these effects persist.[15] Coscia *et al.* (2003) argue that by contributing to weak verbal, reading, and other abilities, lead exposure "deflects such youth's development in an antisocial direction." Many studies have found higher lead levels among children who are hyperactive or have other behavior problems.[16] Needleman and Bellinger (1981) report that children with above-average (but still moderate) lead levels are more than three times as likely to be distractible, hyperactive, impulsive, and to have low overall functioning.[17]

Following the links further, significant evidence suggests that individuals who exhibit aggression, impulsivity, or ADHD are more likely to commit antisocial and criminal acts. Loeber (1990) argues that decreased levels of impulse control by American children are largely responsible for the increasing prevalence of antisocial and delinquent behavior among juveniles. Richardson (2000) writes that "offenders with ADHD often commit impulsive crimes," that "the ADHD brain has problems putting on the brakes and controlling actions," and that "rage and violence are often life-long problems for people with untreated ADHD."[18] Two studies on groups of teenagers find that children with ADHD are five times more likely to be delinquent than children without ADHD.[19] Another study finds that children with ADHD are five times more likely to be convicted of any crime by age 30 and twelve times more likely to be convicted of a violent crime.[20]

B. Lead, IQ, and Crime

Increased lead levels have also been associated with decreased mental skills, including reduced IQ, reduced verbal competence, increased reading disabilities, and reduced academic performance.[21] The effect on IQ has been debated

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[15] Bellinger, 2004; Needleman *et al.*, 1996.

[16] Denno, 1990; Needleman, 1985.

[17] The study uses dentine lead levels, which are a good indicator of lifetime exposure. While dentine lead levels cannot be directly compared to blood lead levels, the lead levels even for the high lead group in this study were in the range of population averages in the 1970s.

[18] Richardson, "Criminal Behavior Fueled by Attention Deficit and Hyperactivity Disorder and Addiction," pp. 18-5 to 18-7, Chapter 18 in Fishbein, 2000.

[19] Both studies choose their sample to minimize selection bias and also control for socioeconomic status and other factors that might be related to delinquency and crime. Moffitt and Silva (1988) study a random group of 678 thirteen-year-olds. They report that children with ADHD at age 11 were more than five times as likely to be delinquent at age 13 than children without ADHD (58% of ADHD children became delinquent vs. 10% of non-ADHD children). Satterfield (1987) uses a sample of 238 children, finding that ADHD children were six times more likely to be arrested for at least one serious offense as teenagers.

[20] Dalsgaard, 2003.

[21] Bryce-Smith, 1983.

extensively, but the consensus is that an increase in blood lead level of 1 μg/dL produces a decrease of approximately one-half of an IQ point, without any safe threshold.[22] This means that two children who are otherwise identical but whose lead levels differ by 15 μg/dL (approximately the decline in lead levels between 1976 and 1990) would exhibit an average IQ difference of 7.5 points. Lower IQ can then be linked to criminal behavior: one controversial estimate is that criminal offenders have IQs about 10 points below non-offenders on average.[23]

C. Lead, Delinquency, and Crime

Lead has also been associated directly (though not necessarily causally) with delinquent, criminal, and aggressive behavior. Denno (1990) finds that lead poisoning is the most significant predictor of disciplinary problems and one of the most significant predictors of delinquency, adult criminality, and the number and severity of offenses. Needleman *et al.* (1996) find a significant relationship between bone lead and antisocial, delinquent, and aggressive behaviors. Dietrich *et al.* (2001) followed a cohort of 195 inner-city youths from birth through adolescence, and find a clear linear relationship between childhood blood lead levels and the number of delinquent acts committed. In addition, Needleman *et al.* (2002) show that adjudicated delinquents were four times as likely to have high lead levels than non-delinquents, and several studies have shown that violent criminals exhibit higher levels of lead in their bodies than non-violent criminals or the general population.[24] Lastly, two studies have used U.S. data to demonstrate a strong association between lead exposure and crime rates: Nevin (2000) does this with a national time-series, while Masters *et al*. (1998) employ a cross-section of counties.[25]

D. Estimated Size of the Effect

Given that these links to aggressivity, impulsivity, and crime pertain at the moderate lead levels (10-20 μg/dL) common in the U.S. in the 1970s and earlier, it does not seem unreasonable to posit a link at the national level between higher

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22 Schwartz (1994) reports an effect of 0.25 of an IQ point lost per 1 μg/dL of blood lead, controlling for other factors. Canfield *et al.* (2003) report an effect of 0.46, and 0.8 in lower ranges. Liu *et al.* (2002) report that IQ deficits persist even after blood lead levels decline.

23 Herrnstein and Murray, 1996. The controversy stems from debate about appropriately establishing causality and controlling for socioeconomic factors and selection.

24 Masters, 1998; Bryce-Smith, 1983.

25 Both Nevin and Masters *et al*. show strong evidence linking lead and crime, but their data limitations (Nevin uses a single national time series, Masters *et al*. use a cross-section) do not allow them to control sufficiently for other confounders nor find exogenous variation in lead exposure and thereby establish causality. Masters *et al*. do present extensive physiological and individual-level evidence.

childhood lead exposure and higher rates of impulsive or violent crime. The magnitude of the effect of lead on crime can be approximated by performing several quick calculations. First, following the link from lead to ADHD to crime, I find an elasticity of delinquency or criminal behavior with respect to lead of 0.5. Second, following the link from lead to reduced IQ to crime, I find an elasticity of the likelihood of being stopped by the police with respect to lead of 0.06. This elasticity is small, but it only follows the IQ link, not any other aspects of behavior. Third, following the link from blood lead levels to juvenile delinquency, I calculate an elasticity of the number of delinquent acts with respect to an individual's blood lead level of 0.5 to 1.0. This elasticity is calculated on a sample of inner-city, primarily black youths with high rates of juvenile delinquency, and so is not directly generalizable. Overall, these preliminary calculations are based on limited samples with possible endogeneity, but they suggest an elasticity of crime with respect to lead of between 0.06 and 1.00.[26]

IV. Empirical Framework and Measurement of Lead Exposure

A. Empirical Framework

The ultimate goal of this paper is to identify a causal effect of lead on crime: are individuals who were exposed to more lead as children more likely to commit crimes as adults? Ideally, one would estimate an equation that models the propensity to commit a crime as a function of childhood blood lead, preferably with some source of exogenous variation in childhood blood lead:

$$(1) \qquad \text{Prob(crime)} = \alpha_0 \text{ childhood blood lead} + \text{other factors} + \varepsilon \ .$$

While data are not available to estimate this equation, data are available to estimate a closely related equation that models the propensity to commit a crime as a function of childhood lead *exposure*:

$$(2) \qquad \text{Prob(crime)} = \alpha_1 \text{ childhood lead exposure} + \text{other factors} + \varepsilon \ .$$

In addition, the Clean Air Act directly influenced the lead content of gasoline, thereby providing variation in childhood lead exposure. Furthermore, limited data are available to test the implicit first-stage relationship between childhood lead exposure and childhood blood lead:

$$(3) \qquad \text{childhood blood lead} = \alpha_2 \text{ childhood lead exposure} + \text{controls} + \varepsilon \ .$$

Thus, this paper estimates equation (2) and verifies the validity of using that

[26] These calculations draw on results from the literature just discussed. More detail can be found in the Appendix (available at the B.E. Press website for this paper).

reduced form equation in place of the structural equation (1) by also estimating the first stage equation (3).

B. Measuring Lead

Gasoline lead is released into the environment from the exhaust pipe of a car, but its effects on child development do not occur until it is absorbed into a child's body. A chain of events links the source to a child, and this paper must do that as well: the goal is to find a good measure of the average child's exposure to lead. Several sources of data provide opportunities to take a multi-faceted approach to this challenge. First, measures of blood lead in children are available, but only for the years 1976 to 1980. While not usable as a primary lead measure, the blood lead data can be used to test the validity of other measures. Second, measures of lead in the air are available for the period 1960 to 1990, but measurement problems limit their usefulness. Third, measures of lead released by automobile sources are available for the entire period 1956 to 1990. Grams of lead per gallon of gasoline will be the primary lead measure: it is attractive because it is simple and was the target of EPA regulation. I will also outline a strategy whereby lead in gasoline is used as an instrument for lead in the air. I now discuss the various lead measures in turn.

Blood lead

Blood lead levels measure the concentration of lead in blood directly (μg/dL). The NHANES II measured blood lead levels of a nationally representative sample of 9,372 individuals of all ages (including 2,322 children age 0 to 5) in the years 1976 to 1980.[27] As discussed above, the NHANES data confirm that blood lead levels dropped drastically as lead was phased out from gasoline.[28] Because of the limited time span, these data cannot provide the temporal and geographic coverage necessary for the primary analysis in this paper. However, these data do cover a time period – the central portion of the phase-out of lead from gasoline – with substantial variation in lead exposure and levels. Consequently, they provide an excellent opportunity to test the validity of the implicit first-stage.

Air lead

The EPA's Aerometric Information Retrieval System (AIRS) supplies information on the lead content of the air people breathe. Since the 1960s, the EPA has used individual monitors to measure the levels of various pollutants and

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[27] More detail on the NHANES can be found in the Data Appendix (available at the B.E. Press website for this paper).

[28] Appendix Table 1 shows average blood lead levels by year, region, and demographic group.

