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Monetary benefits of preventing childhood lead poisoning with lead-safe window replacement

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Abstract

Previous estimates of childhood lead poisoning prevention benefits have quantified the present value of some health benefits, but not the costs of lead paint hazard control or the benefits associated with housing and energy markets. Because older housing with lead paint constitutes the main exposure source today in the US, we quantify health benefits, costs, market value benefits, energy savings, and net economic benefits of lead-safe window replacement (which includes paint stabilization and other measures). The benefit per resident child from improved lifetime earnings alone is $21,195 in pre-1940 housing and $8685 in 1940–59 housing (in 2005 dollars). Annual energy savings are $130–486 per housing unit, with or without young resident children, with an associated increase in housing market value of $5900–14,300 per housing unit, depending on home size and number of windows replaced. Net benefits are $4490–5,629 for each housing unit built before 1940, and $491–1629 for each unit built from 1940–1959, depending on home size and number of windows replaced. Lead-safe window replacement in all pre-1960 US housing would yield net benefits of at least $67 billion, which does not include many other benefits. These other benefits, which are shown in this paper, include avoided Attention Deficit Hyperactivity Disorder, other medical costs of childhood lead exposure, avoided special education, and reduced crime and juvenile delinquency in later life. In addition, such a window replacement effort would reduce peak demand for electricity, carbon emissions from power plants, and associated long-term costs of climate change.

Keywords: Lead poisoning; IQ; Energy efficiency; Cost benefit analysis; Housing; Climate change

1. Introduction

Early childhood lead exposure impairs neurobehavioral development, reducing average educational achievement and lifetime income (National Academy of Sciences, 1993). Previous studies (Schwartz, 1994; Salkever, 1995; Landrigan et al., 2002; Grosse et al., 2002) of the monetized health benefits of avoided preschool lead exposure have focused on the present value of higher lifetime earnings, but not the cost and non-health benefits of lead paint hazard control. Some elevations in childhood blood lead can be caused by lead paint chip ingestion, inhaled air lead, and other types of exposure, but the most pervasive pathway affecting young children today in the US is lead contaminated settled house dust ingested via normal hand-to-mouth activity (Lanphear et al., 1998; Duggan and Inskip, 1985; Bornschein et al., 1987). Leaded gasoline settled as dust lead in years past, but lead emissions fell sharply through the 1980s with the phase out of lead in gasoline (US Environmental Protection Agency, 1986). The use of lead in residential paint was banned after 1977, but lead paint and the contaminated dust and soil it generates remained a hazard in 24 million older housing units in 1999–2000 (Jacobs et al., 2002).

The US Environmental Protection Agency (2001) now defines housing units with ‘‘lead paint hazards’’ to include units that exceed regulatory standards for lead in soil and/or household dust, and/or deteriorated lead paint. Lead paint hazard reduction can be achieved via interim controls that remove lead dust hazards and stabilize deteriorated lead paint, or via permanent abatement of these hazards

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(US Department of Housing and Urban Development, 1999) or a combination of the two. Interim controls that do not remove lead paint may be less expensive in the short term but do not provide a permanent solution without ongoing specialized maintenance. Targeting housing with young children is also problematic because the housing units with children are constantly changing as families move. However, lead hazard control using "lead-safe window replacement" is a strategy that can remove dust lead and lead paint surfaces likely to contaminate dust and soil. This can be expected to yield substantial health benefits for young children occupying such units now or in the future, plus substantial energy savings and increased residential market value (Jacobs and Nevin, 2006; Nevin and Jacobs, 2006). Here, we define lead-safe window replacement to be:

(1) Replacement of all single-pane windows with high-efficiency Energy Star windows;
(2) Stabilization of any significantly deteriorated paint;
(3) Specialized cleaning to remove any lead-contaminated dust following the repairs; and
(4) Clearance testing (which includes dust wipe analysis) to confirm the absence of lead dust hazards after project cleanup.

Replacing single-pane windows substantially reduces energy bills and also effectively targets older housing likely to have lead dust, because single-pane windows are likely to have lead paint on interior surfaces and friction on window surfaces with lead paint cause a large percentage of lead dust hazards (Jacobs and Nevin, 2006). This paper quantifies health benefits realized by young children who occupy housing that has undergone lead-safe window replacement. It also quantifies energy savings and an associated increase in home value that provide ongoing monetary benefits in units not currently occupied by families with children. We quantify the upgrade costs, market benefits, annual energy bill savings, quantifiable health benefits, and net economic benefits of lead-safe window replacement in pre-1978 housing.

2. Methods

2.1. Trends in preschool blood lead, and blood lead reduction from window replacement

National Health and Nutrition Examination Survey (NHANES) 1999–2002 blood lead data for children ages 1–5 are compared with 1991–1994 NHANES data to show the 1990s trend in elevated preschool blood lead by age of housing. The 1999–2000 National Survey of Lead and Allergens in Housing (NSLAH) data on lead paint hazard prevalence by age of housing (Jacobs et al., 2002), and trends in other lead exposure pathways, are then compared with the NHANES trend to confirm that lead paint hazards now cause the vast majority of preschool lead exposure.

