EPIDEMIOLOGICAL INVESTIGATION TO ASSESS ENVIRONMENTAL CONTRIBUTIONS TO CHILDHOOD BLOOD LEAD LEVELS

by

Stacey M. Benson

BS, St. Lawrence University, 2000

MS, University of Pittsburgh, 2005

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This dissertation was presented

by

Stacey M. Benson, M.S.

It was defended on

May 20, 2014

and approved by

Committee Member
LuAnn L. Brink, MPH, PhD, Adjunct Instructor, Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh

Committee Member
Gary M. Marsh, PhD, Department of Biostatistics, Graduate School of Public Health, University of Pittsburgh

Committee Member
Ravi K. Sharma, PhD, Department of Behavioral and Community Health Sciences, Graduate School of Public Health, University of Pittsburgh

Dissertation Advisor
Evelyn O. Talbott, MPH, DrPH, Professor, Department of Epidemiology, Graduate School of Public Health, University of Pittsburgh

Evelyn O. Talbott, MPH, DrPH

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ABSTRACT

Reduction in childhood blood lead levels has been one of the most successful public health efforts in history. However, there is ongoing evidence that declines in cognition and social behavior occur at levels well below 10 µg/dL and the effects of lead exposure are irreversible. This body of work will address current and continuous sources of lead in the environment and its potential impact on childhood blood lead levels. Toxic Release Inventory (TRI) lead emissions and ambient air lead estimated by the National Air Toxics Assessment (NATA) were used to assess associations between environmental lead and childhood blood lead levels (n = 3,223) measured in the National Health and Nutrition Examination Survey (1999-2006). After adjustment (gender, race, age in months, percent pre-1950 housing, reference adult's education, poverty income ratio, region and survey cycle) a 10,000 lb/mi^2 increase in TRI resulted in a 1.13% (95%CI: 0.45, 1.81) increase in blood lead. Neither TRI nor NATA estimates were significantly associated with blood lead after adjusting for cotinine and floor lead dust.

Two additional studies were conducted with a specific focus on children living in Pennsylvania and New Jersey. The first study assessed if living within 3km of an airport was associated with elevated blood lead levels (n = 493,956). After adjustment for percent pre-1950 housing, poverty and race, gender, age in months, and industrial emissions, children living near an airport (n = 25,684) did not have a higher prevalence of elevated blood lead (≥ 5µg/dL) than children living further away. Finally, a geospatial regression was performed to determine the

distribution of children with elevated blood lead levels (n = 855,291). Children living in large rural towns and isolated rural towns have a higher prevalence of elevated blood lead levels than urban areas after adjusting for percent male, pre-1950 housing, poverty, race, and industrial air lead emissions. Other sources such as neighborhood lead contamination and residential lead dust may contribute to childhood blood lead levels. The public health significance of these studies is to determine current sources of environmental lead so primary prevention programs can be implemented to further limit exposures in children.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

PREFACE

I would like to take the time to thank everyone who made this journey possible. I was raised by an incredible family who supported me through all of my educational and occupational endeavors. My father, the dreamer, never questioned my choices regarding working in the real world or pursuing an advanced degree. My grandfather always provided intellectual challenges. He would give me calculus questions at the dinner table. "What is the best way to determine the volume an orange wedge?" After a brief discussion we would then proceed to an evening of bridge, pinochle or euchre. Those family card games taught me problem solving skills. I also learned that no matter how well you play a hand, sometimes the cards are stacked against you and you just have to roll with it. Grandma never discouraged new horizons. I would walk into the farm house on a Friday afternoon and casually make a comment about a pottery wheel. The next weekend when we visited a wheel would be sitting in the dining room. Creativity was never stifled. As her grandchildren we could never be too noisy, messy, dirty, shy, flamboyant or exuberant. Her arms and her heart were always open.

From an academic standpoint, I have been most fortunate. I started as an undergraduate physics student at St. Lawrence University. It had to be the only department in the country where there were more female professors and female students than male professors and male students. Dr. Karen Johnson taught me that it was OK to have to think things out and it was OK to not know an answer immediately. She graded me on my potential and had high expectations.

Dr. Catherine Jahncke and Dr. Aileen O'Donoghue taught me that being unique and different were great qualities. All three women gave me a safe space to explore my development as a woman and scientist. These strong women helped me build the confidence I needed to be successful while working at Carnegie Mellon University, pursuing my advanced degrees at the University of Pittsburgh and while working at the National Institute for Occupational Safety and Health. As an employee at NIOSH, Dr. Deborah Novak provided mentorship. She was a strong advocate for returning to graduate school and remains an adviser that I rely on to this day.

As a student at the University of Pittsburgh, Graduate School of Public Health, I was guided through the maze of graduate school milestones by Dr. LuAnn Brink. She was a great listener and always provided keen insight on the best way to approach difficult and challenging situations. My advisor, Dr. Evelyn Tablott, has been instrumental in my success as an environmental epidemiologist. She provided me with opportunities to write manuscripts and present research at national and international conferences. She has introduced me to colleagues and encouraged training across disciplines. My doctoral committee has been fantastic and without their continuous support and mentoring, completion of this degree would not have been possible.

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1.0 INTRODUCTION

This dissertation was funded and aims to continue the work conducted as part of the Centers for Disease Control and Prevention BAA 200-2010-37444: Update the Use of Biomonitoring Data for a Linkage Study through the Tracking Network. The original research used individual blood lead data from tracking states to assess the relationship between childhood blood lead levels and ambient air lead levels as estimated by the National Air Toxics Assessment, as well as proximity to Toxic Release Inventory facilities. Research presented below seeks to assess 1) how environmental exposures impact childhood blood lead levels across the nation using National Health and Nutrition Examination Data; 2) determine if children in Pennsylvania and New Jersey who live near airports are at an increased risk of elevated blood lead levels; and 3) conduct geospatial regression analyses for children living within Pennsylvania and New Jersey to determine the spatial distribution of children with elevated blood lead levels.

1.1 HISTORICAL PERSPECTIVE

Lead is a common trace element found in nature, but its properties as a poison have been observed for hundreds of years. Roman aristocracy suffered from lead poisoning and lead salts were used to sweeten wine during the Middle Ages. Benjamin Franklin observed dropsy in his type setters who refused to wash their hands prior to consuming food [1]. Lead poisoning was

observed in Brisbane Australia in 1892. An epidemic of lead poisoning in children who played on verandas with railings coated in white lead paint resulted in Australia banning the use of lead in household paint in 1920. In 1914 lead poisoning was recognized in the U.S. but it was believed that children either died due to poisoning or recovered completely. It was not until 1943 that a follow-up study of 20 children who survived acute toxicity demonstrated that children did not fully recover; behavioral and cognitive deficits remained. Next it was believed that only children who showed clinical signs of poisoning suffered from long term deficits. However, in the 1970s deficits in IQ sores, attention and language development were found in children with subclinical exposures [2].

Lead can be measured in soil, ambient air and water. Individuals living in homes built before 1978 may also find lead in both interior and exterior residential paint. Children under 6 years of age are most susceptible to residential and neighborhood sources, while adults are most likely exposed in occupational settings [3]. Blood lead levels in children have been shown to be associated with environmental and household sources for decades. As evidence linking exposure to lead with adverse health effects emerged, legislative changes were made to limit sources of lead in the environment and the household. With the introduction of each legislative act, the prevalence of elevated blood lead levels declined accordingly. Lead was phased out of gasoline beginning in 1973, and was banned form residential paint in 1978. By 2001, lead dust and soil hazard standards were developed and lead solder in food cans had been eliminated for over 6 years. By 2007 the geometric mean blood lead level for the nation had fallen below 2 µg/dL [4].

Prior to 1980, the primary sources of lead exposure in children were lead solder used to seal cans of food, lead paint used in residential homes and tetraethyl leaded gasoline. Current

limits for lead in these sources are as follows: lead solder is no longer permitted to seal food containers, lead in gasoline is limited to 0.1 g/L and paint for residential homes cannot contain more than 0.06% lead [5]. Total suspended particulates are particles that are 100 um in diameter or less. In 2008 the Environmental Protection Agency (EPA) lowered ambient lead levels as measured in total suspended particulates from 1.5 ug/m^3 to 0.15 ug/m^3 [6]. The maximum concentration level goal for lead in drinking water is zero [7].

The most significant impact on childhood blood lead levels in the U.S. was the removal of lead from gasoline. An engineer, Thomas Midgely, for General Motors and DuPont developed methods to introduce lead additives into gasoline in the 1920. Originally he developed additives from plant based derivatives, but since natural derivatives were not proprietary or patentable he was encouraged to look for other ways to control the combustion process in automobile engines[8]. In 1923, tetraethyl lead was fabricated for use in gasoline. Almost immediately, some of the workers at all three plants began to show signs of psychosis and others died. The production of tetraethyl lead was put on hold for two years. By 1926 it was believed that these health effects only occurred at high levels of exposure and that lead in the atmosphere was of no concern, so production of tetraethyl leaded gasoline continued until 1965. Clair Patterson, a geochemist, was the first to show that lead in the atmosphere was directly related to industrial activity. He evaluated the concentration of lead in snow cores dating back to 800 BC. His research showed how environmental concentrations of lead increased in conjunction with industrialization. Prior to the 1800s snow core lead levels were below 0.02 ppb, but by 1900 levels rose to 0.06 ppb and climbed dramatically by 1950 with lead concentrations exceeding 0.20 ppb [9]. These findings resulted in an increased push to assess blood lead levels in the US population and to assess health effects associated with such levels. By the mid-1980s the U.S. Environmental Protection

Agency (EPA) was able to show parallel declines between lead consumed in gasoline and ambient air lead and blood lead levels in the US population. From 1975 to 1984 the annual consumption of lead in gasoline fell from over 160,000 tons of lead to 40,000 tons while ambient air lead concentrations dropped from 1.2 ug/m^3 to 0.4 ug/m [10].

Lead hazard awareness resulted in restricted usage of lead in France and Belgium starting in 1909 [5], but the U.S. did not recommend action to reduce blood lead levels (originally defined as blood poisoning) in children until the 1970s. Recommendations were set to define levels indicating when children needed to receive treatment, usually in the form of chelation, to aid the body in excreting lead from their systems. From 1960 to 1990 the childhood blood lead "level of concern" was reduced from 60 µg/dL to 25 µg/dL. In 1991 the Centers for Disease Control reduced the "level of concern" to 10 µg/dL. Finally, in 2012, the Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) recommended the discontinued use of "level of concern" because no threshold effect limit has been found. It is recommended that goals to reduce blood lead levels should be based on the 97.5 percentile of blood lead levels measured in children between the ages of 1 to 5 who participated in National Health and Nutrition Examination Survey (NHANES) [11]. The most recent assessment of the NHANES blood lead levels in 1 to 5 year old children indicates an elevated blood lead level as greater than or equal to 5 µg/dL [12].

1.2 PATHWAYS FOR LEAD EXPOSURE

There are several potential sources of exposure to lead: air, water, and soil. Lead paint exposure in homes built before 1950 remains one of the primary risk factors associated with elevated

blood lead levels. Approximately 35% of U.S. homes still contain lead paint. The U.S. Department of Housing and Urban Development (HUD) estimates that 37 million homes have lead based paint and children less than 6 years of age live in 3.6 million of those homes [13]. However, over 30% of children assessed in 2006 with blood lead levels greater than 10 µg/dL could not be linked to lead paint exposure [14]. For children with blood lead levels less than 10 µg/dL a single source of exposure has not been identified [15]. Lead is used in several types of manufacturing including but not limited to: municipal waste combustors, wire and cable manufacturing, rubber and plastics manufacturing, hazardous waste facilities and metals manufacturing. Ambient air lead concentrations are highest near battery plants and smelters [14]. The U.S. consumes approximately 1.4 million metric tons of lead a year. As a nation the U.S. is the third largest producer of lead in the world [16] and the second largest consumer [17]. Several high profile lead industries have been linked to serious lead poisoning in children (i.e. smelters located in KS and El Paso).

There are three pathways for lead to enter the human body: absorption, ingestion and inhalation. When tetraethyl leaded gasoline was in use, lead released through the combustion process could be absorbed directly through the skin [5]. Tetraethyl lead is fat soluble making it the only source of lead that is easily absorbed through the skin. Once lead reaches the blood stream it is taken up by the brain [2]. With the removal of tetraethyl lead from automobile gasoline this pathway of exposure is now limited to individuals who live near or work at airports. Aviation fuel for small, piston driven planes still contains leaded gasoline. The primary pathway of lead exposure in children is through ingestion because of the increased likelihood of hand to mouth activity. Lead released into the environment either naturally or through industrial activities is not biodegradable and does not dissipate with time, making it a source for long term exposure [18].

Corrosion of lead in pipes and solder associated with residential plumbing can also be a source of exposure. The action limit in water is 15 ppb [4]. An evaluation of lead concentrations in the US water supply from 2000 to 2003 was performed by the EPA. For both systems that serve less than 50,000 people and those that serve more than 50,000 people it was determined that less than 4% of suppliers exceeded the action limit at least once over the evaluation time period. Less than 1% had lead levels of 25 ppb. Determining the exact contribution of lead exposure from water consumption is very difficult because several variables impact the amount of lead in the water consumed: pH, temperature and alkalinity [19]. The duration of flushing prior to sampling also impacts lead concentrations in the water. Lead is also present in the atmosphere, especially in urban settings where industrial activity and traffic density are higher [20]. The amount of lead deposited in the lungs depends on particle size. Up to 95% of submicron lead aerosols are inhaled and directly enter the blood [21]. While adults only absorb 10-15% of lead ingested, children can absorb up to 50% [5]. A developing central nervous system is more sensitive to toxins than a mature central nervous system and children's guts absorb more lead than adults [2]. There are several factors that influence the amount of absorption: mineral levels in the child (Calcium, phosphorus, zing and iron), adipose tissue levels, protein levels, the presence of vitamin D, and the amount of exposure [21].

Once lead is absorbed by the body it can reside in the blood, in soft tissues and in bone. The residence time of lead in bone is 10 to 30 years for adults [22], while the residence time in blood is 10-12 days. Lead in blood is taken up by two types of bone: compact and trabecular. Compact bone only has a marrow volume of 30% and is very dense. The marrow volume of trabecular bone ranges from 30-90% and trabecular bone is porous [23]. The turnover from bone back into blood is slow (4.4% per year) for compact bone but rapid (32.5% per year) for

trabecular bone in adults. The formation and resorption of bone in children is very different than adults. The accretion rate of calcium in bone is several times higher in children than adults[24]. Due to the differences in residence times between body locations, lead concentration in bone is a good metric for assessing long term chronic exposures, while whole blood lead measures indicate recent exposures in addition to levels being released from the bone back into the blood[25].