TABLE 1 — Summary of Variables

Variable	*1965-1980*		*1970 only*		*1980 only*		*%Δ 70-80*
Total lead from gasoline (kilotons)	7.63	(5.46)	9.67	(6.65)	3.08	(1.91)	-68%
Gasoline lead (grams per gallon)	2.00	(0.62)	2.60	(0.16)	0.72	(0.12)	-72%
Per-capita lead (kilograms per person)	0.94	(0.30)	1.20	(0.25)	0.37	(0.10)	-69%
Air lead ($\mu g/m^3$)	1.04	(0.61)	1.23	(0.54)	0.40	(0.13)	-68%

Variable	*1985-2002*		*1990 only*		*2000 only*		*%Δ 90-00*
Crime rate (crime per 1000 population)							
Violent crime	6.26	(2.65)	7.32	(3.13)	5.06	(1.70)	-31%
Property crime	44.81	(11.74)	50.88	(11.70)	36.18	(8.01)	-29%
Murder	0.077	(0.041)	0.094	(0.051)	0.055	(0.026)	-42%
State unemployment rate	5.7	(1.57)	5.5	(0.83)	4.0	(0.78)	-27%
State personal income per capita	26674	(3963)	25785	(3655)	29760	(4105)	15%
Poverty rate	13.2	(3.45)	13.5	(3.28)	11.2	(2.61)	-17%
AFDC generosity (15 year lag)	7270	(3009)	7975	(2858)	6093	(2403)	-24%
Prisoners per 1000 population	3.33	(1.56)	2.65	(1.03)	4.52	(1.67)	71%
Police per 1000 population	2.98	(0.69)	2.79	(0.64)	3.30	(0.74)	18%
Beer consumption per capita (gallons)	22.70	(3.36)	24.04	(3.22)	21.76	(3.32)	-9%
Share of population age 15 to 29	0.22	(0.02)	0.23	(0.01)	0.21	(0.01)	-11%
Effective teen pregnancy rate (for violent crime)	0.12	(0.03)	0.12	(0.03)	0.11	(0.02)	-3%

TABLE 1 — Summary of Variables — continued

Variable	***1985-2002***		***1990 only***		***2000 only***		%Δ *90-00*
Effective gasoline lead exposure (grams per gallon)							
Violent crime	1.27	(0.36)	1.58	(0.10)	0.80	(0.09)	-49%
Property crime	1.25	(0.47)	1.64	(0.11)	0.65	(0.07)	-60%
Murder	1.19	(0.30)	1.45	(0.09)	0.80	(0.09)	-45%
Effective per-capita lead exposure (kilograms per person)							
Violent crime	0.58	(0.17)	0.69	(0.13)	0.42	(0.10)	-39%
Property crime	0.59	(0.22)	0.76	(0.15)	0.35	(0.08)	-55%
Murder	0.54	(0.14)	0.62	(0.11)	0.43	(0.10)	-31%
Effective air lead exposure ($\mu g/m^3$)							
Violent crime	0.62	(0.28)	0.79	(0.34)	0.47	(0.16)	-41%
Property crime	0.59	(0.29)	0.85	(0.35)	0.40	(0.12)	-53%
Murder	0.59	(0.26)	0.72	(0.32)	0.47	(0.16)	-36%
Effective abortion exposure (abortions per 1000 births)							
Violent crime	124	(120)	47	(42)	235	(110)	402%
Property crime	179	(140)	102	(77)	289	(130)	183%
Murder	95	(100)	22	(26)	199	(100)	822%

Notes. Means are calculated across 51 observatinos (50 states plus the District of Columbia) for the years indicated and are weighted by state population. Standard errors are in parentheses. Variables are defined in the text and in the Data Appendix.

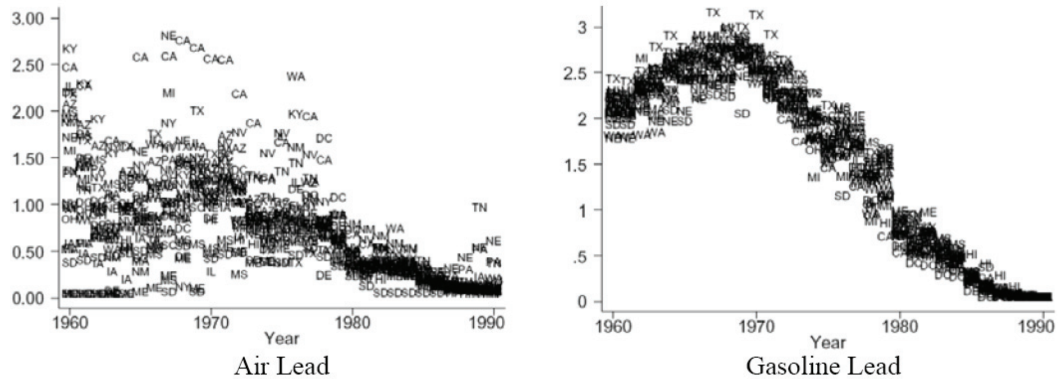

FIGURE 1. Lead Exposure 1960 to 1990

particulates at locations throughout the United States, placing monitors in order to accurately represent the pollutant content of the air in a given county. Through a Freedom of Information Act request, I obtained a data file with the average lead reading within each quarter of each year for each monitor during the years 1960 to 2000.[29] By averaging the readings within a state (weighting by population), I construct a measure of the average concentration of lead in the air (measured in μg/m^3) in each state in each year. This measure is called *air lead exposure*.

Table 1 shows that this measure of air lead exposure averaged 1.04 μg/m^3 between 1965 and 1980, and declined by 72% in the 1970s. This trend can also be seen in Figure 1. State-specific values are shown in Appendix Table 2.

By measuring the *actual* lead content of the air people breathe, the air data could potentially provide a good measure of individual lead exposure. Unfortunately, the data are problematic for a number of reasons. First, many observations are missing, particularly in the 1960s.[30] Second, the monitors do not cover the entire area of each state uniformly – they cover less than half of the population of most states. Third, in most years the number of lead readings was too low to be deemed "representative" by the EPA. Fourth, monitors came in and out of operation, reducing the accuracy of the changes in lead exposure from year to year within a given state.[31] In light of these problems, one might be tempted to ignore air lead altogether. However, air lead still provides valuable information

[29] AIRS reports the second maximum average quarterly mean of lead for each monitor in each quarter measured. The EPA began collecting these data in 1960.

[30] The 1960s data is necessary to calculate childhood lead exposure for individuals born in the 1960s, who would be 20-30 years old in the 1980s and 1990s. From 1960 to 1990, 14% of state-year cells have no air lead observations; in the 1960s, 30% have none; in the 1970s, 8% have none.

[31] Only 29 states had one or more monitors that stayed in near-continuous operation from 1965 onward. The number of monitors and readings increased substantially in the late 1970s.

on the lead content of the air people breathed in different states at different times. While it may not be sufficiently well measured to be used when state and year fixed effects are included, it may be relevant when making purely cross-sectional comparisons, when testing robustness of other lead measures, or as part of an instrumental variables strategy. I will use air lead, but do so cautiously and with awareness of its weaknesses, eliminating the most unreliable measurements and interpolating for missing observations as appropriate.

Gasoline lead

Without a usable measure of the lead to which people are directly exposed, it may be worthwhile instead to measure the *lead content of gasoline*. As discussed above, leaded gasoline was the main source of individual lead exposure. Using geographically detailed data on the lead concentrations in different grades of gasoline and the shares of those grades used in each state, I can construct a measure of the average grams of lead per gallon of gasoline in each state in each year for the years 1950 to 1990. Prior to 1973, nearly all gasoline was leaded, and gasoline was broken down into regular, premium, and sometimes super-premium grades. The introduction of unleaded gasoline in 1971-2 led to four grades: regular unleaded, premium unleaded, regular leaded, and premium leaded. The distinction between the different grades is based on octane, and since lead is an octane enhancer the lead content varied across grades: premium leaded gasoline contained significantly more lead than regular leaded gasoline. Furthermore, because of the manner of distribution of gasoline throughout the country, the lead content of each grade of gasoline and the amounts consumed of the different grades also differed significantly from state to state.[32] I calculate the grams of lead per gallon of gasoline (gpg) in state s in year y by averaging over the grades g of gasoline:

$$\text{(4)} \qquad \text{Grams per gallon } (s,y) \;=\; \sum\nolimits_g \text{ share of grade } (s,y,g) \times \text{gpg of grade } (s,y,g)$$

This is called "*gasoline lead exposure*." The gasoline data come from several sources. The shares of the different grades of gasoline are from the *Yearly Report of Gasoline Sales by States* for the years 1976 to 1984, published by Ethyl Corporation, and from the *Petroleum Marketing Annual* for the years 1985 to 1989, published by the U.S. Department of Energy. The grams of lead per gallon for the different grades of gasoline are from the *Petroleum Products Survey* for the years 1947 through 1989, published by the U.S. Department of Energy.[33]

[32] Examples of the variation in gasoline lead content: In 1975, premium leaded gasoline contained 2.23 grams per gallon (gpg) while regular leaded contained 1.85 gpg. Also in 1975, regular leaded in Nebraska contained 1.85 gpg, and regular leaded in Mississippi contained 2.30 gpg. In 1977, the share for premium leaded was 13% in Arkansas and 32% in California.

[33] Data sources and calculations are described in greater detail in the Data Appendix.

Table 1 shows that this measure of gasoline lead exposure averaged 2.0 gpg between 1965 to 1980, and declined by 72% in the 1970s.[34] Figure 1 displays the rise and fall of lead exposure, showing large rises before 1970 and steep declines in the late 1970s. Appendix Table 2 provides additional detail for each state during the phase-out, and demonstrates significant variation across states in the timing and size of these declines in lead exposure.