The reduction in average preschool blood lead resulting from lead-safe window replacement (and the associated lifetime earnings benefit, discussed below) varies by age of housing and whether there is lead paint on interior window surfaces. Lead contaminated dust is more common in housing with lead paint on interior window surfaces. Furthermore, interior lead paint on windows is more common in older homes, and older homes have higher average lead loadings in dust. This analysis examines the percentage of housing units with lead dust hazards, and the associated reduction in average preschool blood lead resulting from lead-safe window replacement in pre-1940, 1940–1959, and 1960–1977 housing units with and without lead paint on interior window surfaces.

2.2. Lifetime earnings benefit from lead-safe window replacement

As explained in the equations and variables defined below, the average lifetime earnings benefit per resident child in housing units with lead-safe window replacement is calculated as the weighted average benefit in units with and without lead paint on interior window surfaces. The overall average benefit per housing unit with lead-safe window replacement is then derived from the benefit per resident child and the average number of resident young children per unit.

The average benefit per resident child in housing units with lead paint on window surfaces is

$$A \times B \times C \times D = E,$$

where A is the present value of lifetime earnings associated with a one point increase in IQ ($/IQ), B is IQ lost per 1 μg per deciliter (μg/dL) increase in preschool blood lead (IQ/μg/dL), C is the lead dust hazard prevalence in units with lead paint on interior window surfaces (%), D is the avoided increase in blood lead for children in units where lead-safe window replacement removes lead dust hazards and windows with lead paint on interior surfaces (μg/dL), E is the Benefit per resident child in units with lead paint on interior window surfaces.
$= A \times B \times C \times D$ ($/resident child).

The average benefit per resident child in housing units without lead paint on interior window surfaces is

$$A \times B \times F \times G = H,$$

where A and B are as defined above. F is the lead dust hazard prevalence in units *without* lead paint on interior window surfaces (%), G is the avoided increase in blood lead for children in units where lead-safe window replacement removes lead dust hazards and windows *without* lead paint on interior surfaces (μg/dL), H is the benefit per resident child in units *without* lead paint on interior window surfaces
$= A \times B \times F \times G$ ($/resident child).

The weighted average benefit per resident child in units with lead-safe window replacement is

$$(E \times I) + (H \times (1 - I)) = J,$$

where E and H are as defined above. I is the percent of housing with mostly single-pane windows that also have lead paint on interior window surfaces (%). J is the lead-safe window replacement weighted average benefit per resident child $= (E \times I) + (H \times (1-I))$ (average $/resident child in units with single-pane windows).

The average lifetime earnings benefit per unit with lead-safe window replacement is the present value of the average benefit per unit in year 1 (M) and years 2–10 (N), where K is the average number of children ages 6–30 months per housing unit, L is the average number of children ages 6–18 months per housing unit ($K \times 0.5$), M is the lead-safe window replacement average benefit per unit in year 1 ($J \times K$), N is the lead-safe window replacement average benefit per unit in years 2–10 ($J \times L$).

The present value of lifetime earnings associated with a one point increase in IQ (A) consists of the indirect effects of increased educational achievement and workforce participation plus the direct effect of higher hourly earnings (Schwartz, 1994; Salkever, 1995). Estimates updated to 2000 dollars discounted at 3% (Grosse et al., 2002) are updated here to 2005 dollars by increasing the 2000-dollar estimates by 3% per year over the 5 years from 2000–2005, which permits a direct comparison with 2005 cost data. Further, the new estimate for the IQ/blood lead slope (i.e., IQ lost per 1 μg/dL increase in blood lead (B)) is from an international pooled analysis of the IQ loss from 2.5 to 10 μg/dL (Lanphear et al., 2005), because the majority of children in older housing units now fall within this range.

The percentage of housing units with lead dust hazards with and without lead paint on interior window surfaces (*C* and *F*) is derived from NSLAH data for pre-1940, 1940–1959, and 1960–1977 housing. The avoided increase in blood lead by age of housing (*D* and *G*) is derived from differences in average preschool blood lead by windowsill lead dust loadings (US Department of Housing and Urban Development, 1999), and NSLAH data on lead dust loading by year-built in units with and without lead paint on interior window surfaces. The percent of units with single-pane windows with lead paint on interior window surfaces, by year-built (*I*), comes from a published comparison of Residential Energy Consumption Survey (RECS) data on single-pane windows, RECS and American Housing Survey (AHS) window replacement data, and NSLAH data on window surfaces with lead paint (Jacobs and Nevin, 2006). These data and the calculations shown above (*E*, *H*, and *J*) are then used to calculate the weighted average monetary benefit per resident children in units with lead-safe window replacement, by year-built.