Once lead has been absorbed is it very difficult to eliminate it from the body. Assessments of the child's environment need to be conducted to remove the current source of the exposure and prevent future exposures. In instances where blood lead levels are very high (above 40 µg/dL) the child may respond to chelation drugs which are designed to increase lead excretion. After treatment blood lead levels drop dramatically, but within days blood lead levels can rebound due to the release of lead from bone [5]. A clinical trial to assess the effects of Succimer on removing lead from the body compared blood lead level reductions in those receiving treatment versus those receiving a placebo. A total of 780 children who had blood lead levels between 20 and 44 µg/dL were enrolled and followed for over a year. If blood lead levels returned to levels greater than or equal to 15 µg/dL two weeks after each course of treatment, an additional treatment was received. Children on Succimer may have received treatment up to three times. After one year the blood lead levels in each group were comparable. In addition, neuropsychological tests were conducted to measure learning deficits. There were no significant differences between the groups [26]. A study of African American (n = 579) children who were screened between 1990 and 1998 as part of the Charleston County Lead Poisoning Prevention Program were assessed to determine how quickly blood lead returned to acceptable levels without chelation therapy. All children were part of a case management program to reduce future lead exposures. The time for blood lead levels to fall below 10 µg/dL was dependent

upon the initial blood lead level in the child. For children with blood lead levels between 10 and 14 µg/dL it took just over 9 months for blood lead levels to fall below 10 µg/dL. However, for children with blood lead levels between 25 and 29 µg/dL it took 2 years [27]. After lead enters into the body, it remains and has long lasting effects on children. With no threshold effect level, it is imperative to discover how the remaining sources of lead are entering the environment. Once discovered, actions can be taken to minimize additional exposures.

1.3 TRENDS IN BLOOD LEAD LEVELS

Many analyses investigating blood lead levels in children were performed from the data collected by the National Health and Nutrition Examination Survey (NHANES). This survey was initiated in the 1960s. The goal of the survey is to assess the health and nutritional status of the U.S. population and includes assessments of both adults and children. Approximately 5000 people from 15 different counties distributed throughout the U.S. are assessed each year. African Americans, Hispanics, and people 60 years and older are oversampled to ensure reliable statistics [28]. Blood lead levels in children between 1 and 5 years of age dropped from 14.9 µg/dL to 3.6 µg/dL between the NHANES II (1976-1980) and the NHANES III (1988-1991). Non-Hispanic whites had a reduction in blood lead level from 13.7 µg/dL to 3.2 µg/dL while non-Hispanic blacks had a reduction from 20.2 µg/dL to 5.6 µg/dL. During this time frame (1982 to 1984) the Hispanic Health and Nutrition Examination Survey (HHANES) was conducted and there was a reduction in blood lead in Hispanic children between 1 and 5 years of age from 8.5 µg/dL to 3.0 µg/dL [29].

The most recent descriptive analysis of childhood blood lead levels for all of the continuous NHANES surveys (1999-2010) shows a continued decline in blood lead levels. Median blood lead levels for the entire population fell from 1.9 µg/dL (NHANES 1999-2002) to 1.3 µg/dL (NHANES 2007-2010). Even though median blood lead levels for the entire country have fallen to less than 2 µg/dL, over 450,000 children between 1 and 5 years of age, in the U.S., have blood lead levels higher than 5 µg/dL [11].

1.4 HEALTH EFFECTS FOR EXPOSURE ≤ 10 µG/DL

It is well understood that high levels of exposure to lead (blood lead greater than 100 µg/dL) can be fatal. Symptoms begin to appear when blood lead levels reach 60 µg/dL. Lead impacts both the central and peripheral nervous system. Toxicity can result in the loss of nerve fibers, lesions in both grey and white matter, and edema. Blood vessels become compromised and oxygen levels drop leading to neuronal necrosis. In very high doses swelling and hemorrhaging in the brain occurs [30]. As more and more studies are conducted, it has become less clear of any existence of a threshold effect with children whose blood lead levels are below 10 µg/dL displaying cognitive and behavioral deficits. Several studies have been conducted that show adverse health effects for blood lead levels less than or equal to 10 µg/dL: delayed onset of puberty in young women [31], poor behavioral outcomes [32] and lower IQ [33,34]. The results from these studies and many others resulted in the CDC lowering blood lead levels of interest to those greater than or equal to 5 µg/dL [11].

An assessment of 8 to 18 year old girls from the NHANES III survey found significant reductions in breast development, pubic hair development and age at menarche when comparing

children with blood lead levels of 3 µg/dL to those with blood lead levels of 1 µg/dL. The 2186 study participants with data on both pubertal measures and blood lead were stratified into three race groups: non-Hispanic white, non-Hispanic black and Mexican American. After adjusting for physical characteristics, demographic variables and socioeconomic indicators, children of all races with blood lead levels of 3 µg/dL were more developmentally delayed for both breast development and pubic hair growth than children with blood lead levels of 1 µg/dL. Only non-Hispanic black girls showed a significant delay for age at menarche [31].

A total of 448 children from the Avon Longitudinal Study of Parents and Children (ALSPAC) had blood lead evaluations at 30 months of age. These levels were compared with developmental, behavioral and educational outcomes measured on those same children when they were between 7 and 8 years of age. Blood lead levels were significantly associated with lower reading, writing and spelling scores as measured on the SATs. In addition, there was a significant association between blood lead levels and anti-social behavior. When blood lead measures doubled from 5 µg/dL to 10 µg/dL, SAT scores dropped by 0.3 points [95% Confidence Interval (-0.5, -0.1)]. Children with blood lead levels greater than 10 µg/dL were 2.82 times more likely to exhibit anti-social and hyperactivity behavior than children with blood lead levels below 10 µg/dL ($p = 0.034$). All models were adjusted for age, gender, IQ, mother's education, home ownership, mother's smoking status, home facility score at 6 months, father's socioeconomic status at pregnancy, parenting attitudes at 6 months and family adversity index [32].

Lanphear et al. conducted a pooled analysis of 7 longitudinal cohort studies conducted in Boston MA, Cincinnati OH, Cleveland OH, Rochester NY, Mexico City, Port Pirie Australia, and Yugoslavia. Children (n=1333) were followed from birth/infancy to between the ages of 5 to 10 years old. Blood lead was measured at 6, 12 (or 15), 36, 48 and 60 months. The blood

lead measurement taken closest to the IQ test was used for the analysis. After adjusting for home inventory, birth weight, mother's education, and mother's IQ, children's IQ dropped 3.9 points when blood lead level increased from 2.4 µg/dL to 10 µg/dL. A reduction in IQ by 1.9 points was observed for an increase in blood lead levels from 10 µg/dL to 20 µg/dL and a 1.1 point reduction was observed when blood lead increased from 20 µg/dL to 30 µg/dL. Additional covariates were investigated, but had no impact on the final model: sex, birth order, mom age, marital status, smoking status at birth, and prenatal alcohol use [33].

A cohort study of 172 children living in Rochester, NY was conducted to assess the relationship between lifetime average blood lead concentration and IQ, as assessed with the Stanford-Binet Intelligence Scale, at 3 and 5 years of age. The IQ scores at 3 and 5 years of age were highly correlated. For a 1 µg/dL increase in blood lead, average IQ decreased by 0.87 points ($p < 0.001$). The linear model showed a 4.6 point decrease in IQ for every 10 µg/dL increase in lifetime average blood lead concentration. The non-linear model estimated that as blood lead increased from 1 µg/dL to 10 µg/dL, IQ dropped 7.4 points. Models were adjusted for maternal IQ, race, level of education, smoking status during pregnancy, household income, Home Observation for Measurement of Environment Inventory score, child's sex, birth weight and iron status [34].

When the results of the Rochester, NY cohort were published, Bellinger and Needleman were inspired to perform supplemental analysis on a long-term follow-up study they conducted on children born in the late 1970s and early 1980s. In the initial study a total of 148 children born at Brigham and Women's Hospital in Boston, MA participated and had blood lead levels assessed at 6 12, 18, 24, and 57 months. These same children took intelligence tests around 9.5 years of age: Wechsler Intelligence Scale for Children-Revised (WISC-R) and the Kaufman Test

of Educational Achievement (K-TEA). There was a 5.8 point decline in WISC-R scores and an 8.9 point decline in K-TEA for each 10 µg/dL increase in 24 month blood lead levels. Models were adjusted for HOME score, child stress, maternal age, race, maternal IQ, Socioeconomic status, sex, birth order, marital status, and number of family residence changes prior to age 57 months [35]. In the follow-up analysis, only the 48 children whose blood lead levels remained below 10 µg/dL were assessed. The IQ of these children at 120 months of age was inversely associated with blood lead levels measured at 24 months of age ($p = 0.03$) [36].

2.0 ENVIRONMENTAL LEAD DATA

This dissertation is focused on exploring the relationship between ambient air lead and childhood blood lead levels. The three primary sources of air emissions used in the following analysis all are available to the public and can be downloaded from the U.S. Environmental Protection Agency (EPA): Toxic Release Inventory (TRI), National Air Toxics Assessment (NATA) and National Emissions Inventory (NEI) data. They each have their own benefits and limitations which will be discussed below.

Toxic Release Inventory data is reported by industries to the EPA. This inventory started in the 1980s as part of the Emergency Planning and Community Right-to-Know Act (EPCRA) which ensured the public would be able to access information about toxic chemical releases in their community. The focus is on chemicals that have been found to negatively impact human health and/or the environment. In addition to lead, over 650 chemicals are on the list of toxic chemicals that must be reported to the EPA [37]. Over 20,000 industries meet the 3 requirements mandating that they report to the EPA. The first criterion is to be a TRI covered industry: mining, utilities, manufacturing, merchant wholesalers, wholesale electronic markets, publishing, hazardous waste or a federal facility [38]. The second criterion is that the company employs 10 or more full-time employees. Finally, the company must manufacture or process at least 25,000 pounds of a TRI chemical or otherwise use 10,000 lbs of a listed chemical annually [39].

Lead emissions are reported annually and the industry data includes the geocoded coordinates of the facility in question. The lead emissions are reported in pounds. However, it is not a direct measure of exposure and there is no information regarding trends in emissions over time. Data across years for some companies are incomplete. For the research presented below, average emissions were used for 2 year periods as part of the National Health and Nutrition Examination analysis. However, it may not be appropriate to believe that an industry who emitted over a 1,000 pounds of lead for years 1 and 3 but who failed to report in year 2, truly had no emissions during that second year.

There are 4 years of NATA data estimates, but the analyses presented in this dissertation focused on the 2005 assessment. NATA data is available for the nation at the state, county and census tract level and includes 177 of 187 clean air act air toxics, including diesel particulate matter and lead [40]. The focus of NATA is to assess respirable hazards. NATA values are modeled based on several emissions source types: point, non-point, on-road mobile, non-road mobile, background and secondary formation and decay. The data sources compiled and combined for use in the model include TRI and NEI as well as federal, state and local air toxics inventories [41]. The modeled data is generated approximately every 3 years and the 2005 estimates were made available in 2011.

NATA is an excellent source of publically available data and each NATA release is generated with continuously improving modeling methods. It is available at several spatial scales and encompasses potential ambient air releases across the nation. It also provides lead data in the units ug/m^3 which is a measure of how much an individual may actually inhale over the course of the year. However, it is only 1 estimate and there is no way to determine how

ambient lead emissions change over the course of the year for which they were estimated or across NATA datasets.

Two National Emissions Inventory datasets are employed below: 2005 and 2008. This data is also modeled and the lead data is made available as tons of lead released. Once again, this is one value that is estimated every three years. NEI estimates are available for point, non-point, on road and non-road sources. They also include event data (e.g. wildfire). Emissions data are available for criteria and hazardous air pollutants [42]. The benefit of NEI over TRI is that the EPA has developed techniques for estimating and accounting for data they may not have been reported in TRI. The downside to NEI is that it meets the same limitations with regard to fluctuations in emissions over time.

3.0 NATIONAL HEALTH AND NUTRITION EXAMINATION SURVEY STUDIES

Many NHANES studies have been conducted that assess blood lead levels, with seven studies focusing specifically on children (Appendix A). For the most part, these national studies have assessed home and lifestyle factors that contribute to elevated blood lead using covariates collected as part of the NHANES survey. Pirkle et al., was the first to evaluate blood lead levels for the nation using this survey. This multivariable analysis used participants aged 1 to 74 years from NHANES II (1976-1980) and phase 1 of NHANES III (1988-1991), and participants aged 4 to 74 years from the Hispanic Health and Nutrition Examination Survey (HHANES) (1982-1984). After adjusting for age, race, gender, poverty income ratio and urban status, a significant decline for all age groups was observed from the first survey to the last. For the entire population of children aged 1 to 5 years a 75% reduction in blood lead levels was observed (14.9 µg/dL to 3.6 µg/dL). By the end of the last survey cycle evaluated, non-Hispanic white children and Hispanic children had similar blood lead levels near 3 µg/dL. However, urban, poor non-Hispanic black children only had a 60% reduction over the same time period (24.0 µg/dL to 9.7 µg/dL) [29].

A second analysis of NHANES III (1988-1994) was conducted by Bernard and McGeehin to evaluate blood lead levels in 4624 children between 1 and 5 years of age for whom there was a blood lead measurement. Sample weighted multivariate logistic regression was used to evaluate differences between children categorized into 1 of 4 blood lead levels: less than 5

µg/dL, greater than or equal to 5 µg/dL but less than 10 µg/dL, greater than or equal to 10 µg/dL but less than 20 µg/dL and greater than or equal to 20 µg/dL. Models were adjusted for race, age of home, age of child, poverty income ratio, Medicaid status, reference person's education, region of the country and smoking in the home. The highest proportion of children with blood lead levels greater than or equal to 5 µg/dL occurred in non-Hispanic black children (47%) while only 28% of Hispanic children and 19% of non-Hispanic white children had blood lead levels this high. Pre-1946 housing, being younger, region, poverty income ratio, having a smoker in the home, Medicaid status and reference person's education were all significant in the logistic regression [15]. Jones et al., also assessed blood lead levels in children between 1 and 5 years of age with the NHANES III (1988-1994) survey, and also included the continuous NHANES surveys cycles (1999-2004) in their analysis. Multivariable logistic and linear regressions adjusted for race, age, age of home, poverty income ratio and Medicaid status showed that the proportion of children with blood lead levels greater than or equal to 10 µg/dL dropped from 8.6% to 1.4%. Similar to the previous findings, more non-Hispanic black children had blood lead levels greater than or equal to 10 µg/dL (3.4%) than Hispanic and non-Hispanic white children (1.2%) [43].

Dixon et al. conducted the first analysis to determine the relationship between home lead dust levels (in homes built before 1978) and blood lead levels in children between 1 and 5 years of age using the continuous NHANES (1999-2004). Of the 2155 children with blood lead measurements, only 731 had a corresponding home dust lead measurement. Models were developed to predict blood lead levels based on floor dust lead values. Models were adjusted for age, race, gender, poverty income ratio, smoking in the home, number of smokers in the home, cigarettes per day and US born. It was estimated that for children living in homes built before

1978, a floor lead dust measure of 12 ug/ft^2 would result in 4.6% of children having blood lead levels ≥ 10 µg/dL while 27% would have blood lead levels ≥ 5 µg/dL [44]. A second assessment of this same NHANES cycle sought to find a relationship between blood lead levels and second hand cigarette smoke while taking into account home dust sample measurements. The authors adjusted their multivariable linear regression using several covariates including cotinine. Cotinine was only captured on children at least 3 years of age so their study population of interest for children only included 3 to 5 year olds. Similar to previous findings non-Hispanic black children, those born outside of the US and those living in homes built before 1950 had the highest blood lead levels. Cotinine levels were found to be highest in those same subgroups as well as kids who were overweight or obese. Dust lead levels were highest non-Hispanic black children, those living in older homes, children living with smokers, children with lower poverty income ratios and those with higher cotinine levels [45].