The variation in grams per gallon is well-suited to the current analysis for two reasons: i) EPA policy specifically targeted grams per gallon; and ii) EPA policy was imposed on petroleum companies, not states. The first point indicates that grams per gallon was the policy target. The second point implies that the changes in grams per gallon at the state level resulted not from state government policy nor from state-specific EPA policy, but rather from the actions of petroleum companies endeavoring to comply with EPA policy. Accordingly, changes in grams per gallon were influenced by a variety of features of the petroleum industry. The network of petroleum pipelines delivered gasoline with different lead contents to different regions of the country. Even within a region, the lead content of different grades of gasoline differed substantially. Demand for the different grades of gasoline also varied with consumer preference and with the age of the stock of cars (which also varied with climate). Even the number of gasoline pumps available at gas stations affected the path of the introduction of unleaded gasoline, and particularly the phase-out of high-lead premium gasoline between 1979 and 1980. Thus, grams of lead per gallon experienced reductions in the period 1975 to 1985 that were substantial, varied significantly from state to state, and were indirectly induced by EPA policy.[35] Additionally, I will show below that grams per gallon is a robust predictor of children's blood lead. Gasoline lead, measured as grams per gallon, will be used as the primary lead measure.

Modified gasoline lead

By paying close attention to the mechanism of exposure to gasoline lead, one might be able to improve upon grams per gallon. Because people are exposed to lead from gasoline sources when a car using leaded gasoline drives past them, other factors may modify the effect of grams per gallon on an individual's lead exposure. For example, the effect of any given level of grams per gallon might be dampened in a state with relatively little driving. Alternately, the effect might be amplified in a state that is very densely populated. Essentially, individual lead exposure depends not only on (i) how much lead is in the gas, but also on (ii) the intensity of driving and (iii) the density of exposure to driving. While gasoline

[34] This drop in lead exposure in the 1970s implies that 20-30 year old cohorts in the 1990s experienced a decline of 40-50% in their childhood lead exposure. This can be seen in the declines in "effective lead exposures," defined later in Section V.C.

[35] Gibbs, 1990, 1993, 1996, and personal communication.

lead content accounts for (i), it does not account for (ii) or (iii).

One could propose correcting for these oversights by generating alternate measures of gasoline lead predicated on particular mechanisms for lead exposure. To account for (ii) the intensity of driving, we can multiply the gasoline lead content by gallons of gasoline per capita to produce a measure of *per-capita lead exposure*: grams of lead per person. To account for (iii) the density of exposure to driving, we can then multiply per-capita lead exposure by the average population density in which people live to produce a measure of *experienced lead exposure*: lead experienced by each individual, or (approximately) grams of lead per square mile.[36] Unfortunately, both of these measures are flawed. Per-capita lead, which multiplies by gallons, divides by population, but does not adjust for density, is likely to be biased downward for high-population high-density states like New York.[37] Experienced lead does correct for density, but probably too much: it is likely to be biased upward because it mistakenly assumes that population density translates directly into driving exposure density, when we could reasonably expect population density to have a declining marginal effect on driving density. Thus, while the modified gasoline lead measures may have merits, they also have potentially serious flaws that limit their usefulness.

However, while these measures may be biased in the cross-section, there is some indication that per-capita lead may be relevant in the longer time series. Hilton and Levinson (1998) document an environmental Kuznets curve for lead, showing that lead first rises due to increasing use of gasoline and then falls due to the reduction of the lead content of gasoline. This pattern is apparent in the U.S. time series, suggesting that the per-capita lead measure (which accounts for gallons of gasoline used per person) may be relevant in the longer time series.

Instrumenting for air lead with gasoline lead

Lastly, in order to make some use of the unique information provided by air lead without succumbing to its numerous measurement problems, I consider using gasoline lead as an instrument for air lead. Gasoline lead has the potential to

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[36] Ideally one would multiply by the density of exposure to driving, but such data are unavailable. However, the density of exposure to driving can be proxied by the density of population (assuming everyone within a state drives or is driven the same amount). Average population density in which people live can be calculated as the population-weighted average of population density (people per square mile) across census tracts in a state and year. If a standard measure of population density were used instead (state population / state area), the resulting lead measure would be equivalent to lead per square mile (= (grams per gallon x gallons / population) x (population / area)).

[37] Dividing by a large population produces an artificially low estimate of lead exposure, and failing to adjust for a high population density exacerbates the bias. New York has the second-highest population and the highest population density by a large margin. Consequently it ranks lowest on per-capita lead even though it ranks only 12th-lowest in grams per gallon (and the population is densely packed and exposed to significant gasoline exhaust). See Appendix Table 3.

TABLE 2 — Regression of Air Lead on Gasoline Lead

	Coefficient on Gasoline Lead (grams per gallon)		R-squared
Baseline	0.337 **	(0.023)	0.28
Weighted by state population	0.433 **	(0.050)	0.36
With state f.e. and year f.e.	0.293 **	(0.145)	0.58
With fixed effects and weighted	0.465 **	(0.203)	0.66
Exclude NY	0.337 **	(0.024)	0.28
Exclude CA	0.325 **	(0.020)	0.29
Exclude NY, CA, DC	0.326 **	(0.021)	0.29
With fixed effects and weighted, exclude NY, CA, DC	0.216 *	(0.132)	0.59
Exclude 11 states [a]	0.372 **	(0.023)	0.35
Including population density	0.315 **	(0.029)	0.30

Notes. Coefficients are from the OLS regression of air lead (μg/m^3) on gasoline lead (grams per gallon). The baseline specification includes state-year level observations for 51 states for the years 1965 to 1985. Observations are not weighted, except where indicated, in which case they are weighted by state population. Each row is modified as indicated on the left of the table. Standard errors are shown in parentheses and are Huber-White robust and corrected for serial correlation in a short panel by clustering on state. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

[a] This specification excludes eleven states that have implausibly low air lead measures in the 1960s. These states are AK, AR, ID, KS, ME, MT, OR, RI, SC, SD, VA, VT, WY.

provide a good instrument: it is highly correlated with available air lead data, is available for all states and all years, has much less measurement error, and was the target of regulation.

Table 2 shows the coefficient on gasoline lead in the first-stage OLS regression of air lead on gasoline lead for the time period 1965 to 1985.[38] The baseline coefficient is 0.337 (standard error 0.023), and is relatively robust to specification checks. Weighting the regression by state population increases the coefficient slightly, and including state and year fixed effects attenuates the coefficient slightly and increases the standard error substantially. Additional sensitivity tests do not provide substantially new information.[39] When state and

[38] The years 1965 to 1985 are used because they contain relatively reliable lead measures for *both* air lead and gasoline lead. In this analysis, I use only the actual raw air lead measures (no interpolated values) and eliminate extreme and unreliable values.

[39] These tests include dropping other high population or high density states, dropping eleven states with very low lead measures in the early years, other sample restrictions, and tests of nonlinearity.

year fixed effects are added to the weighted regression, the coefficient is 0.465 with a standard error of 0.203. These larger standard errors do raise concerns that grams per gallon may be a weak instrument for air lead in a state panel (although standard diagnostics indicate that is not the case).[40] This instrumental variables strategy will be used cautiously, and primarily as a sensitivity check.

C. Verifying the Lead Measures

I now test the validity of these lead measures by investigating whether they actually predict blood lead. I first consider the primary lead measure, gasoline lead. Others have reported that gasoline lead exposure and blood lead levels are highly correlated.[41] I perform OLS regressions of blood lead on gasoline lead using the sample of individuals with blood lead measures in the NHANES II in the 1976-1980 period. In this sample, blood lead and gasoline lead can be linked by month and year: the NHANES II data contain the exact date on which the blood sample was taken, and the gasoline data are available monthly during this period. Table 3 shows these results: column 1 includes only the lead measure, column 2 adds individual-level demographics, and column 3 includes state and year fixed effects. This specification is:

$$\begin{aligned}(5)\quad \text{Blood Lead }(i,s,y,m) = {} & \alpha_1 \text{ gasoline lead }(i,s,y,m) \\ & + \alpha_2 \text{ age }(i,y,m) + \alpha_3 \text{ race }(i) \\ & + \alpha_4 \text{ gender }(i) + \alpha_5 \text{ income category }(i) \\ & + \text{ state fixed effects } + \text{ year fixed effects } + \varepsilon_{isym}\end{aligned}$$

where m is the month of observation. Column 1 shows that gasoline lead is a strong predictor of blood lead: one gram of lead per gallon of gasoline increases blood lead by 3.32 μg/dL. By this measure gasoline lead is able to explain half of the change in average blood lead between 1976 and 1980.[42] This relationship is robust to the inclusion of individual covariates and weakens slightly upon the inclusion of state and year fixed effects. The last column, which allows the effect of lead to vary by age, shows that the effect of lead exposure on blood lead is strong and robust for young children but declines with age. Results are similar in a specification using the log of gasoline lead. Overall, gasoline lead, measured as grams per gallon, appears to be strongly related to children's blood lead levels.

Turning our attention to the other lead measures, the results in Table 4 indicate that per-capita lead and the instrumented air lead also show robust

[40] The F-statistic is in excess of 40 in all relevant specifications, indicating that the instrument is not weak according to the standards set in Staiger and Stock (1997) and Stock and Yogo (2002).
[41] Schwartz and Pitcher, 1989.
[42] The actual reduction in blood lead between 1976 and 1980 was 6.5 μg/dL. Changes in gasoline lead (from 1.8 gpg to 0.7 gpg) predict a reduction in blood lead of 3.4 μg/dL over this time period.