Although NHANES data highlight elevated blood lead prevalence among children under age 6, children ages 6–30 months have higher blood lead levels, are especially vulnerable to lead dust ingestion as they crawl and engage in hand-to-mouth activity, and the brain is in a critical stage of development at this age (National Academy of Sciences, 1993). Therefore, this analysis quantifies average lifetime earnings benefits of avoided lead exposure for children ages 6–30 months in year 1 after lead-safe window replacement, and benefits for a new birth year cohort of children ages 6–18 months protected in years 2–10. The average number of children per housing unit in each age band, by year-built, reflects 2001 data on the average number under age 6 (Jacobs and Nevin, 2006) assuming an even distribution across the age range. The average benefit per resident child is multiplied by the average number of children ages 6–30 months per unit to calculate first-year benefits. To calculate benefits in years 2–10, the average benefit per child is multiplied by the average number of children ages 6–18 months. The lifetime earnings benefit of lead-safe window replacement by year-built is then calculated as the present value of years 1–10 benefits (discounted at 3%).

The methodology described above yields a very conservative (i.e., low) estimate of monetized lifetime earnings benefits. Benefits are only quantified for children ages 6–30 months, but some benefit would also be realized by children ages 30–72 months. Moreover, the average number of very young children per housing unit, by year-built, reflects the overall average in 2001, which likely underestimates the number of children ages 6–30 months in higher-risk housing targeted by lead-safe window replacement. Older housing units with single-pane windows are less likely to have undergone substantial renovation, and more likely to house young children in lower-income rental households, thereby harming more children because lower-income renters move more frequently. The present value calculation assumes lead-safe window replacement (which includes deteriorated paint stabilization on non-window surfaces) protects resident children for 10 years, even though it is likely that this housing improvement will last considerably longer (Jacobs and Nevin, 2006). The IQ/blood lead slope estimate is from an analysis of IQ lost in children with blood lead levels between 2.5 and 10 μg/dL (Lanphear et al., 2005), but the IQ lost per μg/dL increase in blood lead is actually higher for the large proportion of children with blood lead below 2.5 μg/dL (Canfield et al., 2003). This could especially understate lifetime earnings benefits for children in 1960-1977 housing, where most children have blood lead below 2.5 μg/dL.

2.3. Other health benefits from lead-safe window replacement

In addition to reducing average lifetime earnings, preschool lead exposure is also associated with a host of other adverse health and behavioral effects. This paper shows other estimates of additional benefits from avoided Attention Deficit Hyperactivity Disorder (ADHD), mental retardation, other medical costs of childhood lead exposure, and criminal behavior related to early childhood lead exposure.

2.4. Lead-safe window replacement costs, annual energy savings, and market value benefits

Window replacement costs and market benefits vary with home size and windows replaced. Estimates were developed for an 800 ft^2 attached home with 7 windows, a 1200 ft^2 detached home with 10 windows, and a 1800 ft^2 detached home with 16 windows. These estimates are based on U.S. Department of Housing and Urban Development (1999) estimates for replacing 7 windows in an 800 ft^2 attached home, and Remodeling Magazine (RM) estimates for 16 windows in 1993 and 10 windows in 2005 (Alfano, 2001–2005), all updated to 2005 dollars.

The RM "cost vs. value" survey data report costs for 60 US metropolitan areas. In each metro area, real estate agents in diverse neighborhoods (3–7 per metro area) were asked how much the window replacement project would add to the resale value of a "mid-priced house in an established neighborhood." Analysis of the 1993 RM survey and 1991–1996 AHS data found that pre-1980 detached homes ranged from 1600 to 2400 ft^2 across 25 metro areas in both datasets, with an average size of 1800 ft^2 (Nevin et al., 1999). Assuming a similar window to floor area suggests the 2005 RM survey cost and market value is representative of a 1200 ft^2 detached home with all 10 windows replaced. Our estimated 2005 cost and market value for an 800 ft^2 attached home with 7 windows and a 1800 ft^2 detached home with 16 windows is the same cost and value per window as the 2005 RM Survey.

The 2005 RM cost for 10 windows was 76% higher than the 1995 RM cost for 10 windows, and applying the same cost per window yields 2005 cost estimates for the larger detached home and the smaller attached home that are 111% higher than the 1993 RM cost estimate for 16 windows and the US Department of Housing and Urban Development (1999) estimate for 7 windows. These cost increases are larger than a 46% 1995–2005 increase in the Turner (2006) Construction Cost Index, consistent with an inflation-adjustment plus a real cost increase for energy-efficient features in typical 2005 replacement windows relative to mid-1990s replacement windows. Therefore, this paper uses the higher cost estimates from the 2005 RM data.

Average annual household energy savings from replacing single-pane windows with Energy Star windows (Nevin et al., 1999; US Department of Housing and Urban Development, 2000) are updated here to 2005 dollars (US Bureau of the Census, 1998, 2006). The 1993 RM survey value for window replacement has been shown to reflect the sum of the market value related to annual energy savings plus an "appearance value" for new windows (Nevin et al., 1999), but the 2005 RM survey value used in this analysis might not fully reflect the rising energy costs in late-2005 through 2006. Therefore, this analysis will underestimate the current market benefit of window replacement associated with annual energy savings (see Section 4).

Cost and value estimates for interior and exterior paint stabilization, cleanup, and clearance testing used in this paper are drawn from US Department of Housing and Urban Development (1999) estimates for the mid-1990s inflated to 2005 dollars based on the 1995–2005 change in the Turner (2006) Index. Weighted average estimates for paint stabilization reflect the cost and value for a single room, and a limited exterior surface area, divided by 5 to reflect an assumed deteriorated paint prevalence of 20% (80% of units would not require paint stabilization).