A multivariable analysis of NHANES III (1988-1994) and continuous NHANES (1999-2004) of 1085 children between 1 and 5 years of age included region as a covariate. The authors found the highest geometric mean blood lead levels in the Northeast and the Midwest [46]. These results are consistent with a previous assessment of NHANES III (1988-1994) where 43% of children in the Northeast and 31% of children in the Midwest had blood lead levels greater than or equal to 5 µg/dL. Only 22% of children living in the south and 14% of children living in the West had blood lead levels greater than or equal to 5 µg/dL [15]. Scott and Nguyen also found that covariates included in the multivariable regression reached different levels of significance depending on region. In the Northeast females had significantly higher blood lead levels than males, in the Midwest age of the home was significant and in the South non-Hispanic black

children and Mexican American children had significantly higher blood lead levels than non-Hispanic white children [46].

Richmond-Bryant et al., conducted the most recent NHANES study using data from NHANES III (1988 to 1994) and continuous NHANES (1999-2008). It is the first study to date that included potential environmental contributions to blood lead levels. Un-weighted multi-level linear mixed effect models were used to investigate the association between national ambient air lead as measured by monitors and blood lead levels. All ages of individuals in the survey with blood lead measurements were considered. Only participants who lived in a census block group whose centroid was within 4 km of a monitor were included in the analyses (n = 4561). During the time of these survey cycles ambient air lead for 1 to 5 year old children decreased from 0.04 ug/m^3 to 0.01 ug/m^3. At the same time, median blood lead levels for these children decreased from 4.5 µg/dL to 2.4 µg/dL. Even though significant associations were found between monitors and blood lead levels for all age groups for NHANES III, no significant relationships were found between monitor levels and blood lead levels in children between 1 and 5 years of age. However, very few children met the inclusion criteria. Only 654 children were included from the NHANES III and only 205 were included from the continuous NHANES (1999-2008) [47].

The survey ceased collecting dust samples after the 2004 survey cycle, so it is impossible to determine if household lead dust values have dropped in conjunction with the declines in blood lead levels assessed with the NHANES survey. A recent report of NHANES blood lead data shows that median childhood blood lead levels have fallen below 2 µg/dL for the nation [12]. An additional covariate shown to be associated with blood lead levels are smokers in the home. This variable is prone to reporting bias and cotinine measurements are only collected on a people

at least 3 years of age. As additional covariates were added to the model the overall sample size decreased dramatically. Richmond-Bryant et al. argue that ambient air lead does not significantly contribute to blood lead levels [47].

Additional analyses need to be conducted with the NHANES data set that incorporates environmental exposures relevant to the residential location of the child. The attempt to use monitors was the first study to assess environmental contributions to a national sample of blood lead levels, but due to the paucity of monitors distributed across the country only 6% of the entire NHANES survey population met the inclusion criteria for the study. Proxy measures such as residential proximity to known industrial facilities that generate or release lead into the environment need to be considered.

3.1.1 NHANES Data

The National Health and Nutrition Examination Survey has been conducted in the United States since the 1960s. Starting in 1999 the survey turned into a continuous evaluation of the overall health and nutritional status of the nation. Every year approximately 5000 people, from 15 counties distributed across the country are assessed [28]. Sample weights are incorporated into the analysis and provided by the Nation Center for Health Statistics to adjust for the oversampling of certain populations. For survey cycle years 1999-2004 the over sampled population included: African Americans, Mexican Americans, low income white Americans, adolescents between 12 and 19 years of age and adults 60 years of age or older [48]. For the analysis of blood lead levels in children, the population of interest for the proposed study included children between 1 and 5 years of age. Public use variables of interest included: age, race, sex, reference adult's education, poverty income ratio (PIR), blood lead, cotinine, and lead dust. Non-public use

variables included: latitude and longitudinal values for the child's residence, census tract, season of the blood test, and region of the country where the child was located. Data on the age of each child's home was missing for over a third of children with blood lead measures. Instead of using the NHANES survey variable for age of home, a census tract level variable for percentage of homes built before 1950 was used. A total of 3,223 children had non-missing values for the following variables included as part of the base model: gender, age, race, percent pre-1950 housing, poverty income ratio, residential coordinates, reference adult's education and blood lead level. Additional analysis were performed on children with lead dust levels and cotinine measures (n = 1039).

Two proxy measures of environmental lead exposure were considered. National Air Toxics Assessment (NATA) data was available for 2005 as an annual ambient air lead measure in ug/m^3 for each census tract across the U.S. Industrial exposures were determined from Toxic Release Inventory (TRI) was obtained from the EPA [49]. Cumulative exposure for each child was determined as the sum of pounds of lead emitted from each facility divided by the sum of the distance between each facility and the child.

3.1.2 NHANES Specific Aim

Specific Aim 1: Evaluate the effect of environmental lead exposure on blood lead levels in U.S. children between 1 and 5 years of age who participated in the NHANES survey from 1999 to 2006. We hypothesize that the ambient air lead as estimated by NATA and cumulative exposure from TRI facilities will be associated with blood lead levels after adjusting for covariates known to be linked to blood lead levels. Known covariates include: gender, race, age in months, reference adult's education, age of housing within the census tract, PIR, region and survey cycle.

4.0 LEADED GASOLINE, IS IT STILL IMPACTING CHILDHOOD BLOOD LEAD LEVELS?

Tetraethyl lead has been banned in gasoline since the 1970s. However, there are still reservoirs of leaded gasoline that may provide a source of exposure to the U.S. population. In the mid-1990s, Schaffer et al. developed a questionnaire to assess risk factors associated with elevated blood lead levels and compared their questionnaire to the Centers for Disease Control and Prevention (CDC) Lead Risk Assessment Questionnaire. They were concerned that since the CDC questionnaire was designed using urban and suburban children it may not adequately determine the likelihood of blood lead levels above 10 µg/dL for rural children. The CDC questionnaire focused on age of the home, presence of peeling paint, residential proximity to lead industry, and if a sibling or close friend had elevated blood lead levels. The new questionnaire for rural children included questions regarding parental occupation as a farmer as well has having family members who use farm equipment. These additional items were significantly associated with the risk of having elevated blood lead levels in rural children. At the time, leaded gasoline was still used to operate farm equipment [50].

Two occupational studies have shown a dose response relationship between blood lead levels and exposure to exhaust from tetraethyl lead fuel combustion. Until 2008 NASCAR used leaded fuel [51]. Prior to the transition to ethanol, a pilot study was conducted on 47 members of Nextel Cup Teams. Team members with the highest relative risk of elevated blood lead were

exposed to exhaust, followed by those who worked on brakes. The median blood lead level for all team members was 9.4 µg/dL and ranged from 1 to 22 µg/dL [52]. A study of 256 aviation maintenance men, conducted in Korea between March 2012 and July 2012, investigated differences in men who worked exclusively with Avgas (type not specified) versus those who worked exclusively with jet propellant. Men working with Avgas had higher blood lead levels than those using jet propellant (4.2 µg/dL v. 3.57 µg/dL). Those who worked within 200 m of the runway had significantly higher blood lead levels than those who worked more than 200 m away ($p = 0.045$), while men who worked longer hours had significantly higher levels than those who worked shorter hours ($p = 0.017$) [53].

Currently, the largest point source of airborne lead emissions in the U.S. is aviation gasoline [54]. Smaller propeller planes require gasoline with low ignition temperatures so that combustion can be achieved at altitude. The only fuel that meets these requirements contains tetraethyl lead and is known as Avgas. Avgas comes in two main types: 100 octane and 100LL. The allowable lead concentration of 100 octane is 4.24 g/L while 100LL can contain up to 2.12 g/L [55]. A petition was put forth in 2007 requested rulemaking to limit lead emissions from general aircraft (ID:EPA-HQ-OAR-200-0294-001). In 2010 an Advance Notice of Proposed Rulemaking on Lead Emissions from Piston-Engine Aircraft Using Leaded Gasoline was posted. In 2012, an environmental group (Friends of the Earth) filed a lawsuit against the U.S. EPA. The group sited that half of ambient air lead comes from airports. There are concerns that emissions of lead from aviation fuel, (also known as avgas) may be negatively impacting children [56]. The EPA is now conducting their own investigation with a lead monitoring study of airports that emit more than 0.5 tons of lead per year and an external assessment. Currently Eastern Research Group, Inc. (ERG), under contract to the U.S. Environmental Protection Agency (EPA), and is

seeking reviewers to conducting an independent external letter peer review of EPA's draft report, Aviation Lead Demographic Analysis.

Only one study has linked residential proximity to an airport with childhood blood lead levels. Miranda et al., investigated a total of 13,478 children living within 2 km of airports located in 6 North Carolina counties. Their blood lead levels were collected from 1995-2003 and the age of the children ranged from 9 months to 7 years of age. After adjusting for age of housing, census level median income, proportion of public assistance, proportion Hispanic, proportion black and season of the test blood lead levels were significantly associated with residential proximity to the airport. The relationship between blood lead levels and proximity was dose dependent and remained significant for 500 m, 1000 m and 1500 m from the airport. Blood lead levels were 4.4%, 3.8% and 2.1% higher for kids living within 500 m, 1000 m and 1500 m respectively, in comparison to children between 1500 m and 2000 m away [57].

Additional research needs to be conducted to determine if avgas is associated with blood lead levels in children who live in locations other than North Carolina. There are approximately 150 airports located in Pennsylvania and New Jersey that released at least 10 pounds of lead in 2008 [58]. Pennsylvania and New Jersey have participated in the CDC's lead surveillance program since the mid-1990s. Both of these states have long industrial histories that include lead emissions. The objective is to determine if children living in close proximity to airports are more likely to have elevated blood lead levels than children who do not live near airports after adjusting for industrial lead exposures.

4.1.1 Pennsylvania and New Jersey Blood Lead Data

Individual, de-identified data on age, gender, blood lead level, and x,y coordinates of each child's residence were obtained from the Pennsylvania and New Jersey State Health Departments for the years 2006 to 2008. Children ranged in age from 0 to 36 months. Data from both states were combined into a single dataset for a total sample size of 493,956. Approximately 5% of these children lived within 3km of an airport (n = 25,684). In addition to individual level data on gender, census level variables for percent poverty [59], percent black [60] and percent of housing built before 1950 [61] were obtained from the U.S. Census Bureau.

4.1.2 Avgas Specific Aim

Specific Aim 2: Evaluate the contribution that living within 3 km of an airport makes on the likelihood of having childhood blood lead levels greater than or equal to 5 µg/dL. We hypothesize that children living near an airport are more likely to have elevated blood lead levels than children living further away after adjusting for age in months, gender, percent poverty, percent black, percent housing built before 1950 and industrial lead emissions.

5.0 DISTRIBUTION OF ELEVATED BLOOD LEAD LEVEL BY RURAL URBAN COMMUTING CODE DESIGNATIONS

Historically, the Centers for Disease Control and Prevention (CDC) developed their efforts to track elevated blood lead levels in children with a focus on children who lived in city centers and other urban environments. Primary sources of lead exposure were believed to be poor housing including the interior use of leaded paint and areas with dense traffic patterns due to the inclusion of tetraethyl lead in gasoline. A study conducted in Detroit, Michigan in the 1970s evaluated blood lead levels of children 6 years of age or less. During this time, the majority of housing in the city was built before 1950. Even though housing age was consistent across the study area, there was high variability in blood lead levels even after adjusting for parental education level, poverty, and single family homes [62]. Eventually, researchers started to investigate the presence of elevated blood lead levels in children living in suburban [63] and rural environments [64]. It was discovered that even children living in non-urban environments had elevated blood lead levels.

The first study assessing the prevalence of elevated blood lead levels in a non-urban setting took place in Illinois, where children were observed in 14 cities with populations ranging from 10,000 to 150,000. A total of 6151 children between 1 and 6 years of age had their blood lead levels measured between July 21 and September 22, 1971. During this time period the median blood lead level for urban children was 16-27 µg/dL. Forty-four percent of the Illinois children living in these intermediate sized cities had blood lead levels between 20 and 39 µg/dL

and 18% had blood lead levels greater than 40 µg/dL [63]. The second study compared blood lead levels in urban children (Hartford, CT) and rural children (Dutchess County NY and Litchfield County CT). All children were between 1 and 5 years of age. This was an observation study that did not adjust for demographic difference between the urban and rural children. There were 230 rural children of which 91% were white and only 2% were on welfare. Their median blood lead levels was 22.8 µg/dL. There were 272 urban children where 27% were black and 70% were Puerto Rican. Eighty percent of these children were on welfare and they had a median blood lead levels of 32.7 µg/dL [64]. There was a difference in blood lead levels between the two groups of children. However, no adjustments were made to account for poverty and race when comparing blood lead levels between the two groups.

A more recent observational study compared blood lead levels in urban and rural children living in North Carolina. Over 20,000 children between 6 months and less than 6 years of age had blood lead measurements collected between November 1, 1992 and April 30, 1993. Urban rural status was designated at the county level. Elevated blood lead was defined as a level greater than or equal to 15 µg/dL. Rural children were almost 2 times more likely to have elevated blood lead levels than urban children. Assessments of additional cut points (10 µg/dL, 15 µg/dL, 20 µg/dL) found that regardless of the designated blood lead level there was a higher prevalence of elevated blood lead in rural children than in urban children. Regardless of race children living in rural areas had higher blood lead levels than children living in urban areas [65].

One reason children living in intermediate sized cities or rural locations may have elevated blood lead levels could be due to industrial activity within close proximity to residential communities. A study was conducted to see what contributed to the elevated blood lead levels in children between the ages of 1 and 9 years of age living near the Silver Valley Lead Superfund

Site in the mid-1970s. Environmental and residential measurements of lead were captured: ambient air lead, soil lead, indoor and outdoor lead dust and indoor and outdoor paint. The most significant contributor to elevated blood lead levels in these children was ambient air lead which explained 55% of the variance in blood lead measures. Listed by rank of importance ambient air lead was followed by soil lead, age of the child, cleanliness of the home and parental occupation. Lead paint exposure was actually negatively correlated with blood lead level [66].