TABLE 3 — Regression of Blood Lead on Gasoline Lead

		(1) Baseline	(2) Covariates	(3) Covariates and F.E.	(4) Covariates and F.E., lead x age
Lead	Lead	3.325 ** (0.221)	3.016 ** (0.204)	2.095 ** (0.477)	
	lead x age 0-6				3.722 ** (0.599)
	lead x age 6-12				2.806 ** (0.701)
	lead x age 12-18				1.469 ** (0.574)
	lead x age 18-40				1.771 ** (0.539)
	lead x age 40+				1.764 ** (0.532)
Age	age		0.027 ** (0.003)	0.032 ** (0.003)	
	age 0-6				-1.757 ** (0.755)
	age 6-12				-3.152 ** (0.882)
	age 12-18				-2.974 ** (0.701)
	age 18-40				-1.260 ** (0.647)
Demographics	black		1.905 ** (0.202)	2.711 ** (0.211)	2.724 ** (0.205)
	female		-4.143 ** (0.137)	-4.126 ** (0.130)	-4.134 ** (0.129)
	income < $3,000		0.470 (0.307)	0.922 ** (0.288)	0.782 ** (0.289)
	income from $3k to $6k		0.887 ** (0.244)	0.943 ** (0.236)	0.868 ** (0.237)
	income from $6k to $10k		0.742 ** (0.207)	0.812 ** (0.202)	0.812 ** (0.199)
	income from $10k to $20k		0.427 ** (0.166)	0.426 ** (0.160)	0.355 ** (0.158)
Constant		9.316	10.359	12.894	15.461
R-squared		0.036	0.182	0.266	0.294
State fixed effects		NO	NO	YES	YES
Year fixed effects		NO	NO	YES	YES

Notes. Coefficients are from the OLS regression of blood lead on gasoline lead (grams per gallon). Individual data on blood lead and demographics are from the NHANES II. The date on which the blood lead sample was taken is known. Gasoline lead data is available monthly at the state level and is calculated as described in the text and Data Appendix. This regression is on the full sample of 9,372 people of all ages (resident in the U.S.) for the years 1976 to 1980, and is weighted by NHANES II data weights. Standard errors are Huber-White robust and are shown in parentheses. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

TABLE 4 — Regression of Blood Lead on Various Lead Measures

	(1) Baseline	(2) Covariates	(3) Covariates and F.E.	(4) Covariates, F.E., drop 3 states
Gasoline Lead	0.402 **	0.350 **	0.546 **	0.844 **
	(0.040)	(0.036)	(0.101)	(0.118)
Per-capita Lead	0.124 **	0.101 **	0.302 **	0.379 **
	(0.029)	(0.026)	(0.086)	(0.106)
Air Lead	0.114 **	0.128 **	0.006	0.082 *
	(0.013)	(0.012)	(0.034)	(0.048)
IV Air Lead	0.260 **	0.264 **	0.739 **	1.414 **
	(0.020)	(0.017)	(0.137)	(0.198)
Covariates	NO	YES	YES	YES
State Fixed Effects	NO	NO	YES	YES
Year Fixed Effects	NO	NO	YES	YES

Notes. Results are from the OLS regression of blood lead on the lead measure indicated at the left. Elasticities are shown. Covariates (age, black dummy, gender dummy, and income category dummies) and fixed effects are included as indicated. Column 4 excludes individuals living in New York, California, or the District of Columbia. Individual data on blood lead and demographics are from the NHANES II. Lead measures are calculated as described in the text and Data Appendix. This regression is on the sample of 2,322 people under the age of 6 (resident in the U.S.) for the years 1976 to 1980, and is weighted by NHANES II data weights for blood lead. Standard errors are Huber-White robust and are shown in parentheses. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

relationships with children's blood lead.[43] The elasticities of children's blood lead with respect to the lead measures are relatively precisely estimated at 0.55 for gasoline lead, 0.30 for per-capita lead, and 0.74 for the instrumented air lead. Air lead shows a slight relationship, but it is much smaller, less significant, and not robust. For all of the measures, removing the three high-population and high-density states (states that raise potential problems in the appropriate measurement of lead exposure) increases the estimated elasticities substantially. For gasoline lead, the elasticity rises to 0.84.

Overall, the results in Table 4 confirm that gasoline lead, per-capita lead,

[43] Experienced lead generally shows insignificant results in this specification, but some significant results in a log-log specification.

and the instrumented air lead are able to predict children's blood lead reasonably well. The existence of detailed data for the time period during which lead was phased out of gasoline has provided a unique opportunity to validate these lead measures. On the other hand, the limited time period on which this analysis was performed (1976 to 1980) necessitates caution in extrapolating these results beyond this time period.

D. Summary of Lead Measures

Gasoline lead, measured as grams per gallon, will be used as the primary lead measure: it is simple, was the target of EPA regulation, and is a robust predictor of children's blood lead. At the same time, other lead measures may be useful as sensitivity checks, providing opportunities for testing robustness and possibly addressing deficiencies in grams per gallon.

V. EMPIRICAL EVIDENCE ON LEAD EXPOSURE AND CRIME

We now turn our attention to investigating the relationship between childhood lead exposure and adult criminal behavior at the national level. This investigation will use the lead measures discussed above together with per capita crime rates for the United States from the Uniform Crime Reports compiled by the Federal Bureau of Investigation (available annually since 1960).

A. National Time Series

The lead contents of gasoline and paint for the years 1900 to 1990 are shown in Figure 2. Total lead exposure peaked in the 1920s (due to paint) and again in the 1970s (due to gasoline) and declined drastically to nearly zero by 1990. Gasoline lead exposure rose until 1970 and then fell. The most drastic drop in lead from gasoline sources occurred between 1975 and 1985, when the amount of lead dropped by more than 90%.

Figure 3 presents per-capita crime rates for the years 1970 to 2002 for violent crime, property crime, and murder. Violent crime consists of aggravated assault, robbery, murder, and rape; it is dominated by assault and robbery (murders represent less than 3% of violent crime). Property crime consists of burglary, larceny, and auto theft. All three categories of crime rise until 1980, decline, rise again until 1991, and then decline. Violent crime shows this pattern most strongly.

Figure 4 presents gasoline lead for the years 1950 to 1988 together with total violent crime for the years 1970 to 2002.[44] The crime series is presented

[44] Lead shown in Figure 4 is measured as total lead consumed in the U.S. divided by total U.S. population (kilotons per million population). Essentially, this follows standard practice in

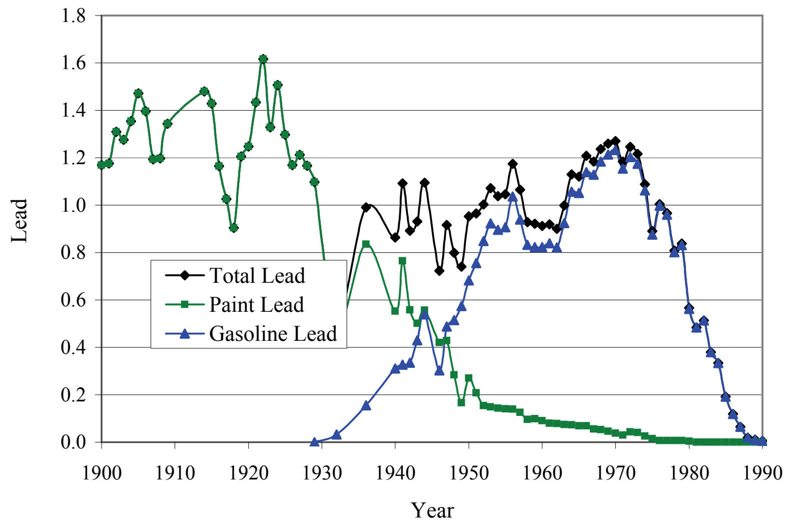

FIGURE 2. Lead in Paint and Gasoline 1900-1990

Notes. Lead is presented as kilotons of lead per 1 million population. *Sources.* U.S. Geological Survey and U.S. Department of the Interior: 1904-1929, Mineral Resources of the U.S.; 1933-1980, Minerals Yearbook; 2001, U.S. Consumption of Lead in Manufacture of Gasoline Additives, 1941-1986.

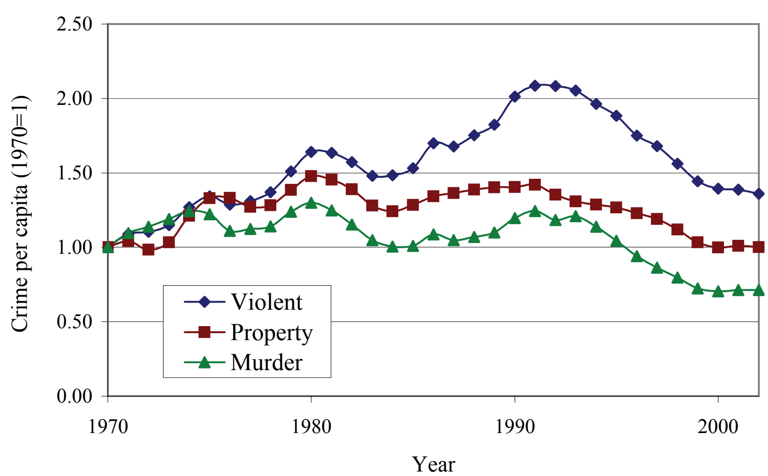

FIGURE 3. Crime Rates 1970-2002

Source: Federal Bureau of Investigation, Uniform Crime Reports for the United States.