3. Results

3.1. Trends in preschool blood lead, and blood lead reduction from window replacement

Table 1 shows that preschool children with blood lead above 10 μg/dL are increasingly concentrated in older housing. The 1991–1994 NHANES data reported a higher prevalence of elevated blood lead in housing built before 1978, but some children in post-1977 housing also had blood lead above 10 μg/dL in the early 1990s (US Centers for Disease Control and Prevention, 1997). In contrast, the 1999–2002 NHANES data show a very low prevalence over 10 μg/dL, and over 5 μg/dL, among children living in housing built after 1977. In fact, children in pre-1940 housing account for only 10% of all 1999–2002 NHANES children ages 1–5, but account for 40% of all children with blood lead over 10 μg/dL. Children in housing with year-built not reported account for another 30% of 1999–2002 NHANES children over 10 μg/dL. The vast majority of the "not reported" cases are low-income children in rental units, and old housing accounts for a disproportionate share of low-income rental units (US Bureau of the Census, 2006), so it is likely that most of the "not reported" cases are also in older housing. The few children in post-1977 housing with 1999–2002 NHANES blood lead over 10 μg/dL were all Mexican-American. The Arizona Department of Health Services (2002) also reports that 79% of Arizona children over 10 μg/dL are Hispanic, with lead glazed pottery and home remedies cited as common sources of lead poisoning. Some NHANES children in post-1977 housing with blood lead over 5 μg/dL were also likely exposed to lead paint visiting relatives or in daycare in older housing, and others could have been exposed in a prior residence.

The increasing concentration of children with elevated blood lead in older housing is consistent with historic use of lead in paint, and a 1990s decline in lead exposure via other pathways. Per capita use of lead in paint peaked from 1900 to 1930 and fell over 90% from the late-1920s to 1960 (Nevin, 2000). These trends are still evident in 1999–2000, because pre-1940 housing has lead paint on more interior surfaces and higher lead levels in paint (Jacobs et al., 2002). The NSLAH found lead paint hazards in 68% of pre-1940 homes, 43% of 1940–1959 homes, 8% of 1960–1977 homes, and just 3% of post-1977 homes. The low lead dust prevalence in post-1960 homes is consistent with a sharp decline in lead emissions and ambient air lead through the 1980s, with ambient air lead falling another 57% from 1993–2002 as lead emissions fell just 5% (US Environmental Protection Agency, 2003). The ongoing decline in air lead after the 1980s fall in emissions suggests that settling air lead still affected some children in the early-1990s, but this lead exposure source was almost entirely eliminated by 2000. A comparison of 1992–1993 and 2000–2004 monitoring data for 166 large water utilities also shows that all 166 utilities were above the action level for lead in drinking water in the early-1990s, but only 15 exceeded that level in 2000–2004 (US Environmental Protection Agency, 2006b).

The NHANES data in Table 1 also show that almost 60% of children in pre-1950 housing, 50% in 1950–1959 housing, and 40% in 1960–1977 housing have blood lead between 2 and 10 μg/dL. These NHANES data show that most of the total national health benefit of lead-safe window replacement would be realized by children with blood lead below 10 μg/dL, where every 1 μg/dL increase in blood lead is associated with an average loss of 0.52 IQ points (Lanphear et al., 2005).

Table 2 shows the increase in preschool blood lead associated with windowsill dust lead loadings above the 250 μg/ft^2 (micrograms of lead per square foot) regulatory definition of a windowsill lead dust hazard (US Environmental Protection Agency, 2001; US Department of Housing and Urban Development, 1999). Children in units with median sill dust lead loadings of 250–500 μg/ft^2 have average blood lead that is 1.98 μg/dL higher than children in units with no sill dust lead hazards, and children in units with sill loadings of 500–1000 μg/ft^2 and over 1000 ug/ft^2 have average blood lead 2.44 and 4.33 μg/dL higher, respectively. Table 3 shows NSLAH data on median sill dust lead loadings in units with lead dust hazards by age of housing and presence of lead paint on interior window surfaces. Together, Tables 2 and 3 indicate that lead-safe window replacement in housing units with dust lead hazards would reduce average preschool blood lead by 4.33 μg/dL in pre-1960 housing units with lead paint on interior window surfaces; by 2.44 μg/dL in pre-1960 units *without* lead paint on interior window surfaces and in 1960–1977 units *with* lead paint on interior window surfaces; and by 1.98 μg/dL in 1960–1977 units without lead paint on interior window surfaces.