Lynch et al., also found that interior lead based paint was not the strongest predictor of elevated blood lead levels. White (n = 187) and Native American (n = 144) children between 1 and 6 years of age living near the Tar Creek Superfund Site (North East Oklahoma, South East Kansas, and South Western Missouri) had their blood lead levels measured. This facility was the largest producer of zinc and lead in the U.S. between 1850 and 1950. Several lead exposure variables were also captured: floor lead dust, soil lead, interior lead paint and residential proximity to the facility. Of all the houses evaluated, 50% contained interior lead paint, 10% had lead dust levels that exceed the U.S. Department of Housing and Urban Development (HUD) standard and 20% had soil lead levels higher than the U.S. Environmental Protection Agency (EPA) standard. For all exposure metrics used, the odds of elevated blood lead levels were highest for floor dust (OR=8.1, 95%CI: 1.8, 37.8), followed by yard dust (OR=6.4, 95%CI: 1.4, 30.7), then proximity (OR=3.4, 95%CI: 1.3, 8.8) and finally interior lead paint (OR=3, 95%CI: 1.2, 7.8) [67]. The children in this study lived in a rural setting, and were exposed to years of lead deposition in the surrounding environment.

There may be pockets of elevated blood lead levels in children due to specific industrial activities occurring in their surrounding area. Saline, Kansas and El Paso, Texas have a history of lead smelting. Local health departments in those specific locations have done studies to assess

blood lead levels in children within the community. The goal was to determine if living near the smelting facility was associated with higher blood lead levels than those living further away. The Exide Technologies batter plant is located in Saline, KS and is in non-attainment for the National Ambient Air Quality Standard for lead. From January 1st, 2000 to December 31st, 2010, children between the ages of 0 and 16 years of age had their blood lead levels monitored. Counties of interest included Saline as well as 6 other counties designated as at-risk due to older housing, population density, income and density of children less than 6 years of age. Up until 2006, children in Saline County had much higher blood lead levels than the remaining at risk counties. By 2007, blood lead levels within all at risk counties and Saline matched levels in the remainder of the state. As of 2010, blood lead levels had dropped to approximately 2 µg/dL for the entire state [68]. In El Paso the community was concerned about soil lead levels due to their proximity to a smelter located on the border between the U.S. and Mexico. Soil samples were collected from residential land and matched to blood lead levels of the children living and playing in this environment. There was a significant association between soil lead levels and blood lead levels. For each 500 ppm increase in soil lead the odds of having an elevated blood lead level (greater than or equal to 10 µg/dL) increased 4.5 times [69].

A total of 28,932 children less than or equal to 5 years of age had blood lead measures collected from 1992 to 1995 in Syracuse, NY. Similar to other studies, black children, followed by Hispanic children had the highest elevated blood lead levels and white children had the lowest. A seasonal relationship was also found, with blood lead levels highest in the summer and lowest in the winter. There was no association between blood lead levels and proximity to major road ways. The researchers speculated that historical deposition of lead from vehicular exhaust does not contribute to current blood lead levels. This relationship held when all cases

and extreme cases were examined [70]. Stroh et al., had similar findings, for data collected in Sweden between 1978 and 2007, when assessing blood lead levels in children (n=3879). Children who participated were less than 3 years of age, between 8 and 10 years of age and those between 10 and 17 years of age. Up until 1987, there was a significant association between residential proximity to road ways and blood lead levels. After 1987 the association was no longer significant. Spatial models were adjusted for sex, number of years in school, having a lead hobby, country of birth, parental smoking status, and child's time at school. Lead was completely fazed out of petrol in Sweden by 1994 [71].

By 2007 blood lead levels had fallen to 1.3 µg/dL in the Sweden study mentioned above [72]. But, this level is still almost 3 times higher than the background level of 0.5 µg/dL found in areas with no environmental lead pollution [70]. Stroh et al, found a significant association between blood lead levels in children and their residential proximity to a lead smelter. The smelter is responsible for the deposition of 200-300 mg/m^2 per year. Children living between 1 and 2 km from the smelter had significantly higher blood lead level than children living 2-3 km or more than 3 km away ($p < 0.001$). A strong dose response relationship between distance and blood lead levels was apparent [71].

The blood lead levels of children less than or equal to 5 years of age were compared to dust lead levels and soil lead levels in Indianapolis, IL between 1999 and 2008. The Westside Cooperative Organization was chosen because of it contained a remediated Super Fund Site (Avanti), the southern portion of the area had a history of lead industrial activity, and the majority of residents are low income, Hispanic or non-Hispanic blacks living in older houses. Soil samples were highest in properties directly adjacent to the Super Fund site. Spatial analysis of soil samples found that lead in the surrounding soil accounted for 57% of the variation in

residential lead dust. The home with the highest lead dust levels was located in the remediated Super Fund Site [72]. Due to the homogeneity of housing characteristics in the study area, it is clear that living in urban settings of past industrial activities is an important consideration when investigating environmental contributions to childhood blood lead levels.

An improvement over the traditional linear regression (treating blood lead levels or the natural log of blood lead levels as a continuous variable) and logistic regression (categorizing children based on the current action level set by the CDC) is the use of geospatial statistical analyses. It has been shown that children who live near each other have similar blood lead levels than those living farther away, regardless of other confounding factors [73].

Brink et al. (2013) performed a national assessment of childhood blood lead levels at the county level. The objective was to determine if there was an association with ambient air lead, as estimated by the National Air Toxics Assessment models for 2002 and 2005 and blood lead levels for 3220 counties in the U.S. NATA takes into account several emission sources: large industrial facilities like coke ovens and smaller sources like gas stations, vehicular exhaust from motor vehicles and trains, background levels from long range transport and natural sources, and the secondary formation of pollutants as primary pollutants interact with the atmosphere. These levels represent one time point and any health effect estimates are based on pollution concentrations remaining at this single estimated level. The lowest quartile of NATA ambient air lead was 0.526 ng/m^3 and the highest quartiles of NATA was 2.97 ng/m^3. Childhood blood lead levels greater than or equal to 10 µg/dL were correlated with older housing, poverty, percent black and rural/urban status ($p < 0.001$). When these covariates were incorporated into a geospatial regression, poverty, housing built before 1950, percent black, urban/rural status and

ambient air lead levels were all significant predictors of blood lead levels greater than or equal to 10 µg/dL ($p < 0.001$) [74].

Currently, when researchers explore elevated blood lead levels in children if an adjustment for residential location is used it is a dichotomized variable indicating urban and rural. On the national scale, Brody et al., used the National Health and Nutrition Examination Survey version III (data collected from 1988 to 1991). Everyone at least 1 year of age with a measured blood lead level was included in the analysis. People most likely to have higher blood lead levels were older adults, younger children, blacks, people who lived in city centers and people living in the North East. In this study, urban was defined as locations with populations greater than or equal to 1,000,000 [75].

Of the studies mentioned above, some provided a definition of urban or rural, but others did not. There are two primary agencies involved with defining rural and urban areas: the U.S. Census and the U.S. Office of Management and Budget. Often, urban designations are defined in very specific ways, but rural is considered anything that is not urban [76, 77]. Most designations of urban and rural status occur at the county level because the borders remain relatively constant over time and that is the level at which annual economic statistics are available [78]. Economists, demographers and political scientist develop these definitions, usually for policy implementation and not for assessing health outcomes. An area is defined as metropolitan if it has 50,000 or more residents. In a given county if more than half the county is defined a metropolitan then the entire county gets that designation. In health research, scientists use urban/rural designations as a proxy measure to capture information about the social and physical environment, as well as an individual's access to health and social services [76].

The U.S. department of Agriculture has developed definitions of urban and rural status at the census tract level. Rural Urban Commuting Areas (RUCA) have 10 primary classifications based on population counts, and secondary classifications based on the amount of commuting traffic into and out of an area. It also incorporates U.S. Census Bureau definitions of urbanized areas and urban clusters [79]. Hall et al, points out that traffic flow of the population to where they work may provide insight into how they also gain access to care [76].

Pennsylvania and New Jersey have similar industrial histories and are adjacent to each other geographically. Recently the Centers for Disease Control and Prevention lowered the blood lead limit of concern from 10 µg/dL to 5 µg/dL [11]. Few studies have evaluated elevated blood lead level as defined by this new designation. Also, by combining these two states, it opens up the possibility of assessing urban rural status at a more refined level. Rather than a dichotomous variable, which is usually how urban rural designations are incorporated into research designs, a 4 tiered variable based on rural urban commuting area (RUCA) definitions is evaluated at the census tract level [79]. Spatial lag regression models were used to assess the distribution of elevated blood lead levels in Pennsylvania and New Jersey to determine as a function of the 4 categorical variables: urban, sub-urban, large rural town and small town/isolated rural.

5.1.1 Rural Urban Commuting Area Data

A total of 855,291 children between 0 and 3 years of age had blood lead screenings between 2003 and 2008 in PA and NJ. Approximately 42% of the children were screened in PA and 48% were screened in NJ. All tests and those children with screened blood lead levels greater than or equal to 5 µg/dL were counted and aggregated down to the census tract level. If a tract had

fewer than 4 children tested, the tracts were merged using ArcGIS 10.1. Adjacent tracts with the most similar characteristics were combined. The majority of census tracts merged together were urban. Figure 5.1 shows the tracts that were merged together.

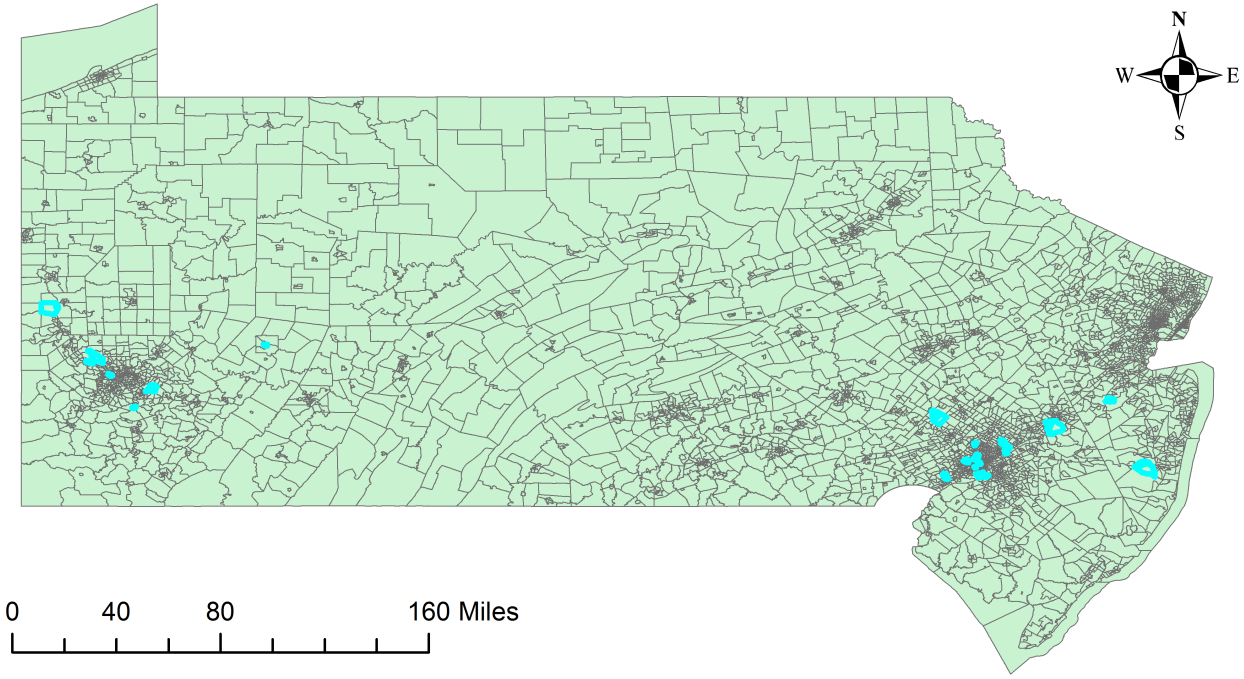

Figure 5-1. Merged census tracts (blue outline) due to limited number of tested children (n ≤ 4).

The RUCA levels as designated by the U.S. Department of Agriculture are shown in can be found on their website. There are ten primary categories with numerous secondary categories based on commuting patterns [80]. In order to use these RUCA definitions at the census tract level, the Washington State Health Department recommends dropping from 10 levels to 4 levels representing Urban, Sub-urban, large rural town and small town/isolated rural. See Table 8-1.

5.1.2 Rural Urban Commuting Area Specific Aim

Specific Aim 3: Employ geospatial statistics to evaluate the distribution of elevated blood lead levels at the census tract level using the following designations: urban, sub-urban, large rural town, small town/isolated rural. We hypothesize that the highest prevalence of elevated blood lead levels will be found in urban census tracts after adjusting for census level variables: percent pre-1950 housing, percent black, percent poverty, percent male and industrial lead emissions.

6.0 ENVIRONMENTAL CONTRIBUTION TO CHILDHOOD BLOOD LEAD LEVELS IN U.S. CHILDREN, NHANES 1999-2006

6.1.1 Abstract

Objective: To assess the contribution of both industry-based measures of lead exposure and modeled ambient air lead estimates on childhood (1-5 years of age) blood lead levels.

Methods: Children who received a blood lead screening as part of the NHANES 1999-2006 survey were included in this study. Toxic Release Inventory lead emissions data were used to determine inverse distance squared weighted exposure from industrial sources for each child using the sum of the pounds emitted by each facility divided by the distance to each facility squared. National Air Toxics Assessment ambient air lead estimates were linked to each child's census tract of residence. Un-weighted mixed effect linear regression models using natural log transformed blood lead levels as the outcome variable were used to determine the relationship between lead exposure and blood lead levels after adjusting for gender, race, age in months, reference person's education, poverty income ratio, region of the country, percent housing built before 1950, and survey cycle.

Results: For every 10,000 pounds per mile squared (lb/mi^2) increase in inverse distance squared weighted exposure there was a 1.13% (95% CI: 0.45%, 1.81%) increase in blood lead ($p = 0.001$). Stratified analyses by region of the country showed that for children living in the west

there was a 0.74% (95%CI: 0.29%, 3.20%) increase in blood lead level for each 1 nanogram per meter cubed (ng/m^3) increase in ambient air lead and a 1.25% increase in blood lead levels for every 10,000 $pound/mi^2$ in inverse distance squared weighted exposure. Stratified analyses by race showed that non-Hispanic black children had a 2.88% (95% CI: 1.18%, 4.60%) increase in blood lead levels for every 10,000 $pounds/mi^2$ in inverse distance squared weighted exposure. All other variables included in the model were also significantly associated with changes in childhood blood lead levels: gender, race, poverty income ratio, region, reference adult's education, survey cycle, place of birth and percent housing built before 1950.

Conclusions: Environmental estimates of lead emissions are associated with childhood blood lead levels. However, with the inclusion of home environmental factors (smoking and lead dust) these relationships were attenuated. More evidence is needed to determine if inverse distance squared weighted exposure from Toxic Release Inventory facilities is an appropriate proxy measure of childhood exposure to lead.