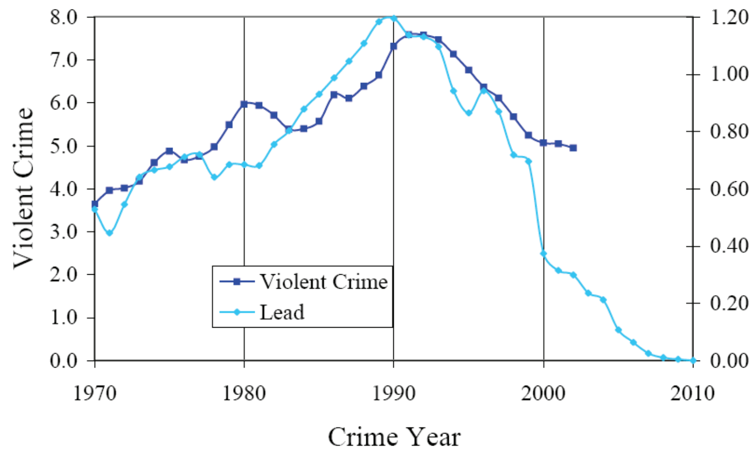

FIGURE 4. Violent Crime and Lead (20-year lag)

Notes. Violent crime per capita and kilotons of lead per 1 million population at the national level are shown. *Sources:* Federal Bureau of Investigation, Uniform Crime Reports for the United States. U.S. Consumption of Lead in Manufacture of Gasoline Additives, 1941-1986.

with a 20-year lag relative to the gasoline lead exposure series because 22 years is the peak of the age-crime profile for violent crime, and lead exposure between ages 0 to 3 should matter most for behavior.[45] The relatively close match between the series suggests a relationship between lead exposure in a given year and violent crime approximately 20 years later, supporting the hypothesis that higher childhood lead exposure is associated with higher adult crime rates. Earlier history also supports this link: lead was introduced into gasoline in the late 1920s, and lead content increased in the late 1930s and early 1940s, while violent crime rates were almost flat between 1950 and 1963, and rose steeply thereafter.

B. State Cross-Section and Differences-in-Differences

Cross-state variation provides another opportunity to examine the relationship between lead and crime. I regress log crime in each state in 1992 (the crime peak) against the lead exposure in that state 22 years earlier. The results of this analysis are encouraging. For gasoline lead, the R-squared values are 0.10 for violent

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rescaling an aggregate national value by national population to adjust for population growth. Using this lead measure in the national time series also acknowledges the importance of increasing *gasoline usage* in the rise of lead exposure nationally. (It could be seen as adjusting grams per gallon by *gallons per person* at the national level.) Note that this correction is *not* done at the state level and so is not subject to the bias that plagues per-capita lead due to cross-state variation in population and population density.

[45] Federal Bureau of Investigation, *Uniform Crime Reports for the United States 1985*.

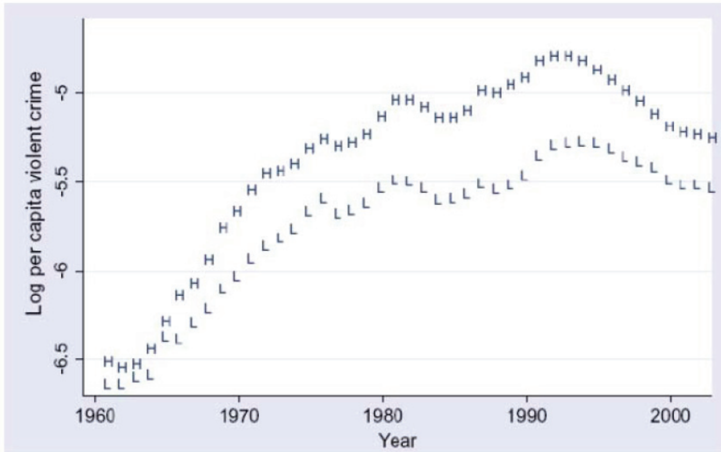

FIGURE 5. Violent Crime 1960 to 1990,
States with High Changes in Lead vs. States with Low Changes in Lead

crime, 0.02 for property crime, and 0.18 for murder; for air lead, these values are 0.26, 0.14, and 0.15 respectively.[46] These preliminary results imply elasticities of 4.0 and 0.9 of violent crime with respect to gasoline lead and air lead respectively.

A differences-in-differences analysis can investigate whether crime rates evolved differently in states with large changes in lead exposure versus states with small changes.[47] Since the lead content of gasoline began to decline in the early 1970s, we would not expect to see bigger decreases in crime in states with bigger lead changes until the cohorts born in the early 1970s were old enough to commit crimes (at least 17). Differences should therefore show up from approximately 1990 onward. However, since big-change states probably had larger increases in lead exposure in the 1950s, these states might also exhibit relatively larger increases in crime in the 1970s. Figure 5 displays the trends in violent crime for the two categories of states for the entire period 1960 to 2000, showing that the states with bigger changes in lead also experienced bigger changes in crime; their path of crime over time is an amplified version of that in the small-change states.

More specifically, I can compare the percent changes in crime in specific

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[46] For violent crime, 1 gram of gasoline lead (gpg) increases violent crime by 158% (standard error 53%) and 1 μg/m^3 of air lead increases violent crime by 87% (standard error 23%).

[47] States are categorized by the size of the decrease in lead exposure between 1970 and 1980. States with big changes are those in the top tercile; states with small changes are those in the bottom tercile. The analysis is similar when states are categorized by the level in 1970. The two categories of states are otherwise similar: comparing the means of observable variables (state-level covariates listed in Table 1) across these states shows few significant differences. Police and prisoners per capita show the only significant differences; given that these crime prevention and criminal justice variables are unlikely to be orthogonal to crime, this is not surprising.

time periods between these two categories of states. For the period 1992 to 1997, states with larger lead decreases had differentially larger crime decreases for all three categories of crime: 14.5 percentage points more for violent crime (-24.5 vs -10.0), 12.4 for property crime, and 21.2 for murder. Over the entire period 1985 to 2002, these states also experienced larger crime decreases: 27.7 percentage points more for violent crime, 20.4 for property crime, and an insignificant 17.0 for murder.[48] Prior to 1990, the differences between the states were not consistent in one direction and were mostly insignificant. Overall, this preliminary differences-in-differences analysis provides some mild support for an association between lead and crime.

C. State-year Panel Data Analysis

An ideal way to determine the relationship between lead exposure in childhood and criminality in adulthood might be to employ individual, city, or county-level data. Unfortunately, appropriate individual-level data is unavailable, and migration renders a city- or county-level analysis infeasible. The best feasible method is what I employ now: analysis on a long panel of state-level observations. By using cross-state variation over time to identify the effect of lead exposure on crime, this approach makes good use of the state-level changes in lead exposure that resulted from the Clean Air Act.

Calculating effective exposure

Before using the state-year panel, one further calculation is necessary in order to link lead exposure in early childhood to crime committed in adulthood. Following Donohue and Levitt's approach to abortion, I define the *effective lead exposure* relevant to crime c in state s in year y as the weighted average of early childhood (age 0 to 3) lead exposure across all cohorts of arrestees:

(6) Effective Lead (c,s,y) =

$$\sum_{\text{ages } a} \left\{ \left[\text{Lead}(s,y-a) + \text{Lead}(s,y-a+1) + \text{Lead}(s,y-a+2) + \text{Lead}(s,y-a+3) \right] / 4 \times \left[\text{Arrests}(c, a, 1985) / \text{Arrests}(c, \mathit{total}, 1985) \right] \right\}$$

This measure is calculated separately for each crime c for each year 1985 to

[48] For the 1985 to 2002 period, states with large decreases in lead had an average violent crime change of -26.8%, compared with +0.9% in the group of states with small decreases; for property crime the comparison is -40.9% vs. -20.5%; for murder it is -46.3% vs. -29.3%. The differences, with standard errors in parentheses, are thus -27.7% (10.2), -20.4% (8.5), -17.0% (11.3). More detail can be found in Reyes (2007).

2002.[49] By weighting lead exposure in the prenatal year plus the first three years of life using the age distribution for potential offenders, this effective lead measure represents the early childhood lead exposure of potential offenders. Consequently, it measures the critical lead exposure that could affect crime rates in that state and year. The age distribution for arrestees is not specific to the crime year or to the state but instead is taken from 1985 national numbers so that it is not affected by changing lead exposure. Note that the effective lead measure shown in equation (6) implicitly assumes that individuals do not migrate from the state in which they were born. Since cross-state migration between birth and age 22 is generally in excess of 25%, it is important to control for such migration in order to link adults back to their childhood lead exposure. I use state-of-birth distributions by age, year, and state of residence from the decennial U.S. censuses to make this correction. This is described in the Data Appendix.[50]

Specification

The basic specification is a regression of the log per capita crime rate on the effective gasoline lead exposure in a panel of states for the years 1985 to 2002. The regressions include state fixed effects to control for any time-invariant state characteristics that might affect crime, and year fixed effects to control for any national trends. Furthermore, to establish clearly the significance of the effect of lead exposure on crime, I control for other possible determinants of crime rates. These include variables indicating the state of the economy and employment (unemployment rate, income per capita, and poverty rate), variables pertaining to law enforcement (prisoners per capita and police per capita in the previous year), and other variables that might affect crime rates (gun laws, beer consumption, AFDC generosity 15 years earlier, teen pregnancy rate in birth years, and the population age distribution). This list includes nearly all factors that have been considered as possible determinants of crime rates. In addition, I control for the "effective abortion rate" as defined by Donohue and Levitt (2001).[51] Donohue and Levitt found significant and robust effects of the effective abortion rate on crime, concluding that the legalization of abortion can account for nearly 50% of

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[49] Because calculation of effective lead exposure for a given crime year requires lead exposure from 29 years prior (equation (6) sums over arrestees age 8 to 29), and 1956 is the earliest year for which all gasoline lead variables are available, the earliest crime year for which effective gasoline lead exposure can be calculated is 1985. Imputation enables calculation back to 1980, and the results are largely unaffected by including the additional crime years 1980-1984.