3.2. *Lifetime earnings benefit from lead-safe window replacement*

Table 4 calculates the weighted average lifetime earnings benefit of lead-safe window replacement based on the

Table 1
Preschool blood lead (BL) prevalence by housing year-built

Year Housing Unit Built	1991–1994 BL > 10 μg/dL (%)	1999–2002 BL > 10 μg/dL (A) (%)	1999–2002 BL > 5 μg/dL (%)	1999–2002 BL > 2 μg/dL in pre-1978 Housing (B) (%)	1999–2002 BL of 2-10 μg/dL in pre-1978 Housing (A–B) (%)
Post-1989	N.A.	0.0	1.2		
1977–1989	1.6	0.6	2.8		
1960–1977	4.6	0.8	4.4	39.4	38.6
1950–1959	4.6	1.1	6.2	50.2	49.1
1940–1949	4.6	0.8	10.4	60.3	59.5
Pre-1940	8.6	5.3	20.2	64.7	59.4
Not reported	5.6	1.7	14.3	59.1	57.5

monetized value of one IQ point, the fraction of IQ lost per 1 μg/dL increase in blood lead, NSLAH data on lead dust hazard prevalence by age of housing, the reduction in average blood lead in units with lead dust hazards with and without lead paint on window surfaces, and the percent of housing units with single-pane windows that also have lead paint on interior window surfaces. The weighted average lifetime earnings benefit per young resident child is $21,195 in pre-1940 housing, $8685 in 1940–1959 housing, and $2219 in 1960–1977 housing. The average lifetime earnings benefit across all housing, based on the fraction of units with children ages 6–30 months, is $6847 in pre-1940 units, $2847 in 1940–1959 units, and $632 in 1960–1977 units. This assumes that new birth cohorts of young children are protected for a time horizon of 10 years, although the benefit is likely to last considerably longer.

Table 2
Increase in average preschool blood lead associated with windowsill dust lead

Sill dust lead (μg/ft^2)	Blood lead relative to sill dust lead < 250 μg/ft^2 (μg/dL)
250–500	+1.98
500–1000	+2.44
Over 1000	+4.33

Table 3
Median windowsill dust lead loading in units with lead dust hazards

	Pre-1960 housing (μg/ft^2)	1960–1977 housing (μg/ft^2)
Units with lead paint on interior window surfaces	Over 1000+	500–1000
Units without lead paint on interior window surfaces	500–1000	250–500

3.3. Other health benefits from lead-safe window replacement

The benefits quantified in Table 4 reflect only lifetime earnings benefits, but lead exposure also imposes many other health costs (Schwartz, 1994; Salkever, 1995; Landrigan et al., 2002). The direct health care costs for children exposed to lead includes chelation, follow-up, monitoring, visits to physicians and health care institutions, laboratory testing and related home inspections, and other costs such as transportation and time. The average cost of follow-up treatment per child is $55 (Kemper et al., 1998), which does not include the much higher cost of treating severely poisoned children. For example, for children with blood lead levels between 45 and 70 μg/dL and over 70 μg/dL, the costs are $1017 and $2625, respectively (Kemper et al., 1998).

Severe lead poisoning can also cause mental retardation, resulting in lifetime costs per affected child of just over $1 million (Honeycutt et al., 2003), including special education, home care, long-term care, other health care costs, and productivity losses due to premature morbidity. Recent data show a substantial decline in severe lead poisoning cases (Meyer et al., 2003), so there is considerable uncertainty with respect to how many mental retardation cases could be avoided due to further reductions in severe lead poisoning via lead-safe window replacement.

Lead exposure also accounts for 290,000 excess cases of ADHD in US children ages 4–17 (Braun et al., 2006). This association between increased blood lead and ADHD was evident even among children with blood lead below 5 μg/dL. Children with ADHD have a higher likelihood of receiving medical diagnoses in multiple categories, including major injuries (59% vs. 49%), asthma (22% vs. 13%), hospitalization, and emergency department admissions (Leibson et al., 2001). Median health care costs for those with ADHD were $4306 versus $1944 for those without ADHD over a 9-year time period. These medical costs related to ADHD are separate from the direct medical care costs of lead exposed children. Multiplying this $2362 increase in median health care costs times the 290,000 excess cases of ADHD associated with lead exposure indicates that an additional $685 million of health benefits could be realized by avoiding lead-induced ADHD over each 9-year time period.

There is also substantial evidence linking preschool lead exposure to crime and other behaviors that impose substantial societal costs (Denno, 1990; Dietrich et al., 2001; Needleman et al., 1996, 2002, Nevin, 2000, 2007). While other factors also contribute to criminal behavior, juvenile delinquency and other anti-social behaviors, lead exposure consistently emerges as one of the significant independent variables involved. Analysis of nine nations with very different lead exposure and crime trends shows that preschool blood lead trends explain 63–93% of the temporal variation in index crime rates (violent crime plus property crime), with a 19-year time lag, consistent with early-childhood neurobehavioral damage and the typical age of index crime offenders (Nevin, 2007). This analysis found that murder rates could be especially associated with severe lead poisoning, but there was no evidence of a lower blood lead threshold associated with trends in property crime offending by juveniles. Among the many neurochemical effects of preschool lead exposure linked to behavior is the activation of protein kinase C (PKC). PKC is known to affect long-term potentiation (a form of neuronal plasticity) and the effects of lead on PKC are potent at doses several orders of magnitude below 10 μg/dL (Lidsky and Schneider, 2003; Birnbaum et al., 2004). The National Institute of Justice (1996) has estimated the annual costs of crime in the United States to be $105 billion in property and productivity losses and medical expenses, plus an additional $345 billion per year in intangible costs for pain and suffering. Even if only 10% of these costs are associated with childhood lead poisoning, the