6.1.2 Introduction

The National Health and Nutrition Examination Survey (NHANES) was initiated in the 1960s as a way to monitor the nutritional status and health of the U.S. population [28]. Numerous NHANES studies have been conducted that assess blood lead levels in children[15, 25, 43-46]. The majority of these studies focused on the residential and lifestyle factors that contributed to elevated blood lead levels. Blood lead levels of 60 µg/dL or higher are associated with neurological impairment [30] and at lower levels declines in cognition, behavior and IQ have been observed [32]. Pirkle et al., was the first to evaluate blood lead levels for the nation using this survey. A combination of subjects from NHANES II (1976-1980), NHANES III (1988-1991) and the Hispanic Health and

Nutrition Examination Survey (HHANES) (1982-1984) were used to determine trends in blood lead levels over time. For the entire population of children between 1 to 5 years of age a 75% reduction in blood lead levels was observed (14.9 µg/dL to 3.6 µg/dL) from 1976 to 1991 [29].

Many investigators have found gender, race, age of residence, age of the child, poverty income ratio, and Medicaid status to be significantly associated with childhood blood lead levels [15, 29, 43-46]. Having smokers in the home [15,44,45], living in the northeast region of the country [15] and residential dust lead levels [44] have also been linked to elevated blood lead levels. The most recent descriptive analysis of childhood blood lead levels for all of the continuous NHANES surveys (1999-2010), as reported in Morbidity and Mortality Weekly Report, showed a continued decline in blood lead levels. Median blood lead levels for the entire population fell from 1.9 µg/dL (NHANES 1999-2002) to 1.3 µg/dL (NHANES 2007-2010) [12].

In 2012, the Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) recommended the discontinued use of a "level of concern" because no threshold effect limit has been found for childhood blood lead. They decided that goals to reduce blood lead levels should be based on the 97.5 percentile of blood lead levels of children between 1 and 5 years of age who were measured as part of NHANES [11,81]. The most recent assessment of the NHANES blood lead levels in 1 to 5 year old children indicates an elevated blood lead level as greater than or equal to 5 µg/dL [11]. Even though median blood lead levels for the entire country have fallen to less than 2 µg/dL, over 450,000 children between 1 and 5 years of age, in the U.S., have blood lead levels $\geq$ 5 µg/dL [12].

The most recent NHANES study was conducted with NHANES III (1988 to 1994) and continuous NHANES (1999-2008). Richmond-Bryant et al. (2013) conducted the first study to date that included environmental lead as measured with by ambient air lead monitors across the

U.S. Instead of survey weighted linear regression, multi-level linear mixed effect models were used to investigate the association between national ambient air lead monitors and blood lead levels. Individuals of all ages in the survey with blood lead measurements were included. Only 6% of NHANES survey participants lived in a census block group whose centroid was within 4 km of a lead monitor (n = 4561) and were included in the analyses. During the time of these survey cycles ambient air lead for 1 to 5 year old children decreased from 0.04 ug/m^3 to 0.01 ug/m^3. At the same time, median blood lead levels for these children decreased from 4.5 µg/dL to 2.4 µg/dL. Even though significant associations were found between monitors and blood lead levels for all age groups for NHANES III, no significant relationships were found between monitor levels and blood lead levels in children between 1 and 5 years of age for continuous NHANES (1999-2010). However, very few children met the inclusion criteria. Only 654 children were included from the NHANES III and only 205 were included from the continuous NHANES (1999-2008) [47].

Recently, Brink et al. (2013) found significant associations between ambient air lead levels, as estimated by the National Air Toxics Assessment (NATA) at the county level and the likelihood of elevated blood lead for childhood across the nation [74]. Therefore, our objective was to use all children between 1 and 5 years of age (n = 3223) who participated in the NHANES survey between 1999 and 2006, and apply both industry based measures of exposure and modeled ambient air lead estimates to investigate associations with blood lead levels.

6.1.3 Methods

6.1.3.1 Study Population

Data from four cycles of NHANES (1999-2000, 2001-2002, 2003-2004, 2005-2006) were used in the analysis. The continuous phase of the survey began in 1999. Every year approximately 5,000 people in 15 counties across the U.S. are surveyed. Details regarding sampling and survey weights can be found at the National Health Nutrition Examination Survey website [82]. The sample population of interest for this study was children between 1 and 5 years of age who had their blood lead levels measured.

6.1.3.2 Child and Housing Characteristics

Survey interviews included information regarding each child's age, race and sex. In addition, the socioeconomic status of the household, as measured by poverty income ratio (PIR) and the education of the child's reference adult were obtained. PIR indicates where the family income falls in relation to the poverty threshold with a PIR of 100% illustrating a family whose income is at the poverty threshold and a PIR of 50% specifying a household income that is half of the poverty threshold. Higher PIR values are related to higher household incomes [83]. Cotinine, a metabolite indicative of second hand cigarette smoke exposure, and floor lead dust values were also captured for a subset of children. The primary housing variable of interest was the age of the home. The use of lead paint in a residential setting was banned in 1978 so it was important to be able to account for potential exposure to lead from paint remaining in older homes. However, this variable was missing for over 1000 children (33%). To provide the most robust sample size for the analysis and to minimize bias, a census tract estimate of percent housing built before 1950 was obtained from the U.S. Census Bureau American Fact Finder website [61].

During the time of the NHANES survey cycles of interest, 38 million homes in the US had lead-based paint with children less than 6 years of age living in 1.2 million homes [84]. Finally, the restricted use variable of geocoded residential address was requested. The acquired x,y coordinates allowed for the linkage between individual and census level data. To ensure confidentiality of all study participants all analyses were conducted at the National Center for Health Statistics Research Data Center.

6.1.3.3 Environmental Lead

Two different types of non-residential lead emissions were obtained. NATA data were estimated from multiple sources: National Emissions Inventory, Toxic Release Inventory, point, on-road mobile, non-road mobile, non-point, secondary formation and decay and background sources. NATA has been modeled by the EPA since 1996 with additional modeled estimates for 1999, 2002 and 2005. It models ambient air levels for 187 toxins including lead at the state, county and census tract level [85]. NATA ambient air lead data for 2005 were downloaded from the EPA at the census tract level [86]. All children within a given census tract were linked to the estimate of ambient air lead for their census tract of residence.

Lead monitors are sparsely located across the U.S. (n = 250), however, there were 2,299 industrial locations across the U.S. that reported lead emissions to the Environmental Protection Agency Toxic Release Inventory (TRI) in 2011 [87]. Industries are required to report to the TRI Program if they employ 10 or more full time employees (or the equivalent) and if they processes or manufacture 25,000 lbs or more of a chemical in a given year [39]. Since there are more industrial facilities reporting lead emissions than lead monitors and they cover a broader swath of the U.S., industrial releases were used as a proxy measure of exposure. The location and amount of lead emissions for each facility that reported to the Environmental Protection Agency's Toxic

Release Inventory during the years of interest were obtained from the EPA [49]. Data reported to the EPA were averaged in two year intervals to coincide with the data collection cycles for NHANES. Distances were calculated from each child's residence to all lead TRI facilities using the distm() function in R package [88] "geosphere" [89]. The ellipsoid method was specified to obtain point distances. Inverse distance squared weighted exposure was calculated for each child as the sum of pounds of lead released by each facility divided by the sum of the distance between each child and each industrial facility squared. Reported lead emissions and distances between each child and each facility were calculated separately for each NHANES survey cycle. In other words, the inverse distance squared weighted exposure for children assessed during the 1999 – 2000 NHANES cycle was calculated based on the industries who reported to the EPA TRI in 1999 and 2000.

6.1.3.4 Statistical Analyses

Survey weighted descriptive statistics were calculated using SAS version 9.2 for Windows (SAS Institute Inc., Cary, NC) to assess the distribution of childhood blood lead levels and covariates associated with blood lead for the nation. Covariates under consideration included race, age in months, sex, PIR, reference adult's education, percent pre-1950 housing, survey cycle, and region of the country. PIR was broken into four groups: < 50% poverty, 50 to 99% poverty, 100 to 199% poverty and 200% poverty or above. Reference adult education was dichotomized into high school graduate or less and those that completed or participated in some college education. Two different data sets were considered: all children with measured blood lead levels and data on the covariates of interest (n = 3223) and children who had data on both residential floor lead dust and cotinine measures (n = 1039).

Two variables of interest for the total sample were only available at the census tract level (NATA, percent housing built before 1950). NHANES participants are not selected using simple random sampling. The survey is designed to obtain a sample of participants who represent the non-institutionalized, civilian, U.S. population and is based on a complex, multistage, probability sampling design [28]. Due to the unequal probability of selection at each stage, multilevel modeling with such data usually leads to biased parameter estimates [90]. As the survey weights are not inverse probabilities of selection, use of sampling weights in post stratification analyses results in invalid corrections [91]. In addition, individual and census level variables are being employed in the analysis. Likelihood ratio tests for univariate and multivariable mixed effects models indicated that tract level effects were significant. For these reasons, un-weighted multilevel linear regressions were performed to assess how residential and environmental lead sources impact childhood blood lead levels using Stata 13 (StataCorp., College Station, Texas). The outcome variable was the natural log transformed blood lead level so each beta coefficient was interpreted as the percent change in blood lead level for a one unit increase in the covariate of interest.

The primary objective of this analysis was to determine if environmental lead exposures were associated childhood blood lead levels after adjustment for gender, race, PIR, age in months, percent pre-1950 housing, survey cycle, region, reference adult's education, and place of birth. Then additional exploratory analyses were performed to determine if significant associations were observed after controlling for residential contributors to blood lead levels: floor lead dust and smoking. Finally stratified analyses were performed to determine if there were differences in associations between environmental exposure and blood lead levels by grouping variable (i.e. by race). For all models under consideration, the likelihood ratio test was

significant at $p < 0.001$, indicating the mixed effect logistic regression models provided a better fit to the data than traditional logistic regression models.

6.1.4 Results

6.1.4.1 Summary Statistics

A total of 3,223 children met the requirement for inclusion in the full model. However, the sample size dropped considerably when investigating children whose homes were evaluated for lead dust (n = 2253) because lead dust samples were not captured for the final cycle (2005-2006). Sample sizes were further reduced when considering children with smoking related measures because cotinine was only captured on children who were at least 3 years of age. The final sample size for children with both cotinine and lead dust measures was 1,041. The demographic characteristics between these subsets of children are very similar (Tables 6-1 and 6-2).

For all children (n = 3223) the survey weighted proportion of males to females was approximately 53% to 47%. The weighted distribution of the sampled children was 22.1% Hispanic, 57.5% non-Hispanic white and 14.4% black. Approximately 29% of the children live below 100% poverty and more than 38% of the children live in the southern region of the US. The overall geometric mean blood lead level for children with complete data on the covariates of interest was 1.73 µg/dL (95%CI: 1.65, 1.82). Of the 3223 children, 272 children had blood lead levels greater than or equal to 5 µg/dL (Table 6-1). Non-Hispanic black children having higher geometric mean blood lead (2.58 µg/dL) than non-Hispanic white (1.59 µg/dL) and Hispanic children (1.69 µg/dL). When evaluated by region, childhood blood lead measures are highest in the Northeast (2.21 µg/dL; 95%CI: 2.04, 2.40) and lowest in the West (1.34 µg/dL; 95%CI: 1.26,

1.42) for the entire sample. Over the entire study period geometric mean blood lead levels fell from 2.17 µg/dL (1999-2000) to 1.44 µg/dL (2005-2006) (Table 6-1).

For children with lead dust and cotinine measures (n = 1039) the survey weighted distribution of children was 21% Hispanic, 57% non-Hispanic White and 15.6% non-Hispanic Black. Approximately 29.6% of the children live below 100% poverty and the overall geometric mean blood lead 1.70 (95%CI: 1.59, 1.82) µg/dL is very similar to the entire sample population. Non-Hispanic black children have a geometric mean blood lead of 2.52 µg/dL while non-Hispanic white and Hispanic children have blood lead levels of 1.56 µg/dL and 1.66 µg/dL, respectively. Highest geometric mean blood lead levels are found in the Midwest (2.06 µg/dL; 95%CI: 1.79, 2.39) and lowest in the West (1.35; 95%CI: 1.26, 1.45) (Table 6-2). It is difficult to compare blood lead levels between the two datasets because cotinine was only captured on children between 3 and 5 years of age and as a group, older children have lower blood lead levels than children between 1 and 2 years of age. Additionally, lead dust measures were not captured in the final cycle under consideration and blood lead levels have fallen over time.

The distribution of non-residential exposure depends upon the environmental source of lead. The median ambient air lead level as estimated by NATA was 1.77 nanograms per meter cubed (ng/m^3) while the median inverse distance squared weighted exposure from lead TRI facilities was 1748 pounds per square mile (lb/mi^2) for the full sample and these levels were very similar in children who had measures for lead dust and cotinine. The relationship between environmental lead and categorical group holds for the full sample population as well as for children with lead dust and cotinine levels. The highest inverse distance squared weighted exposure occurs for children living in the west with median levels greater than 4000 lb/mi^2 and the lowest levels are in the south with median inverse distance squared weighted exposure less

than 1000 lb/mi^2 (Tables 6-1 and 6-2). Children with blood lead levels greater than or equal to 5 µg/dL and those living at less than 50% poverty have higher inverse distance squared weighted exposure than children with lower blood lead levels and those with higher incomes. Median ambient air lead as estimated by NATA is 1.77 ng/m^3 for the full sample and 1.72 ng/m^3 for children with lead dust and cotinine measures. Children born outside of the U.S. live in census tracts with higher estimated ambient air lead levels than children born in the US. Non-Hispanic black children live in census tracts with the highest NATA levels and non-Hispanic white children live in census tracts with the lowest. The regional distribution of NATA indicates that children living in the northeast experience higher ambient air lead than all other regions of the country. Similar to inverse distance weighted exposure, children with a blood lead level greater than or equal to 5 µg/dL live in areas with the highest estimated ambient air lead levels (Tables 6-1 and 6-2).

NATA is modeled from many sources including TRI emissions and inverse distance squared weighted exposure is calculated from TRI. One might expect that the distributions of environmental lead, regardless of exposure variable, to be similar. In spite of that, the distributions of the two environmental variables across subgroups differ (Figure 6-1). Inverse distances weighted exposure is comparable across race groups, but Hispanic children and non-Hispanic black children live in census tracts with higher NATA ambient air lead levels. Children living in families with the highest PIR level have the highest NATA estimated air lead level but the lowest inverse distance squared weighted exposure levels. Meanwhile, children living in families with the lowest PIR have lower NATA levels but the highest inverse distance squared weighted exposure levels. NATA estimates are highest for children living in the northeast while children in the west have the highest inverse distance squared weighted exposure.