[50] Census data include state of residence, state of birth, and age, so they permit correction for cross-state migration when performing analysis at the state level. Analysis at the county level is infeasible: such analysis would require data on cross-county but within-state migration (approximately 30%, calculated from Census migration reports), which is unavailable.

[51] Abortion exposure is in units of abortions per 1000 births. Effective abortion exposure is calculated as defined by Donohue and Levitt (2001). Equation (6) is parallel to their definition.

the recent drop in crime. Their basic premise was that "children born after abortion legalization may on average have lower subsequent rates of criminality," either because women who have abortions are more likely to have children who would engage in criminal activity or because abortion enables a woman to choose to have a child when she is most able to provide a nurturing environment. Therefore, because it appears to be an important potential determinant of crime rates, I include the effective abortion rate as an additional control variable.[52]

Thus, the full regression equation is:

$$(7)\quad \begin{aligned} \ln(\text{crime per capita})\,(s,y) \;=\; & \alpha_1 \text{ lead exposure } (s,y) \\ & + \alpha_2 \text{ abortion exposure } (s,y) \\ & + \text{state-level controls } (s,y)\ \beta \\ & + \text{state fixed effects} + \text{year fixed effects} + \varepsilon_{sy} \end{aligned}$$

This equation is estimated separately for the three different categories of crime (violent crime, property crime, and murder) on a panel of 51 observations for the years 1985 to 2002. Standard errors are Huber-White robust and are clustered within each state to correct for serial correlation in the panel.[53] Observations are weighted by state population so that the analysis is representative of the typical person in the United States.

Main results

The main results of the panel data regression analysis of crime on effective gasoline lead exposure (grams per gallon) are presented in Table 5. The table shows results for each of three crime categories in three specifications: with state and year fixed effects only, adding nearly all state-level covariates (not abortion), and finally adding effective abortion exposure. The coefficients on lead exposure and abortion exposure are rescaled so that they represent elasticities.[54]

The table shows a significant effect of lead exposure on violent crime. Without controls, the estimated elasticity for gasoline lead exposure is 0.976 (standard error 0.542). The elasticity drops somewhat upon the inclusion of controls for the economy, employment, law enforcement, and other factors, and

[52] The effect of abortion exposure on crime has been debated by Joyce (2004a,b); Donohue and Levitt (2004) respond to Joyce. Foote and Goetz (2005) also argue that some of Donohue and Levitt's results are not robust due to an omission of certain fixed effects from some regressions. Donohue and Levitt (2006) respond that improvements to their analysis restore robustness. The issues raised by Foote and Goetz pertain primarily to analysis of abortion and age-specific arrest rates, and consequently are not directly relevant to the state panel analysis in this paper.
[53] Bertrand, Duflo, and Mullainathan, 2004.
[54] In a log-linear specification, multiplying the coefficient by the weighted mean of the independent variable yields the average elasticity in the sample. The weighted means for the sample are shown in Table 1. Standard errors are also rescaled by the means.

TABLE 5 — Panel Data Estimates of the Relationship Between Childhood Lead Exposure and Crime

	Violent Crime			Property Crime			Murder		
Variable	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
Lead (grams per gallon)	0.976 *	0.888 **	0.785 *	0.427	-0.046	-0.078	1.084	0.492	0.369
	(0.542)	(0.449)	(0.403)	(0.368)	(0.304)	(0.281)	(0.656)	(0.650)	(0.596)
Abortion			-0.224 **			-0.144 **			-0.232 **
			(0.057)			(0.056)			(0.067)
State unemployment rate		-0.023	0.702		2.329 **	2.878 **		2.086 **	2.845 **
		(1.057)	(0.839)		(0.880)	(0.819)		(1.314)	(1.221)
Log income per capita		-0.547	-0.073		-0.434	-0.171		-0.092	0.440
		(0.350)	(0.371)		(0.277)	(0.285)		(0.387)	(0.491)
Poverty rate		-0.007	-0.003		-0.009 **	-0.008 **		-0.016 **	-0.011 *
		(0.005)	(0.004)		(0.004)	(0.004)		(0.008)	(0.007)
AFDC generosity (15 yr lag)		0.013	0.008		0.005	0.003		0.010	0.005
		(0.013)	(0.011)		(0.012)	(0.012)		(0.024)	(0.021)
Teen pregnancy rate (effective)		2.276	0.263		0.444	-0.511		6.376	3.734
		(3.961)	(3.471)		(2.888)	(2.597)		(5.364)	(5.004)
Log prisoners per capita (1 yr lag)		0.119	0.061		-0.138	-0.150		-0.133	-0.214
		(0.110)	(0.092)		(0.111)	(0.108)		(0.159)	(0.133)
Log police per capita (1 yr lag)		-0.221 **	-0.181 *		-0.214	-0.189		-0.424 **	-0.383 **
		(0.117)	(0.110)		(0.152)	(0.150)		(0.179)	(0.173)
Shall-issue concealed weapons law		0.060 **	0.041 *		0.066 **	0.058 **		-0.020	-0.044
		(0.030)	(0.026)		(0.028)	(0.026)		(0.054)	(0.050)
Beer consumption per capita		0.043 **	0.020 **		0.059 **	0.047 **		0.031 *	0.004
		(0.013)	(0.011)		(0.011)	(0.012)		(0.019)	(0.020)
Share of population age 15 to 29		1.141	-1.285		1.310	-0.121		2.384	-0.303
		(1.855)	(1.737)		(1.291)	(1.151)		(2.389)	(2.287)
R-squared	0.95	0.96	0.96	0.94	0.96	0.96	0.94	0.96	0.96

Notes. The dependent variable is the natural log of the per capita crime rate shown at the top of the column. Lead is effective gasoline lead exposure (grams per gallon) in the first 3 years of life, corrected for migration. To represent elasticities, coefficients and standard errors for effective lead exposure have been multiplied by the mean of the effective lead exposure variable over the sample period (1.27 grams per gallon, c.f Table 1.) A similar adjustment is made for effective abortion exposure. The data include observations for 50 states and the District of Columbia for the years 1985 to 2002 (918 observations). Observations are weighted by state population. State and year fixed effects are included in all columns. Standard errors are Huber-White robust and clustered on state. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

after controlling for abortion it drops to 0.785 (standard error 0.403). Effective abortion exposure shows a significant elasticity of 0.22 for violent crime, slightly larger than the elasticity originally reported by Donohue and Levitt. Most of the other controls have the correct sign but insignificant coefficients: only police, guns, and beer consumption are significant.

These results suggest that childhood lead exposure is significantly associated with violent crime. Based on these estimates, the fall in gasoline lead would be responsible for a 56% drop in violent crime between 1992 and 2002. These results also imply that abortion legalization was responsible for a 29% drop in violent crime between 1992 and 2002.

Turning to the other crime categories, Table 5 shows insignificant results. Childhood lead exposure does not appear to show a significant relationship with property crime or murder. Abortion exposure is significant for both property crime and murder, with elasticities of 0.14 and 0.23 respectively.

Sensitivity analysis

I test the robustness of the above results by employing alternate samples, specifications, functional forms, and lead measures. We will see that the violent crime results are robust, that little evidence supports a causal effect of lead exposure on property crime, but some evidence suggests an effect of lead exposure on murder.

Alternate samples and specifications

Table 6 shows a variety of different specifications using effective gasoline lead exposure. The baseline specification includes state fixed effects, year fixed effects, all controls, and abortion (identical to columns 3, 6, or 9 in Table 5). The next four rows exclude some states with either high population density or high population.[55] The following rows include state-specific linear trends and region-year interactions. The next group shows results of unweighted regressions and results when effective lead exposure is not corrected for cross-state migration (i.e., assuming individuals remain in the state in which they were born). The last two rows show results for a log-log, rather than log-linear, specification.

The results for violent crime are robust to nearly all of these sensitivity tests. In most specifications, the coefficients change slightly and remain significant, with elasticity estimates ranging between 0.7 and 1.1 and significance levels below 0.05. When New York, California, and the District of Columbia are dropped from the sample individually or as a group, the point estimate rises and becomes slightly more significant. As discussed above, the fact that grams per

[55] New York and the District of Columbia have the highest densities by far, and California and New York have the highest populations. See Appendix Table 3.

TABLE 6 — Sensitivity Analysis for Panel Data Estimates of the Relationship between Childhood Lead Exposure and Crime

	(1) Violent Crime	(2) Property Crime	(3) Murder
Baseline	0.785 *	-0.078	0.369
	(0.403)	(0.281)	(0.596)
Exclude New York	0.963 **	-0.103	0.684
	(0.377)	(0.244)	(0.560)
Exclude California	0.930 **	0.086	0.749
	(0.416)	(0.291)	(0.555)
Exclude the District of Columbia	0.826 **	-0.049	0.394
	(0.383)	(0.280)	(0.567)
Exclude NY, CA, DC	1.146 **	0.053	1.075 **
	(0.325)	(0.208)	(0.393)
Include state-specific trends	0.241	0.096	0.534
	(0.754)	(0.174)	(0.634)
Include region-year interactions	1.813 **	0.637	1.887 **
	(0.466)	(0.501)	(0.740)
Unweighted	0.969 **	-0.328	0.745
	(0.440)	(0.216)	(0.468)
Unweighted, exclude NY, CA, DC	1.081 **	-0.268	0.938 **
	(0.406)	(0.196)	(0.403)
Not cross-state migration corrected	0.447	-0.147	0.170
	(0.312)	(0.196)	(0.480)
Not cross-state migration corrected	0.874 **	0.044	0.853 **
exclude NY, CA, DC	(0.273)	(0.165)	(0.342)
Use log of lead exposure	0.786 **	0.638 **	-0.070
	(0.323)	(0.295)	(0.416)
Use log of lead exposure	0.898 **	0.254	0.310
exclude NY, CA, DC	(0.334)	(0.296)	(0.402)

Notes. Coefficients shown are average elasticities of crime with respect to lead over the sample period. The baseline specification is identical to that shown in Table 5, Columns 3, 6, and 9. It includes all state-level controls and state and year fixed effects. Each additional row is modified as indicated on the left of the table. Standard errors are shown in parentheses and are Huber-White robust and corrected for serial correlation in a short panel by clustering on state. Observations are weighted by state population. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

gallon does not make specific adjustments for the intensity or density of individual exposure to lead may render it somewhat less accurate for dense or heavily populated states. Recalling that the average population density in New York and the District of Columbia are extremely high, it is not surprising that removing these states from the sample increases the estimated strength of the relationship between gasoline lead (gpg) and violent crime. (Note also that this result is parallel to the blood lead results shown in Table 4, in which removing these states increased the estimated elasticity of blood lead with respect to gasoline lead.) Including state-specific trends reduces the coefficient substantially, increases the standard error, and yields an insignificant elasticity. This specification is identified using the residual variation of each state around its own time trend, and is likely to reduce the signal to noise ratio and to increase attenuation bias. Controlling for omitted factors with region-year fixed effects more than doubles the point estimate, yielding an elasticity of 1.81.