Table 4
Lost LifeTime Earnings Health Benefit

Value per IQ point (*A*)		$16,809	
IQ per 1 μg/dL (*B*)		0.52	
Value per avoided 1 μg/dL ($A \times B$)		$8741	
Benefit in Units with lead paint on window surfaces	Pre-1940	1940–1959	1960–1977
Lead dust hazard prevalence (*C*) (%)	56	43	34
Avoided μg/dL (*D*)	4.33	4.33	2.44
Average benefit per resident child ($E = A \times B \times C \times D$)	$21,195	$16,275	$7251
Benefit in units without lead paint on window surfaces			
Lead dust hazard prevalence (*F*) (%)	N.A.	17	6
Avoided μg/dL (*G*)	N.A.	2.44	1.98
Average benefit per resident child ($H = A \times B \times F \times G$)	N.A.	$3626	$1038
Percent of single-pane window housing units with lead paint on interior window surfaces (*I*) (%)	100	40	19
Weighted average benefit per resident child ($J = (E \times I) + (H \times (1–I))$)	$21,195	$8685	$2219
Number of children ages 6–30 months per unit (*K*)	0.068	0.069	0.060
Number of children ages 6–18 months per unit (*L*)	0.034	0.0345	0.030
Year 1 average benefit per unit ($J \times K$)	$1,441	$599	$133
Years 2–10 average benefits per unit ($J \times L$)	$721	$300	$67
Present value benefit per unit over 10 years	$6847	$2847	$632

crime-prevention benefits of preventing such poisoning would be $45 billion per year.

3.4. Lead-safe window replacement costs, annual energy savings, and market value benefits

Table 5 shows the estimated costs and market benefits of lead-safe window replacement for an 800 ft^2 attached home with 7 windows, a 1200 ft^2 detached home with 10 windows, and a 1800 ft^2 detached home with 16 windows.

As explained below, homes with mostly single-pane windows are likely to have monthly energy costs close to $0.09 per square foot in 2006, and replacing those windows with Energy Star windows would reduce energy bills by 15–25%. Replacing wood-frame windows lowered 1991–1996 energy bills by 15–25% in almost all of 25 metro areas examined (Nevin et al., 1999). Average 1995–1997 monthly energy bills in pre-1980 detached housing were $0.07 per square foot in the Northeast and South, and about $0.06 in the Midwest and West, but many of these units already had old windows replaced, so the average energy bill would be higher in units with inefficient single-pane windows (US Department of Housing and Urban Development, 2000). Median household costs for natural gas and fuel oil were about 50% higher in 2005 than in 1997, and median electricity costs were almost 10% higher (US Bureau of the Census, 1998, 2006). Therefore, monthly energy bills would be about $0.09 per square foot today in pre-1980 housing with mostly single-pane windows. A 15–25% reduction in monthly costs of $0.09 per square foot would yield annual savings of $130–216 in an 800 ft^2 home, $194–324 in a 1200 ft^2 home, $292–486 in an 1800 ft^2 home (as shown in Table 6). This estimated savings for an 1800 ft^2 home is also roughly consistent with a US Environmental Protection Agency (2006a) analysis showing annual energy savings from window replacement (in a 2000 ft^2 home) of $330–600 in 37 cities, $225–320 in another 38 cities, and $55–205 in just 18 cities (mainly in the South and on the California coast, due to lower EPA estimated AC savings).

3.5. Summary of lead-safe window replacement costs, benefits, and net benefits

Table 6 summarizes energy savings, costs, and market benefits of lead-safe window replacement by home size, and lifetime earnings benefits and net benefits by age of housing. Net economic benefits for each housing unit are at least $4490–5629 in pre-1940 housing and at least $491–1629 in 1940–1959 housing. Additional benefits, not reflected in Table 6, would result from avoided ADHD, other medical costs of childhood lead exposure, criminal behavior related to early childhood lead exposure and other avoided costs. Table 6 shows average benefits that are lower than costs for 1960–1977 units, reflecting the lower risk of lead paint hazards and lower dust lead loadings in 1960–1977 units that do have lead hazards. However, lower dust lead loadings are associated with the lower blood lead range (see Table 2) where IQ lost per μg/dL increase in blood lead is higher than the IQ to blood lead slope reflected in this analysis. Therefore, lifetime earnings benefits are especially likely to be understated in 1960–1977 units, so net benefits in these units may also be positive. The benefits in Table 6 also reflect average lifetime earnings benefits across all housing with single-pane windows, but these benefits are actually concentrated in the 6–7% of units with children ages 6–30 months. Therefore, net benefits would definitely be positive in 1960–1977 units with young resident children.