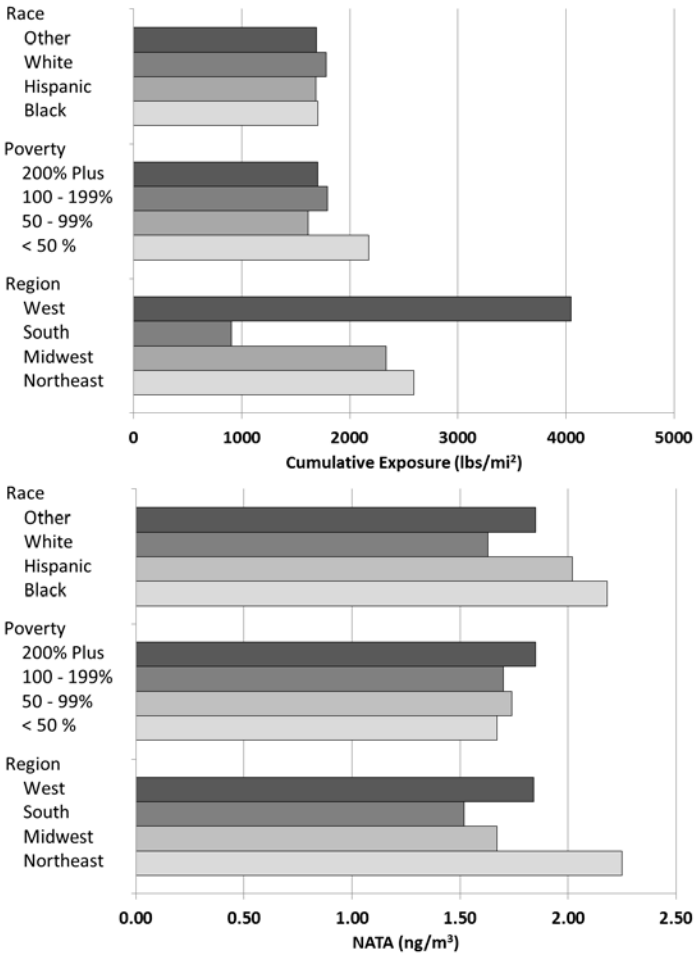

Figure 6-1. Distribution of environmental lead exposure variables by selected subgroups of the NHANES sample population.

Table 6-1. Survey weighted descriptive statistics for all children with blood lead levels and data on the covariates of interest for NHANES (1999-2006)

	All Children								
			Blood Lead (µg/dL)			Inverse Distance Squared Weighted Exposure (lbs/mi2)		NATA (ng/m3)	
	n	weighted %	GM	95% CI		Md	IQR	Md	IQR
Overall	3223	100	1.73	1.65	1.82	1748	3587	1.77	1.59
Gender									
female	1561	47.1	1.73	1.63	1.83	1860	3691	1.77	1.63
male	1662	52.9	1.74	1.64	1.84	1699	3520	1.76	1.57
US Born									
Yes	3124	97.4	1.72	1.64	1.81	1756	3611	1.76	1.60
No	99	2.6	2.09	1.86	2.35	1567	3329	2.15	1.68
Race									
Hispanic	1221	22.1	1.69	1.60	1.80	1688	3840	2.02	1.68
white	934	57.5	1.59	1.49	1.70	1782	3377	1.63	1.64
black	895	14.4	2.58	2.37	2.79	1706	4030	2.18	1.67
other	173	6.0	1.63	1.48	1.81	1693	5295	1.85	1.32
Age Group (years)									
1 to <2	773	19.3	1.97	1.86	2.09	2015	3782	1.75	1.63
2 to <3	795	20.4	1.90	1.79	2.02	1725	3323	1.76	1.72
3 to < 4	540	19.1	1.69	1.51	1.88	1746	3738	1.75	1.54
4 to < 5	568	20.4	1.62	1.53	1.72	1649	3474	1.74	1.59
5 to < 6	547	20.8	1.53	1.42	1.64	1715	3464	1.81	1.56
Reference Education									
<= highschool grad	1963	49.4	2.01	1.90	2.13	1677	3231	1.70	1.85
some college plus	1260	50.6	1.50	1.42	1.58	1814	3955	1.83	1.39
Poverty									
< 50% poverty	548	11.5	2.60	2.39	2.84	2178	5602	1.67	1.97
50 to 99% poverty	742	17.2	2.19	2.06	2.33	1617	3186	1.74	1.75
100 to 199% poverty	924	26.1	1.77	1.63	1.92	1793	3772	1.70	1.53
200% plus poverty	1009	45.2	1.41	1.33	1.49	1706	3467	1.85	1.54
Region									
Northeast	432	14.9	2.21	2.04	2.40	2591	5645	2.25	1.70
Midwest	615	22.3	1.92	1.67	2.20	2336	2137	1.67	1.98
South	1307	38.7	1.74	1.62	1.87	907	949	1.52	1.43
West	869	24.1	1.34	1.26	1.42	4051	13703	1.84	1.49
BLL ≥ 5 µg/dL									
Yes	272	5.9	7.45	7.07	7.85	2252	4706	2.28	1.73
No	2951	94.1	1.58	1.52	1.64	1696	3517	1.75	1.58

Table 6-1 Continued

Survey Years									
	1999-2000	628	20.9	2.17	1.93	2.45	1454	1958	1.71	1.41
	2001-2002	837	25.7	1.71	1.55	1.90	2517	5724	1.77	1.51
	2003-2004	860	27.2	1.75	1.60	1.92	1582	3650	1.54	1.92
	2005-2006	898	26.2	1.44	1.35	1.55	1593	3260	2.01	1.69

Table 6-2. Survey weighted descriptive statistics for all children with blood lead levels, floor lead dust measures, cotinine and data on the covariates of interest for NHANES (1999-2004) for children 3 to 5 years of age.

			Blood lead (µg/dL)			Inverse Distance Squared Weighted Exposure (lbs/mi2)		NATA (ng/m3)		Lead Dust (ug/ft2)		Cotinine (ng/mL)	
	n	weighted %	GM	95% CI		Md	IQR	Md	IQR	Md	IQR	Md	IQR
Overall	1039	100	1.70	1.59	1.82	1793	4111	1.72	1.67	0.45	0.72	0.12	0.73
Gender													
female	492	47.7	1.68	1.53	1.83	1738	3982	1.72	1.60	0.46	0.71	0.12	0.72
male	547	52.3	1.72	1.57	1.89	1797	4163	1.72	1.72	0.45	0.72	0.13	0.76
US Born													
Yes	991	96.1	1.69	1.57	1.81	1814	4128	1.70	1.69	0.46	0.71	0.13	0.75
No	48	3.9	2.07	1.89	2.26	1533	2826	1.96	1.66	0.42	0.96	0.07	0.56
Race													
Hispanic	368	21.1	1.66	1.54	1.80	1629	4178	1.86	1.95	0.48	0.80	0.05	0.13
white	300	57.1	1.56	1.43	1.71	1811	3756	1.49	1.54	0.41	0.53	0.14	1.12
black	320	15.6	2.52	2.28	2.79	1705	5600	2.28	1.88	0.82	1.12	0.33	0.95
other	51	6.2	1.46	1.29	1.65	3244	5853	1.63	1.36	0.36	0.54	0.17	1.01
Age Group (yr)													
3 to < 4	333	29.8	1.86	1.65	2.10	1886	4961	1.64	1.79	0.49	0.75	0.12	1.21
4 to < 5	352	33.9	1.69	1.58	1.81	1621	4040	1.67	1.68	0.42	0.69	0.13	0.50
5 to < 6	354	36.3	1.59	1.44	1.74	1819	3949	1.77	1.63	0.47	0.75	0.12	0.59
Reference Ed													
<= H.S. grad	645	51.7	1.97	1.83	2.12	1793	3883	1.67	1.89	0.57	0.95	0.32	1.32
some college +	394	48.3	1.45	1.34	1.58	1716	4147	1.76	1.47	0.38	0.46	0.06	2.67
Poverty													
< 50%	184	12.3	2.64	2.37	2.94	2775	6165	1.66	1.81	0.74	1.57	0.73	2.28
50 to 99%	235	17.3	2.29	2.09	2.50	1616	3961	1.73	2.12	0.67	0.99	0.32	1.33
100 to 199%	306	28.1	1.70	1.49	1.93	1941	4401	1.62	1.33	0.49	0.75	0.17	1.23
200% plus	314	42.3	1.33	1.24	1.42	1589	3504	1.77	1.73	0.35	0.42	0.05	0.16
Region													
East	129	14.9	1.91	1.63	2.23	2138	2178	2.22	2.00	0.49	1.61	0.11	0.46
Midwest	212	22.0	2.06	1.79	2.39	3369	5775	1.50	2.22	0.49	0.93	0.38	1.61
South	438	40.2	1.67	1.52	1.83	889	971	1.55	1.44	0.46	0.69	0.13	0.98
West	260	22.9	1.35	1.26	1.45	4789	14080	1.75	1.56	0.36	0.48	0.03	0.21
BLL ≥ 5 µg/dL													
Yes	71	4.9	7.37	6.91	7.86	2235	6649	2.56	2.15	2.64	4.52	1.32	3.09
No	968	95.1	1.58	1.49	1.68	1731	4034	1.67	1.67	0.43	0.62	0.12	0.59
Survey Years													
1999-2000	277	27.0	2.06	1.80	2.35	1435	1587	1.73	1.37	0.67	1.00	0.13	0.53
2001-2002	370	35.7	1.55	1.39	1.72	2599	6585	1.76	1.75	0.36	0.49	0.10	0.67
2003-2004	392	37.3	1.62	1.45	1.81	1541	3789	1.55	2.02	0.43	0.62	0.16	0.99

6.1.4.2 Multilevel Linear Regression Analyses

Univariate analyses revealed that all demographic covariates of interest were significant for both data sets except gender. Inverse distance squared weighted exposure from industrial releases was not significantly associated with childhood blood lead levels prior to adjustment. NATA was significant for all data sets with betas indicating a 2.37 to 2.63% increase in blood lead levels for every 1 ng/m^3 increase in ambient air lead ($p < 0.01$) prior to adjustment. After adjusting for all demographic covariates of interest (sex, race, age in months, reference adult's education level, percent pre-1950 housing, PIR, region and survey cycle), NATA was no longer significant, but inverse distance squared weighted exposure became significant ($p = 0.001$). For every 10,000 lbs/mi^2 increase in inverse distance squared weighted exposure there was a 1.13% (95% CI: 0.45%, 1.81%) increase in blood lead.

Table 6-3 shows the contribution of each variable in the full model, including inverse distance squared weighted exposure, to changes in blood lead level after adjustment. The blood lead levels of non-Hispanic black children are almost 34.7% higher than the blood lead levels of non-Hispanic white children. Similarly, the poorest children have geometric mean blood lead levels 35.4% higher than children living in families with the highest income. Even after adjustment, children in the West have blood lead levels 25.7% lower than children living in the Northeast. This may be due to a higher preponderance of homes built prior to 1950 in the Northeast as well as higher levels of lead industrial activity. Ambient air lead may no longer be the primary exposure pathway for children. Finally, for every 10% increase in census tract percentage of housing built before 1950 blood lead levels increased 8.1%. These contributions to childhood blood lead levels remained when NATA was included in the model instead of inverse distance squared weighted exposure.

Table 6-3. Contribution of each variable in the full inverse distance weighted exposure model to changes in childhood blood lead levels (n = 3223) after adjustment with all other variables in the model.

Poverty	% Change	95% CI		p
100 to 199% Poverty v. 200% Plus Poverty	14.24	8.52	20.26	<0.001
50 to 99% Poverty v. 200% Plus Poverty	31.68	24.50	39.27	<0.001
< 50% Poverty v. 200% Plus Poverty	35.40	27.01	44.35	<0.001
Region				
Midwest v. Northeast	-7.48	-14.73	0.39	0.062
South v. Northeast	-10.39	-17.42	-2.75	0.009
West v. Northeast	-25.72	-31.93	-18.94	<0.001
Reference Adult Education				
Some college v. <= H.S. Graduate	-9.53	-13.35	-5. 55	<0.001
Survey Cycle Start Year				
2001 v. 1999	-17.15	-22.50	-11.43	<0.001
2003 v. 1999	-18.10	-23.36	-12.49	<0.001
2005 v. 1999	-27.27	-31.95	-22.28	<0.001
Race				
Hispanic v. non-Hispanic White	-2.56	-7.79	2.97	0.357
Non-Hispanic Black v. non-Hispanic White	34.68	27.24	42.55	<0.001
Other v. non-Hispanic White	13.18	3.53	23.72	0.006
1 month increase in age	-0.55	-0.65	-0.44	<0.001
Gender				
Males v. Females	4.51	0.79	8.37	0.017
Place of Birth				
US born v. non-US born	-26.57	-34.05	-18.23	<0.001
10 % increase in pre-1950 housing	8.10	6.86	9.34	<0.001
10,000 lbs/mi^2 increase in lead	1.14	0.45	1.81	0.001

The inclusion of cotinine and lead dust in the overall model resulted in neither environmental lead variable being significant, but the sample size dropped considerably. However, the inclusion of lead dust and cotinine impacted the contribution of poverty and region on changes in childhood blood lead levels. As shown in Table 3, children in the lowest two levels of poverty have blood lead levels at least 43% higher than children living in families with the highest income level. The contrast between children living in the West versus those living in the Northeast was reduced to less than an 18% difference between the two groups. With dust

and cotinine in the model there was no significant difference between children living in the Midwest versus those living in the Northeast or children living in the South and those living in the Northeast. The influence of census tract percentage of homes built before 1950 was reduced slightly. For every 10% increase in census tract percent of housing built before 1950 blood lead levels increased approximately 6.6%.

Table 6-4. Contribution of each variable with the inclusion of lead dust and cotinine in the inverse distance weighted exposure model to changes in childhood blood lead levels (n = 1039) after adjustment with all other variables in the model.

Poverty	% change	95% CI		p
100 to 199% Poverty v. 200% Plus Poverty	18.49	9.08	28.72	<0.001
50 to 99% Poverty v. 200% Plus Poverty	43.43	30.90	57.15	<0.001
< 50% Poverty v. 200% Plus Poverty	45.45	31.40	61.00	<0.001
Region				
Midwest v. Northeast	7.65	-4.68	21.57	0.235
South v. Northeast	-2.13	-13.35	10.54	0.729
West v. Northeast	-17.15	-27.30	-5.58	0.005
Reference Adult Education				
Some college v. ≤ H.S. Graduate	-7.97	-14.13	-1.36	0.019
Survey Cycle Start Year				
2001 v. 1999	-15.82	-22.69	-8.33	<0.001
2003 v. 1999	-17.92	-24.58	-10.66	<0.001
Race				
Hispanic v. non-Hispanic White	2.70	-6.15	12.38	0.562
Non-Hispanic Black v. non-Hispanic White	30.52	19.62	42.42	<0.001
Other v. non-Hispanic White	5.28	-9.44	20.39	0.503
1 month increase in age	-0.47	-0.75	-0.18	0.002
Gender				
Males v. Females	4.64	-1.48	11.13	0.140
Place of Birth				
US born v. non-US born	-25.77	-35.88	-14.06	<0.001
1 ug/ft^2 increase in lead dust	1.23	0.62	1.84	<0.001
1 ng/mL increase in cotinine	3.69	2.16	5.25	<0.001
10 % increase in pre-1950 housing	6.61	4.79	8.47	<0.001
10,000 lb/mi^2 increase in lead	0.44	-0.59	1.48	0.405

Secondary stratified analyses were performed to determine if the association between environmental lead and blood lead level varied between regions of the country or subpopulations of interest. All models were adjusted for gender, age in months, reference person's education, US birth, PIR, region, survey cycle and race, when appropriate. Since TRI lead emissions are incorporated into NATA estimates, separate analyses were conducted for each environmental lead exposure variable. Table 6-5 shows the individual results for each stratified analysis for NATA and Cumulative exposure separately for the entire sample of children with blood lead measures.