Removing the migration correction reduces the elasticity of violent crime with respect to gasoline lead to an insignificant 0.45. This is not surprising, since generally 25%-40% of the population will migrate out of their state of birth. Such migration introduces noise in the uncorrected effective lead measures by incorrectly assigning lead exposure to the portion of the population that switched states. Interestingly, this effect appears to be most important for the high population and high density states: when these states are dropped, the elasticity is significant and close to the baseline estimate even without the migration correction. The final rows, testing the possibility that the effect of lead exposure on crime has a functional form other than log-linear, show a significant elasticity of 0.79 in a log-log specification.[56] Overall, the analysis in Table 6 shows that the relationship between lead and violent crime is robust to a variety of specification checks.[57]

The sensitivity tests for property crime provide almost no evidence of any connection to lead exposure. The coefficients are of varying sign and are almost always insignificant. Considered in the context of previous research, this is not surprising. The psychological mechanisms by which lead exposure may affect criminality involve a spectrum of impulsive, aggressive, and violent behaviors.

[56] Additional specifications tested a quadratic, a linear spline with breakpoints at quartiles of effective lead exposure, and a linear spline with breakpoints at the 50th, 75th, and 95th percentiles. As discussed below, there is mild evidence for a decreasing marginal effect of lead exposure on violent crime. However, the levels of lead exposure observed in this sample correspond to blood lead levels between 10 and 20 μg/dL, so these results do not speak directly to the form or significance of the relationship at lower blood lead levels.

[57] The results are robust to other sensitivity tests: excluding additional high-population or high-density states; using only birth-year exposure rather than early childhood exposure; controlling for other maternal characteristics (mother with less than high school education, no prenatal care in the first trimester); controlling for more detailed population age shares; including an interaction between lead and abortion.

There is extensive evidence on the effect of lead on violent and aggressive behavior, including violent criminal behavior, but much less evidence indicating an effect on non-violent property crime.[58]

The results for murder provide some mild evidence of a relationship. While the baseline estimate is insignificant, there is a significant elasticity of 1.08 of murder with respect to gasoline lead when high population and high density states are excluded. Significant effects also arise when region-year fixed effects control for unobservables, and in most other specifications dropping these states. Further investigation reveals that this sensitivity arises almost entirely from New York and the District of Columbia, and may reflect the omission of crack cocaine, gangs, and guns from the analysis. These are potentially important factors affecting homicides in central cities in this time period, particularly in New York, as discussed in Maltz (1998) and Fagan *et al.* (1998).[59] It is also possible that access to and quality of hospital trauma care influenced murder rates (by saving the victim, thereby turning some potential murders into violent assaults, see Harris *et al*. (2002)). While future work may explicitly control for these influences, the current results do provide some weak support for the possibility that lead exposure may be linked to murder.[60]

Alternate lead measures and alternate functional forms

Gasoline lead (grams per gallon) has been used as the primary lead measure because it is simple, was the target of EPA regulation, and is a robust predictor of children's blood lead. At the same time, gasoline lead is not a perfect measure and I consider alternate lead measures, some of which may also predict blood lead (per-capita lead and the instrumented air lead both do). Now I investigate the sensitivity of the crime results to these alternate measures of lead exposure and to alternate functional forms. Because of the centrality of population density and population in the choice of the appropriate lead measure, I also consider results that drop just New York from the sample (high on both density and population) and that drop all three high-population and high-density states (New York, California, and the District of Columbia).

[58] Kandel and Mednick (1991) also provide evidence that childhood biological trauma is associated with violent crime but not with property crime.

[59] Levitt (2004), Goldstein *et al.* (1997), Cork (1999), Grogger and Willis (2000), and Fryer *et al.* (2005) all discuss the importance of crack cocaine, particularly in New York and the District of Columbia. Fagan (1998) discusses the hypothesis that gangs and guns produced trends in homicides that differed from trends in violent crime more generally, and that this divergence was particularly important in New York City.

[60] Sensitivity testing for the effect of abortion on crime generally confirms its significance, with a few exceptions: in the unweighted specification, coefficients are smaller and insignificant; when state-year trends are included the coefficients are wrong-signed and large (and significant for property crime and murder); in the log-log specification dropping three states the coefficients are smaller, and significant only for property crime.

TABLE 7 — Violent Crime Results
Using Alternate Lead Measures

	Gasoline Lead Measures		Air Lead Measures	
	Grams per Gallon	Per-Capita Lead	Air Lead	IV
Linear	0.785 *	0.127	0.210 **	0.980 **
	(0.403)	(0.444)	(0.086)	(0.474)
Linear, Exclude NY	0.963 **	0.740 **	0.193 **	1.192 **
	(0.377)	(0.317)	(0.092)	(0.437)
Linear, Exclude NY, CA, DC	1.146 **	0.788 **	0.078	1.374 **
	(0.325)	(0.293)	(0.116)	(0.389)
Log	0.786 **	0.758 **	0.159	1.075 **
	(0.323)	(0.299)	(0.124)	(0.429)
Log, Exclude NY	1.027 **	1.028 **	0.125	1.378 **
	(0.318)	(0.292)	(0.127)	(0.397)
Log, Exclude NY, CA, DC	0.898 **	0.957 **	0.042	1.300 **
	(0.334)	(0.326)	(0.125)	(0.409)

Notes. Coefficients shown are average elasticities of violent crime with respect to lead over the sample period. The baseline specification is identical to that shown in Column 3 of Table 5. It includes all state-level controls and state and year fixed effects. Each additional row is modified as indicated on the left of the table. Each column shows results for the migration-corrected effective lead measure indicated at the top of the column. Standard errors are Huber-White robust and clustered on state. Observations are weighted by state population. Significance is indicated by ** for p-values below 0.05 and * for p-values below 0.10.

Table 7 shows these results for violent crime. The first column (largely reproducing results from Table 6) shows again that the results for gasoline lead (grams per gallon) are robust to dropping the three high-population and high-density states and to the log-log specification. Analysis using a spline at quartiles of lead exposure (shown in Appendix Table 4) yields significant and relatively stable coefficients as well.

Results for the first alternate lead measure, per-capita lead, are shown in the second column of Table 7. Recall that per-capita lead attempts to correct for the intensity of driving in a state, but that it is biased downward for high-population and high-density states, particularly New York.[61] Looking at the results, we see that per-capita lead shows insignificant effects in the linear specification for the full sample, but significant and large effects when New York is removed. Moreover, in a log-log specification per-capita lead shows significant effects for violent crime whether or not New York is included in the sample. Removing the District of Columbia and California has little effect. The spline yields significant and relatively stable estimates over the range of lead exposure, with some indication of non-linearity when New York is included. Overall, the violent crime results that use per-capita lead are extremely similar to those that use gasoline lead, with estimated elasticities in the range of 0.7 to 1.0 and standard errors of 0.3 to 0.4.[62]

The next two columns show results for air lead and the instrumented air lead.[63] Air lead, subject to many measurement problems and ineffective in predicting blood lead, is similarly ineffective in predicting violent crime. The estimated elasticities are much smaller (0.04 to 0.21), imprecisely estimated, and mostly insignificant.[64] By contrast, the instrumented air lead, a good predictor of blood lead, shows strong results in all samples and all specifications. Elasticity estimates lie between 1.0 and 1.4, slightly higher than those obtained using gasoline lead. Note the general concordance between the earlier results testing the implicit first stage (Table 4) and these results testing the reduced form: measures of childhood lead exposure that predict children's blood lead appear also to be strongly related to violent crime in adulthood.

Similar sensitivity testing for murder (shown in Appendix Table 5) aligns with earlier results, yielding slight evidence in favor of a relationship between lead and murder. No significant results are observed in the full sample nor in the log-log specification for any of the lead measures. The only significant results are observed for grams per gallon, per-capita lead, and the instrumented air lead in the log-linear specification in the reduced sample. These elasticities are of the order observed elsewhere, between 0.7 and 1.3. Further investigation of non-linearity using a spline points to an increasing marginal effect of lead on murder, with significant effects primarily in the fourth quartile of lead exposure. This may

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[61] Per-capita lead divides by population (New York's is 2nd-highest) but does not adjust for population density (New York's is highest), producing a severe downward bias for New York.

[62] Experienced lead produces generally fragile results, except in the log-log specification for which the elasticities are significant, reasonably robust, but slightly smaller than those found using grams per gallon or per-capita lead. Note that this parallels the blood lead results.