Table 5
Costs and market benefits of lead-safe window replacement

	800 ft^2 attached, 7 windows	1200 ft^2 detached, 10 windows	1800 ft^2 detached, 16 windows
Costs			
Window replacement	$6118	$9684	$15,494
Weighted average interior paint stabilization	$146	$146	$146
Weighted average exterior paint stabilization	$291	$291	$291
Specialized cleanup	$386	$510	$510
Lead dust clearance testing	$175	$219	$219
Average total cost	$7,116	$10,850	$16,660
Market value benefits			
Windows	$5485	$8681	$13,890
Weighted average interior paint stabilization	$144	$144	$144
Weighted average exterior paint stabilization	$270	$270	$270
Average total market value benefit	$5899	$9095	$14,304

Table 6
Net benefits of lead-safe window replacement

	800 ft^2 attached, 7 windows	1200 ft^2 detached, 10 windows	1800 ft^2 detached, 16 windows
Average annual energy savings: 15–25%	$130–216	$194–324	$292–486
Average cost (*A*)	($7,116)	($10,850)	($16,660)
Average market value benefit (*B*)	$5,899	$9,095	$14,304
Average lifetime earning benefit (*C*)			
Pre-1940 housing	$6847	$6847	$6847
1940–1959 housing	$2847	$2847	$2847
1960-1977 Housing	$632	$632	$632
Net societal benefit per housing unit ($B+C$–A)			
Pre-1940 housing	$5629	$5092	$4490
1940–1959 housing	$1629	$1092	$491

4. Discussion

In 2005, there were roughly 22 million pre-1960 housing units with single-pane windows, about equally divided between pre-1940 and 1940–1959 units (Jacobs and Nevin, 2006; US Bureau of the Census, 1998, 2006). Lead-safe window replacement in these units, at the average benefits and costs in Table 6 for a 1200 ft^2 home, would yield net benefits of at least $67 billion. Table 6 reflects lifetime earnings benefits for children under the age of 30 months, but children ages 30–72 months would also benefit from avoided lead exposure. The lifetime earnings benefits calculated here assume lead-safe window replacement protects resident children for 10 years, but it would likely abate lead paint hazards for much longer in most units. Lead-safe window replacement would also yield benefits from avoided ADHD, other medical costs, and criminal behavior related to early childhood lead exposure, which are not included in Table 6. The benefits reported here also do not include many other avoided costs and intangible benefits, such as lead paint litigation, special property maintenance, stress on parents, premature mortality and memory loss from lead exposure in childhood, treatment of dental caries associated with lead exposure, hearing loss, and liver, kidney and other diseases associated with lead exposure.

The lifetime earnings benefits in Table 6 reflect avoided lead dust exposure, but paint chip ingestion is often a factor in severe lead poisoning. A 1989–1990 study found that children with X-ray evidence of recent paint chip ingestion had average blood lead of 63 μg/dL (McElvaine et al., 1992). The US Department of Housing and Urban Development (1999) estimated avoided paint chip ingestion benefits to be about 10% of avoided lead dust ingestion benefits, reflecting a smaller fraction of children ingesting paint chips and a much larger benefit per child due to the severity of lead paint chip poisoning. Recent data show a substantial decline in severe lead poisoning cases (Meyer et al., 2003), so paint chip ingestion risks have likely declined relative to the risk of lead dust hazards. Therefore, this analysis does not quantify avoided paint chip ingestion benefits, but lead-safe window replacement would clearly accelerate the decline in severe poisoning cases because lead paint chips are often found in old window wells, and paint stabilization would address other paint chip ingestion risks (Jacobs and Nevin, 2006).

Extensive research clearly shows an inverse relationship between early childhood blood lead and IQ later in life, with a higher slope at lower blood lead levels, but data limitations leave some uncertainty about the differential impact of a brief exposure with blood lead of 2–10 μg/dL as opposed to a more chronic exposure at this level. However, the chronic nature of most childhood exposure to lead contaminated dust, and especially lead dust associated with old windows with lead paint, suggests that chronic exposure is far more common than brief exposure among children in housing targeted for lead-safe window replacement. Moreover, the 30-day half-life of lead in blood suggests that NHANES blood lead data are little affected by brief exposures of 2–10 μg/dL, because a child who briefly has blood lead of just under 8 μg/dL without continuing exposure would have to be tested within the next 2 months to detect blood lead over 2 μg/dL. On the other hand, the half-life of lead in blood suggests that NHANES data on children with measured blood lead of 2–10 μg/dL do include some number of children recovering from more severe lead poisoning due to recent paint chip ingestion. Children with paint chips evident in intestinal X-rays (i.e., likely swallowed within 24 h) had average blood lead over 60 μg/dL, which means that even without further exposure those children would have average blood lead over 15 μg/dL 60 days later, and over 2 μg/dL almost 5 months after paint chip ingestion. Therefore, the data on children with measured blood lead of 2–10 μg/dL likely include relatively few children with just a brief exposure of 2–10 μg/dL, and some significant number of children with a brief exposure above 10 μg/dL.