(a) Total Sample of Children

NATA was significantly associated with childhood blood lead levels for two stratified groups. For children living in the west there was a 0.74% (95%CI: 0.29%, 3.20%) increase in blood lead level for each 1 ng/m^3 increase in ambient air lead. For children who participated in the NHANES survey from 1999-2000 there was a 2.1% (95%CI: 0.62%, 3.61%) increase in blood lead level for each 1 ng/m^3 in ambient air lead. No other survey cycles showed significant associations between ambient air lead estimates and childhood blood lead levels. Inverse distance squared weighted exposure was significant for 8 stratified groups. For children with a reference adult who attended at least some college, blood lead levels increased 1.36% (95% CI: 0.46%, 2.27%) for every 10,000 lb/mi^2 increase in inverse distance squared weighted exposure. For children born in the US there was a 1.16% (95% CI: .47%, 1.86%) increase in blood lead for every 10,000 lb/mi^2 in inverse distance squared weighted exposure. There was a 1.25% increase in blood lead levels for children living in the west for every 10,000 lb/mi^2 in inverse distance squared weighted exposure. Non-Hispanic black children had a 2.88% (95% CI: 1.18%, 4.60%)

increase in blood lead levels for every 10,000 lb/mi^2 increase in inverse distance squared weighted exposure. Children in the lowest poverty groups and those who participated in NHANES for 2003-2004 and 2005-2006 also had significant increases in blood lead level for incremental increases in inverse distance squared weighted exposure.

Table 6-5. The separate effects of NATA and cumulative exposure by stratification category on geometric mean blood lead levels as determined with multivariable mixed effect linear regressions for all children (n = 3225).

	NATA				Cumulative Exposure			
Category	% Change	95%CI		p	% Change	95%CI		p
Gender								
female	1.08	-0.19	2.37	0.096	1.64	0.72	2.58	<0.0001
male	-0.16	-1.56	1.55	0.984	0.74	-0.16	1.64	0.107
Education level								
≤ H.S. Graduate	1.23	-23.89	2.51	0.055	0.67	-0.37	1.72	0.207
Some College +	-1.70	-3.69	0.33	0.099	**1.36**	**0.46**	**2.27**	**0.003**
PIR Group								
< 50%	-0.27	-2.14	1.63	0.778	**1.39**	**0.27**	**2.52**	**0.015**
50 to 99%	0.61	-1.67	2.93	0.603	**1.38**	**0.20**	**2.56**	**0.021**
100 to 199%	1.13	-0.77	3.07	0.246	0.60	-0.96	2.19	0.450
200% plus	0.65	-1.50	2.85	0.554	1.08	-0.88	3.08	0.282
Region								
North East	0.40	-2.50	3.39	0.789	2.35	-5.45	10.79	0.566
Midwest	1.13	-2.27	4.64	0.520	0.28	-1.32	1.90	0.733
South	-1.80	-3.96	0.43	0.113	-4.36	-9.59	1.16	0.120
West	**1.74**	**0.29**	**3.20**	**0.018**	**1.25**	**0.50**	**2.00**	**0.001**
Survey Years								
1999-2000	**2.10**	**0.62**	**3.61**	**0.005**	0.22	-1.22	1.67	0.769
2001-2002	-1.82	-4.81	1.26	0.243	0.07	-1.35	1.51	0.923
2003-2004	0.71	-1.25	2.70	0.482	**3.64**	**0.11**	**7.29**	**0.043**
2005-2006	-2.12	-5.32	1.18	0.205	**1.64**	**0.65**	**2.63**	**0.001**
Race								
white	-2.98	-5.97	0.11	0.058	0.96	-0.23	2.17	0.114
hispanic	1.34	-0.04	2.73	0.057	0.54	-0.42	1.51	0.268
black	0.10	-1.92	2.17	0.921	**2.88**	**1.18**	**4.60**	**0.001**
other	-7.34	-15.93	2.13	0.125	2.29	-0.58	5.25	0.118

***All models where appropriate were adjusted for the following covariates: sex, reference person's education, US birth, PIR, Region, Survey cycle, age in month and race.**

(b) Children with lead dust and cotinine measures

These stratified analyses were also conducted on the sample of children with cotinine and lead dust measures (not shown). After the inclusion of cotinine and floor lead dust, NATA was significantly associated with increases in blood lead levels for children who participated in the 1999 – 2000 NHANES survey cycle. For each 1 ng/m^3 increase in NATA there was a 2.16% (95%CI: 0.29%, 4.07%) increase in blood lead level. Living in the West was no longer associated with significant associations between NATA estimated air lead levels and childhood blood lead level. Inverse distance squared weighted exposure remained significant for children who participated in the 2003-2004 survey cycle and for females there was a 1.92% (95%CI: 0.14, 3.73%) increase in blood lead levels for each 10,000 pound/mi^2 increase in inverse distance squared weighted exposure. However, there were no significant associations between inverse distance squared weighted exposure and blood lead level for the remaining categories.

6.1.5 Discussion

This investigation was the first of its kind to consider to what extent ambient air lead contributed to childhood blood lead levels for children between 1 and 5 years of age using both residential (indoor) and environmental (outdoor) lead variables. Inverse distance squared weighted exposure for TRI was significantly associated with childhood blood lead levels for the entire study population (1999-2006). When lead dust and cotinine were introduced into the model, sample size was reduced and neither environmental lead variable was associated with childhood blood lead levels in the un-stratified analyses. Upon stratification, the contributions of environmental lead to childhood blood lead levels varied by the subpopulation under

consideration. Inverse distance squared weighted exposure was significantly associated with childhood blood lead levels for more subpopulations than ambient air lead as estimated by NATA.

The NATA results for the stratified analysis by region and survey cycle are consistent with a study assessing the association between county level NATA ambient air lead estimates and percentage of children with blood lead levels greater than or equal to 10 µg/dL. Brink et al. obtained county data for the number of children tested and the number of children with elevated blood lead (≥ 10 µg/dL) for over 1500 counties across the US. This blood lead data was collected as part of the Healthy Homes and Lead Poisoning Prevention Branch at the Centers for Disease Control and Prevention (2000-2006). Multivariable negative binomial regression showed that NATA estimates at the county level significantly predicted percent of children elevated after adjusting for census level variables of percent pre-1950 homes and percent poverty, racial distribution for the county and urban rural classification at the county level [74]. Nevertheless the results are only significant for the first survey cycle under consideration (1999-2000). This may be due to the successful reduction in ambient air lead levels over time.

The results for inverse distance squared weighted exposure are consistent with the analysis of ambient air lead monitor data and childhood blood lead levels. Richmond-Bryant et al., found significant associations for children with blood lead measures collected as part of NHANES III [47]. They were unable to find significant associations between monitor data and childhood blood lead levels for children who participated in continuous NHANES (1999-2008) but their sample size for those children was only 205. By using TRI lead reported releases, the sample size for this study was only limited by the number of children who received a blood lead screening.

Proximity to industrial locations has been shown to affect blood lead levels. It has been documented that children living near industrial facilities associated with lead production are at an increased risk of having elevated blood lead levels. Aelion et al. studied metal soil toxicity in land surrounding TRI facilities in a state in the southeastern US and found an inverse distance relationship between soil concentrations and proximity to the facility. Several metals were measured, including lead, and there were significant correlations between lead and other metals as well as the inverse distance to the facilities [92]. Stroh et al., found a dose response relationship with children living in close proximity to a lead smelter having significantly higher blood lead levels than children living further away ($p < 0.0001$) [71]. Saline, Kansas and El Paso, Texas have a history of lead smelting. Local health departments in those specific locations have done studies to assess blood lead levels in children within the community. The goal was to determine if living near the smelting facility was associated with higher blood lead levels than those living further away. Children living in Saline County, the home of the Exide Battery plant, had significantly higher blood lead levels than children living in the surrounding counties [68]. In El Paso, there was a significant association between soil lead levels and blood lead levels. For each 500 ppm increase in soil lead the odds of having an elevated blood lead level (greater than or equal to 10 µg/dL) increased 4.5 times [69].

There are some limitations associated with the current study. Inverse distances squared weighted exposure is not a measure of the amount of lead that can be directly absorbed, inhaled or ingested by the body. It is a proxy measure that accounts for the number of industrial facilities located within close proximity to each child and the amount of lead released as reported to the EPA. There is potential exposure misclassification from facilities failing to report lead emissions or under reporting lead emissions for a given year. NATA data was from the 2005

estimates which is an annual measurement estimated at the census tract level. This estimate was applied to all children in the data set. Brink et al compared NATA ambient air lead estimated at the county level for 2002 and 2005 and found the difference in ambient air lead between the two estimates was 0.2 ng/m^3 [72]. Census level variables may adequately represent individuals in urban areas because tracts are based on population size. However, in rural locations the tracts can be quite large and the estimated values for age of housing may not adequately account for living conditions of all children living within the specified census tract. Finally, the results of the regression analyses are not generalizable to the nation as a whole. The children included in the analysis are not a random sample of the US population.

NATA data is based in part on TRI lead emissions so it may be surprising to see that inverse distance squared weighted exposure and NATA did not coincide. NATA is an average value attributed to an entire census tract. It does not take into account a child's residential proximity to a facility releasing lead into the air. A child living across the street from an industry is given the same NATA ambient air lead level as a child living much farther away from the industry but still residing within the same census tract. It is possible that inverse distance squared weighted exposure is over estimating the potential effect of industry on childhood blood lead levels. An alternative explanation is that the poorest children live in very close proximity to lead based industries. Based on the regional distribution children in the west have the highest inverse distance weighted exposure, implying that children in the west live in closer proximity to industrial facilities than children in other regions of the country. However, these same children have the lowest lead dust, cotinine and childhood blood lead levels. The multivariable mixed effect linear models provided different results depending upon which environmental lead variable was used. In order to understand if inverse distance weighted exposure is an appropriate

proxy for environmental lead exposure additional research needs to be conducted. Further work needs to be carried out exploring the relationship between NATA data, monitor data and inverse distance weighted exposure. It is recommended that all NHANES participants who live in a census tract with an air monitor be evaluated. This would provide a way to determine if there is consistency between the association of blood lead level and monitor data, census estimated ambient air lead and inverse distance squared weighted exposure data.

7.0 THE RELATIONSHIP BETWEEN EXPOSURE TO LEADED AVIATION FUEL IN AIRPORT LEAD EMISSIONS AND CHILDHOOD BLOOD LEAD LEVELS

7.1.1 Abstract

Objective: Leaded gasoline is still used in smaller aircraft to ensure combustion at altitude. The objective was to compare the likelihood of elevated blood lead levels in children who live within 3 km of an airport to children who live further away.

Methods: Individual, de-identified data on children between 0 and 3 years of age were obtained from Pennsylvania and New Jersey State Health Departments for children who were screened between 2006 and 2008. In addition to age in months and gender, geocoded residential coordinates were obtained so a child's residence could be linked to their respective census tracts. Distance to the nearest airport, as well as average industrial exposures based on 2008 National Emissions Inventories were determined for each child.

Results: There was no difference in the risk of elevated blood lead level for children living near an airport versus those living further away after adjusting for gender, age in months, average industrial exposure and census level variables: percent housing build before 1950, percent black and percent poverty. The mean blood lead level for children living near an airport was 3.00 (SD = 2.00) while the mean blood lead level for children who did not live within close proximity to the airport was 3.14 (SD = 2.38).

Conclusions: Children who live in Pennsylvania and New Jersey do not experience an increased risk of elevated blood lead level if they live near an airport. However, annual lead emissions from airports in these two states range from 10 pounds to 720 pounds. Future studies focusing on areas where ambient air lead levels are elevated due to airport traffic are warranted.

7.1.2 Introduction

One of the most successful public health initiatives in the U.S. has been reducing childhood exposure to lead which in turn has resulted in dramatic declines in childhood blood lead levels. The largest decline in childhood blood lead levels was due to the removal of tetraethyl lead from automobile gasoline [9]. In addition to phasing lead out of automotive gasoline (initiated in 1973 and completed by 1995), lead was banned from residential paint in 1978 and from food can solder in 1995 [4]. As assessed with data collected as part of the National Health and Nutrition Examination Survey (NHANES), median childhood blood lead levels have dropped from 13.7 µg/dL (NHANES II 1976-1980) [29] to 1.3 µg/dL (NHANES 2007-2010) [12].

Lead exposure, has been linked to cognitive [33,34] and behavioral deficits [32] and delayed onset of puberty in adolescent females [31]. These health effects were observed at blood lead levels below 10 µg/dL. Results from these studies and many others led, the Advisory Committee on Childhood Lead Poisoning Prevention (ACCLPP) to recommend the discontinued use of "a level of concern" because no evidence of a threshold exists. They recommend using the 97.5 percentile of blood lead levels measured in children between the ages of 1 to 5 as part of the National Health and Nutrition Examination Survey (NHANES) to determine blood lead levels of interest [11]. The most recent NHANES survey (2007 – 2010) indicates the top 2.5 percentile of

children in the US have blood lead levels ≥ 5 µg/dL [12]. Over 450,000 children between 1 and 5 years of age, in the U.S., have blood lead levels ≥5 µg/dL [11].

The U.S. consumes approximately 1.4 million metric tons of lead annually. As a nation the U.S. is the third largest producer of lead in the world [16] and the second largest consumer [17]. Over 88% of lead consumption in the US is for the creation of lead-acid storage batteries with additional consumption for the creation of ammunition, ceramics and sheet lead [93]. Currently, the largest point source of airborne lead emissions in the U.S. is aviation gasoline [54]. These internal combustion engines release particles smaller than 0.5 um in size [94]. Smaller propeller planes require gasoline with low ignition temperatures so that combustion can be achieved at altitude. A fuel that meets these requirements contains tetraethyl lead and is known as Avgas. Avgas comes in two main types: 100 octane and 100LL. The allowable lead concentration of lead in 100 LL is 2.12 g/L while 100 octane can contain up to 4.24 g/L [55].

Only one study to date has been conducted to investigate the relationship between a child's residential proximity to an airport and their blood lead level in the U.S. Miranda et al. investigated the relationship between proximity to airports and childhood blood lead levels. A total of 13,478 children lived within 2 km of airports located in 6 North Carolina counties. Their blood lead levels were collected from 1995-2003 and the age of the children ranged from 9 months to 7 years of age. After adjusting for age of housing, census level median income, proportion of public assistance, proportion Hispanic, proportion black and season of the test blood lead levels were significantly associated with residential proximity to the airport. The relationship between blood lead levels and proximity was significant for 500 m, 1000 m and 1500 m from the airport. Mean blood lead levels were 4.4%, 3.8% and 2.1% higher for kids

living within 500 m, 1000 m and 1500 m respectively, in comparison to children living between 1500 m and 2000 m away [57].