[63] Effective instrumented air lead is calculated in three stages. First, the relationship between air lead and gasoline lead (grams per gallon) is estimated using air lead and gasoline lead data from 1965 to 1985, as shown in Table 2. Second, that estimated equation is used to predict air lead for each state in each year from 1956 to 1990. Third, equation (6') is used to calculate effective instrumented air lead for the crime years 1985 to 2002.

[64] The few significant results are largely driven by California. Analysis using the most reliable air measures (from the 29 states with near-continuous monitoring) provides no improvement.

explain why a log-log specification, which imposes a *decreasing* marginal effect, shows weak results, while a log-linear specification yields some significant results. As discussed above, the three states may be influential due to the omission of other factors important to homicide rates.

For property crime, again little evidence suggests any influence of lead exposure (results not shown). The log-log specifications do yield significant elasticities of 0.4 to 0.7 for all measures other than air lead, but these results are not robust to the removal of the three states.

VI. INTERPRETATION

Childhood lead exposure appears to be significantly related to adult violent crime. The central result from the above analysis is an elasticity of violent crime with respect to gasoline lead of 0.79, with estimates ranging between 0.7 and 1.1 with standard errors of 0.3 to 0.4. I now endeavor to assess the importance of this effect in influencing violent crime at the societal level.

A. Accounting Crime Trends

To understand the societal magnitude of these effects, I first consider the period from 1992 to 2002, during which time violent crime declined by 34%. The above results predict a 56% decline in the per capita violent crime rate due to reductions in lead exposure. At the same time, the increased effective abortion rate would reduce per capita violent crime by 29%. Other factors (police, prisons, beer consumption, and crack) appear to be responsible for an approximate 23% decline.[65] In total, then, all of these influences substantially over-explain the decline in crime, and some other unknown factors must have increased crime.

I can also look at a longer time frame, to examine both the rise and the decline in crime. In the earlier period from 1972 to 1992, violent crime went up 83%. In this period, effective grams per gallon rose 19%, which would lead to a 28% increase in violent crime. However, as discussed above, much of the *rise* in lead exposure came from the increase in driving and the concomitant *use* of gasoline (rather than the increase in lead content).[66] Because per-capita lead takes this intensity of gasoline *use* into account (multiplying by gallons per capita), it may better describe the rise in lead exposure. Such an approach yields an estimate of a 91% increase in violent crime due to increasing lead exposure.

[65] The current results support a role for police and beer consumption (4% decline each), and Levitt (2004) presents evidence that the growth in prisons was responsible for a 12% decrease and the decline in crack usage (and associated violence) was responsible for a 3% decrease.

[66] Hilton and Levinson provide evidence on an Environmental Kuznets Curve for lead, as discussed previously. In addition, recall that results for per-capita lead are very similar to those using grams per gallon, with the exception of sensitivity to the inclusion of New York.

Abortion and other factors were relatively unimportant in this time period, but Levitt (2004) argues that the growth of prisons was responsible for a 35% reduction in violent crime.[67]

Putting the pieces together, the long story is approximately as follows. From 1972 to 1992, violent crime rose 83%: increasing lead exposure produced a 28-91% increase, the growth of prisons produced a 35% decrease, and a remaining 24-87% increase remains unexplained. From 1992 to 2002, violent crime dropped 34%: declining lead exposure produced a 56% decrease, legalized abortion produced a 29% decrease, other factors produced a 23% decrease, and a remaining 74% increase remains unexplained. Thus, the current results imply that lead exposure was likely an important factor in both the rise and the decline of violent crime in the last 30 years. At the same time, the history of violent crime is not fully understood: a sustained rise in crime of about 3-5% annually remains unexplained.

Lastly, we can ask what these results might imply about future trends in crime. This projection should be undertaken with caution: not only will unknown and unpredictable factors certainly influence crime in the coming decades, but the effect of childhood lead exposure might be different at the lower levels relevant to coming cohorts.[68] With those caveats in mind, I make the following tentative predictions. By the year 2020, when the effects of the Clean Air Act and *Roe v. Wade* would be complete, violent crime could be as much as 70% lower than it would be if lead had remained in gasoline, and as much as 35-45% lower than it would be if abortion had never been legalized. At the same time, history suggests that other unknown factors would have increased crime by perhaps 3-5% per year.

B. Benefits of Crime Reduction

Another way to assess the magnitude of these impacts is to compare the social costs of the removal of lead from gasoline to the benefits in the form of crime reductions. The costs of the removal of lead from gasoline are discussed at length in the 1985 EPA report *Costs and Benefits of Reducing Lead in Gasoline: Final Regulatory Impact Analysis*.[69] The report uses a linear programming model of

[67] Levitt (2004) estimates the effects of other factors between 1973 and 1991 as follows: increases in the number of police, -3%; the rise of crack, +8%; legalized abortion, -2%.

[68] In the period 1992 to 2002, the childhood lead exposure of the adult U.S. population declined by about half, approximately from 18 μg/dL to 10 μg/dL. The remaining half of the decline, to less than 3 μg/dL, will occur from 2002 to 2018. Most neurotoxins show a "hockey-stick" effect, with a much lower marginal effect below some threshold. Research does not show evidence of a clear threshold for lead, but it is certainly plausible. If there is a declining marginal effect for lead on crime, the predicted crime reductions would be lower. The 70% decline in violent crime that is quoted in the paper is calculated assuming that the elasticity below 10 μg/dL is approximately half of that estimated in the paper. If that assumption were not made, the decline would be 83%.

[69] EPA, 1985, Chapter II.

refinery behavior to estimate the social costs of lead reduction regulations. The model estimates that the marginal manufacturing cost differential between leaded gasoline containing 1.10 grams per gallon and unleaded gasoline was less than 3 cents per gallon. This value matches well with estimates based on inter-refinery trades of lead permits (3 to 4 cents per gallon) as well as spot prices of gasoline (2 to 6 cents per gallon differential). I use these values, together with the more detailed cost estimates in the report, to estimate that the cumulative social cost for the period 1970 to 1995 of the switch to unleaded gasoline was between 15 and 65 billion dollars.[70]

To calculate the social value of crime reductions, I employ estimates of the monetary and quality of life costs of violent crimes from Cohen (1988) and Miller, Cohen, and Rossman (1993). Monetary costs include lost productivity, lost property, and medical bills, while quality of life costs attempt to capture pain and suffering (by estimating from jury awards). In these estimates, the average violent crime incurs \$3,600 of monetary costs and \$54,700 of quality of life costs.[71] I combine these figures with the estimated reductions in violent crime that can be attributed to lead exposure for the period 1990 to 2020 (from 0% rising to 70%), to produce an estimate of 1.22 trillion dollars (\$75 billion monetary and \$1.15 trillion quality of life).

Thus, the cost of the removal of lead from gasoline is similar in size to the monetary value of the resultant reduction in violent crime, and is approximately twenty times smaller than the full value of the crime reductions.

C. Extensions

The relationship between lead and violent crime has further implications. First, it may contribute to explaining rural-urban differentials in crime rates as well as the cross-sectional relationship between crime and city size. Larger cities have much higher per-capita crime rates, and Glaeser and Sacerdote (1999) account for half to three-quarters of this gap with differential deterrence, returns to crime, and individual characteristics. If individuals living in dense cities are exposed to more automobile exhaust and consequently more lead, exposure to lead could be an important additional factor. Second, lead may be a factor in explaining crime rates by race or income. If disadvantaged groups live in denser and more polluted neighborhoods, they will experience higher lead exposure as children and therefore exhibit more criminal behavior as adults. It may be possible to use the indices of segregation outlined by Cutler, Glaeser, and Vigdor (1999) to test this

[70] All dollar values are reported in year 2000 dollars.

[71] Monetary costs of the average violent crime in each category (in thousands of 2000 year dollars) are: murder 21.8, rape 12.6, assault 2.3, robbery 3.7; quality of life costs are: murder 3,462, rape 52.3, assault 13.1, robbery 19.1. The share of violent crime that each category represents is: murder 0.01, rape 0.06, assault 0.64, robbery 0.29.

hypothesis. Third, lead may explain and predict certain cross-national patterns of crime and other behaviors. Hilton and Levinson (1998) use international data to document the existence of an environmental Kuznets curve for lead. If lead pollution rises with income and then declines, the current results imply that violent crime would also rise with income and then decline, but with a 20-year lag. The result would be a crime Kuznets curve, as well as Kuznets curves for other social behaviors such as substance abuse, teenage pregnancy, and suicide. Further work could investigate these and other hypotheses.

VII. CONCLUSION

This paper shows a significant and robust relationship between lead exposure in childhood and violent crime rates later in life. The estimates indicate that the reduction in lead exposure in the 1970s is responsible for a 56% drop in violent crime in the 1990s and will likely produce further declines in the future, up to a 70% drop in violent crime by the year 2020. The legalization of abortion, as identified by Donohue and Levitt, remains an important and significant factor. Thus, two major acts of government, the Clean Air Act and *Roe v. Wade*, neither intended to have any effect on crime, may have been the largest factors affecting violent crime trends at the turn of century. These results emphasize the importance of accounting for earlier life influences when explaining adult behavior. While some evidence supports an effect of lead exposure on murder rates, no evidence supports an effect on property crime.

While the results herein imply that lead could be one of the most important factors influencing violent crime in the United States, this effect on crime may be just the tip of the iceberg. Increases in impulsivity, aggression, and ADHD can affect many other behaviors such as substance abuse, suicide, teenage pregnancy, poor academic performance, poor labor market performance, and divorce. Future research will investigate these outcomes, and further explore the potentially far-reaching effects of environmental policy.

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