The 2005 RM survey market value estimates may not fully reflect the increase in residential energy costs in late-2005 through 2006, and extensive evidence links home value to energy efficiency (Dinan and Miranowski, 1989; Laquatra, 1986; Johnson and Kaserman, 1983; Corgel et al., 1982; Longstreth, 1986; Halvorsen and Pollakowski, 1981). Horowitz and Haeri (1990) found that home value reflects a rational trade-off between energy bills and after-tax mortgage interest expense, as demand for energy-efficient homes raises their price relative to other homes until that higher price results in higher after-tax mortgage costs that approximately offset energy bill savings. Nevin and Watson (1998) tested this ‘‘rational market’’ theory against 1991–1996 AHS data, and showed a consistent rise in home value of about $20 for every $1 reduction in annual energy bills, regardless of main heating fuel (gas, electric, or fuel oil), after controlling for other variables affecting home value. The 1991–1996 after-tax mortgage interest rate was about 5%, so home buyers paying $20 more for homes per $1 reduction in energy bills made a rational trade-off between energy savings and after-tax mortgage interest. A subsequent study (Nevin et al., 1999) specifically found that the 1993 RM window replacement value estimate reflected energy efficiency value (20 times annual energy savings) plus ‘‘appearance’’ value of about $100 per window.

Rising energy prices increase annual savings from energy efficiency, and trends in RM survey window replacement value estimates appear to reflect such energy bill savings. The 1993 RM survey reported higher cost recovery in the East, consistent with higher Northeast fuel costs, but low-E glass that reduces solar gain to save on air conditioning costs became common in the 1990s, as did ‘‘warm-edge’’ spacers to improve thermal performance (Swanson, 2005). As window efficiency and energy prices increased, the RM value estimate for window replacement rose from 69% of cost in 1995 to 85% in 2003 and 2004 and 90% in 2005 (Alfano, 2001-2005). In California, large surcharges were added to residential electricity rates in 2001, and RM value estimates for window replacement in San Francisco, San Diego, Sacramento, and Los Angeles rose from an average of 61% of cost in 1999, to 91% in 2001 and 114% or higher in 2002 through 2004 (Alfano, 2001–2005).

RM survey value estimates also reflect residential energy costs that do not reflect time-of-day pricing for the higher marginal cost of peak-load generating capacity, and low-E windows produce the greatest savings when peak demand strains generating capacity. Moreover, these market value benefits do not reflect the value of avoiding emission costs not fully reflected in energy prices, including the long-term benefits of reducing carbon emissions (Stern, 2006).

For all the reasons described above, the estimated net economic benefit of $67 billion from lead-safe window replacement in pre-1960 units with single-pane windows substantially understates total benefits. In fact, benefits from avoided crime and reductions in carbon emissions from power plants due to improved housing energy efficiency from new windows could increase the minimum net economic benefits reported here by several orders of magnitude.

5. Conclusions

Lead-safe window replacement would yield at least $67 billion in net monetary benefits. It would also lower energy costs by 15–25% in pre-1960 homes with single-pane windows, which account for about 20% of all US housing units. Homes with single-pane windows were built before the era of home energy codes and are some of the least energy-efficient homes. A 15–25% energy use reduction in this inefficient segment of the housing stock could reduce total national residential energy use by 5% or more, with low-E windows yielding the greatest savings when peak demand strains generating capacity.

Lead-safe window replacement would yield additional benefits from avoided crime, special education, and medical costs, and reductions in power plant emissions and peak-load demand. The 2005 Energy Policy Act provided a federal tax credit for 10% of energy efficient improvement costs, including a credit of up to $200 for window replacement (US Environmental Protection Agency, 2006c), but more generous credits and/or direct payments via housing assistance programs are warranted by the benefits of lead-safe window replacement. For example, credits or payments of $100 per window up to

$1000 per housing unit would entail a maximum *one-time* federal expenditure of $22 billion if this incentive resulted in lead-safe window replacement in each of the 22 million pre-1960 homes with single-pane windows. By comparison, the No Child Left Behind program provides States and local school districts with more than $22 billion of federal funds *per year* (House Committee on Education & the Workforce, 2006). The combination of lifetime earnings benefits, market benefits, and energy savings alone will more than recover the one-time investment needed for lead-safe window replacement in older housing.

Public policy priorities are often evaluated from the narrow perspective of a single academic discipline, but the potential net benefits of lead-safe window replacement require a broader perspective. Weatherization programs might not recommend window replacement as the most cost-effective way to reduce home energy costs, but lead-safe window replacement benefits far exceed the energy savings per household. For those especially concerned about climate change, window replacement might seem like a small part of the global effort required, but it could be an important part of carbon emission reduction efforts. From the perspective of electricity supply planning to accommodate economic growth, the potential for peak-load demand reduction from window replacement might not be as evident as the need for new generating capacity, but the peak load impact of a large-scale window replacement initiative could be substantial. Criminologists urging additional funding for law enforcement are likely to be unaware of the growing body of research linking childhood lead exposure to crime. Education professionals and economists may be unaware of the documented impact of childhood lead exposure on educational achievement and lifetime earnings.

Lead-safe window replacement might not be viewed as the most cost-effective way to achieve policy goals defined in terms of any single discipline. But the net benefits of at least $67 billion from such an initiative are compelling and large. In fact, the lifetime earnings benefit of removing lead paint hazards and windows likely to cause lead poisoning in the future is essential to the spirit of the No Child Left Behind program. Despite substantial progress in reducing elevated preschool blood lead prevalence, lead dust hazards in older housing still leave millions of children behind when they begin their first day of school.

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