The current study focuses on children who received blood lead screenings between 2006 and 2008 in Pennsylvania or New Jersey. The objective was to determine how lead emissions from airports and industrial facilities, as estimated by the National Emissions Inventory, contribute to the likelihood of a child having elevated blood lead levels (≥5 µg/dL).

7.1.3 Methods

7.1.3.1 Data

Pennsylvania and New Jersey participate in the Centers for Disease Control and Prevention (CDC) Childhood Lead Poisoning Surveillance Program. Their blood lead data is shared with the CDC in an effort to maintain a national database of childhood blood lead levels. This program was initiated by the CDC in 1995 [81]. Individual, de-identified data on age, gender, blood lead level, and x,y coordinates of each child's residence were obtained from the Pennsylvania and New Jersey State Health Departments for the years 2006 to 2008. Children ranged in age from 0 to 36 months. Data files from each state were de-duplicated based on their identification number. If a child was present in the data set for more than one time point then the maximum blood lead level was used for this analysis. Children with blood lead levels ≥ 5 µg/dL were considered to have elevated blood lead levels. Data from both states was combined into a single dataset for a total sample size of 493,956. Approximately 5% of these children lived within 3km of an airport (n = 25684). In addition to individual level data, census tract level data were obtained from the U.S. Census American Fact Finder website: percent pre 1950 housing [61],

percent black [60], and percent below poverty [59]. The residential coordinates for each child were used to link them to their respective census tracts.

National Emissions Inventory (NEI) lead air data (2008) for airports and non-airport facilities were downloaded from the Environmental Protection Agency (EPA) [58]. Average lead intensity was calculated as follows:

$$Average\ Intensity = \frac{\sum \frac{c(i)}{d(i)}}{\sum \frac{1}{d(i)}},$$

where c(i) is the air lead emissions reported at site i and d(i) is the distance weight for site i. Both airport and industrial facility exposure are important because PA and NJ are highly industrialized. Between the two states there are over 800 non-airport industrial facilities that had 2008 NEI lead emissions data, and there were 150 airports with annual lead emissions greater than 10 lbs (Figure 7-1). A single average intensity value was determined for each child and included emissions from industry and airports located within 5 km of their residence. An indicator variable was also created to flag those children who lived within 3 km of an airport.

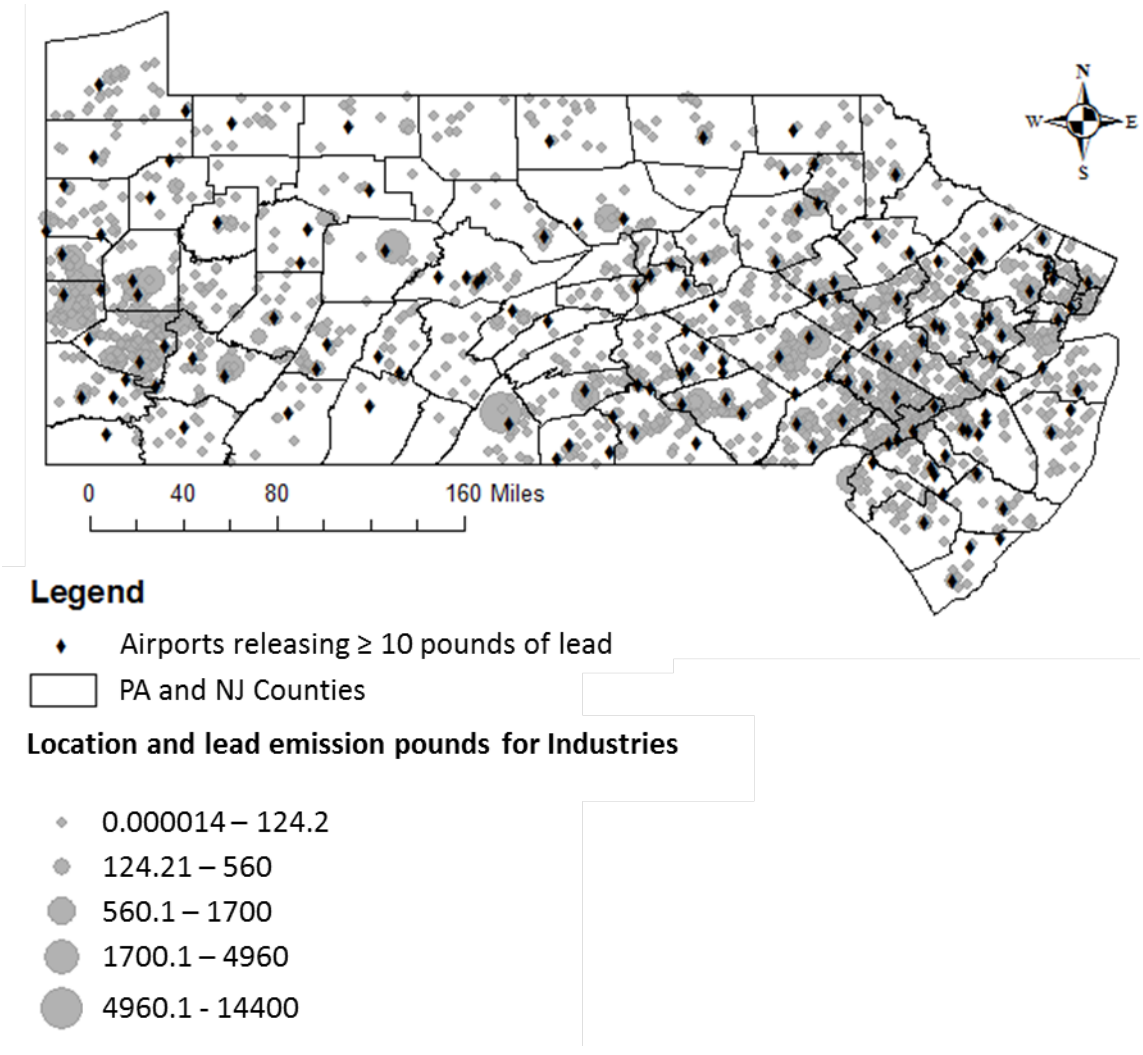

Figure 7-1. Airports that released 10 pounds of lead or more annually and industrial facilities with lead emissions according to the 2008 NEI report.

The distances to each airport and each industrial facility for all children were calculated with R version 3.0.1 [88] using the 'distm' a function as part of the geospatial package 'geosphere' [89]. The distance between each child's residence and each lead facility was determined. All lead emitting facilities (airport and industry) within 5 km of a child's residence were included in the calculation for average intensity. The nearest airport was determined for each child using this same geospatial package.

7.1.3.2 Statistical Analyses

Children with blood lead levels ≥ 5 µg/dL were considered to have elevated blood lead. Multilevel logistic regression models were used to determine if children living within 3km of an airport had higher odds of elevated blood lead than children living further away. In addition to the individual and census tract level variables, exposure variables for each child were calculated based on lead emissions reported in NEI. Tertiles of exposure based on the 33rd and 66th percentiles were determined from the average intensity of lead exposures and the categorical variable for low, medium, and high average lead intensity was included in the model. All statistical analyses were conducted with Stata 13 (StataCorp, 2013).

7.1.4 Results

Descriptive statistics and blood lead levels for children who participated in blood lead screenings between 2006 and 2008 in both Pennsylvania and New Jersey are shown in Table 7-1. The median blood lead level for children in both states combined is 3 µg/dL with a mean and standard deviation of 3.28 (3.08) µg/dL. Overall, 51% of the children were males and 49% were females. Blood lead screenings were evenly distributed across the years of interest. Children less than 1 year of age made up 53% of the Pennsylvania tests and 33% of New Jersey tests. Children between 13 and 24 months of age accounted for 31% of PA screenings and 47% of New Jersey screenings. Five percent of all children included in the analysis lived within 3 km of an airport. Children living more than 3km from an airport had higher blood lead levels than children living within 3 km of an airport ($p < 0.001$) prior to adjustment. A higher proportion of PA children living within 3km of an airport have elevated blood lead levels (22.5%) than New Jersey children (13.8%). Blood lead levels are higher in males ($p = 0.007$) and higher for

children who live in PA ($p < 0.0001$). Finally, a non-parametric test for trend showed that with each increasing age group, childhood blood lead levels increase significantly ($p < 0.001$) (Table 7-1).

Table 7-1. Descriptive statistics and blood lead levels for children whose blood lead levels were evaluated between 2006 and 2008 in PA and NJ.

	PA			NJ			All		
	n	(%)	mean (sd)	n	(%)	mean (sd)	n	(%)	mean (sd)
Entire Sample	228705		3.44 (3.74)	265251		3.14 (2.36)	493956		3.28 (3.08)
Gender									
Male	117404	51.3	3.50 (3.80)	135281	51.0	3.17 (2.42)	252685	51.2	3.33 (3.14)
Female	111301	48.7	3.38 (3.68)	129970	49.0	3.11 (2.30)	241271	48.8	3.23 (3.02)
Year									
2006	63880	27.9	3.93 (4.08)	85926	32.4	3.50 (2.47)	149806	30.3	3.68 (3.26)
2007	78205	34.2	3.64 (3.56)	88071	33.2	3.25 (2.38)	166276	33.7	3.43 (3.00)
2008	86620	37.9	2.90 (3.56)	91254	34.4	2.70 (2.17)	177874	36.0	2.80 (2.94)
Age Group (months)									
1 to 12	121725	53.2	2.75 (2.99)	85633	32.3	2.78 (1.88)	207358	42.0	2.77 (2.59)
13 to 24	71759	31.4	3.99 (4.11)	123576	46.6	3.17 (2.41)	195335	39.5	3.47 (3.16)
25 to 36	35221	15.4	4.71 (4.67)	56042	21.1	3.61 (2.80)	91263	18.5	4.04 (3.68)
Distance (km)									
3km or less	15640	6.8	3.14 (3.22)	10013	3.8	3.00 (1.97)	25653	5.2	3.07 (2.80)
more than 3km	213065	93.2	3.46 (3.77)	255238	96.2	3.15 (2.38)	468303	94.8	3.29 (3.10)
Average Intensity of Exposure*									
Low	99033	43.3	3.51 (3.71)	64848	24.4	3.05 (2.23)	163881	33.2	3.33 (3.21)
Medium	52925	23.1	3.48 (3.67)	112463	42.4	3.17 (2.42)	165388	33.5	3.27 (2.89)
High	76747	33.6	3.33 (3.82)	87940	33.2	3.17 (2.38)	164687	33.3	3.25 (3.14)
BLL > = 5 µg/dL									
Yes	51373	22.5	8.16 (5.19)	36662	13.8	7.11 (4.08)	88035	17.8	7.72 (4.79)
No	177332	77.5	2.08 (1.38)	228589	86.2	2.50 (0.94)	405921	82.2	2.32 (1.17)

*Calculated based on proximity to and lead emission data as reported in the 2003 and 2008 NEI

Children who live near airports have different demographic characteristics than children who live farther away from airports (Table 7-2). Children who live more than 3 km from an

airport are more likely to live in a census tract with a higher proportion of homes built before 1950, higher poverty levels and higher proportion of black residents. Minority status, lower income and old housing have been found to be strongly associated with higher blood lead levels. There is no significant difference in the age distribution between the two groups of children, but blood lead levels are higher for children who live further away from the airport ($p < 0.001$).

Table 7-2. Demographic comparison of children who lived near an airport versus those who did not.

	Within 3 km of an Airport					
	PA		NJ		All	
	n = 15640		n = 10013		n = 25653	
	Md (IQR)	mean (SD)	Md (IQR)	mean (SD)	Md (IQR)	mean (SD)
Blood Lead (µg/dL)	3 (2.8)	3.13 (3.22)	3.0 (1.0)	3.00 (2.00)	3 (2)	3.07 (2.80)
Age (months)	12 (12)	15.4 (7.6)	14 (12)	17.2 (7.4)	13 (13)	16.1 (7.5)
% Poverty	7.5 (12.7)	10.7 (9.3)	4.5 (8)	11.5 (15.7)	6.2 (10.6)	11.0 (12.2)
% Black	4.6 (9.2)	8.5 (11.6)	5.8 (19.1)	16.1 (21.8)	4.6 (12.6)	11.5 (16.7)
% Pre50 housing	44 (57)	45 (29)	22 (30)	26 (20)	32 (45)	38 (27)
Industrial Exposure (lbs)	27.1 (58.8)	52.7 (99.5)	48.7 (86.7)	78.5 (76.4)	38.0 (68.0)	62.8 (92.0)
	Beyond 3 km of an Airport					
	PA		NJ		All	
	n = 213065		n = 255238		n = 468303	
	Md (IQR)	mean (SD)	Md (IQR)	mean (SD)	Md (IQR)	mean (SD)
Blood Lead (µg/dL)	3 (2.9)	3.46 (3.77)	3 (1.2)	3.14 (2.38)	3 (2)	3.29 (3.10)
Age (months)	12 (13)	15.6 (7.6)	14 (12)	17.4 (7.6)	13 (12)	16.6 (7.6)
% Poverty	10 (18.4)	15 (14.1)	8.4 (15)	12.6 (12)	9.1 (16)	13.7 (13.0)
% Black	5.3 (28)	20.9 (30.0)	7.3 (19)	17.7 (24.0)	6.7 (22)	19.2 (26.9)
% Pre50 housing	47 (43)	47 (25)	31 (39)	33 (22)	39 (43)	40 (25)
Industrial Exposure (lbs)	0.7 (9.1)	28.3 (120)	0.8 (10.3)	17.2 (45.8)	0.8 (7.3)	22.3 (88.1)

Proportion of cases (blood lead level $\geq$ 5 µg/dL) and distribution of percent pre-1950 housing, percent poverty and percent black population are shown by average intensity lead emission levels in Table 7-3. The average intensity lead emission tertile breakpoints occurred at

0.704 pounds and 5.776 pounds. For children living in close proximity to an airport, the highest percentage of cases occurs in children receiving a moderate level of lead exposure (19.4%). These children also live in census tracts having the highest median poverty, proportion black population and homes built before 1950. For children living farther away from airports the highest proportion of cases occurred in the lowest (18.7%) and highest (18.3%) lead exposure groups. Children experiencing the highest average intensity lead emissions live in census tracts with the highest median poverty, proportion black population and homes built before 1950.

Table 7-3. A comparison of the distribution of cases, poverty, proportion black and percent pre-1950 houses for children who live near an airport versus those who do not live within close proximity to an airport.

Industrial Exposure Level (lbs)	n	Cases %	% Poverty Median (IQR)	% Black Median (IQR)	% Pre-1950 Median (IQR)
Live Near an Airport					
Low (0 to 0.704)	417	13.4	7.3 (13.2)	5.5 (20)	33.6 (39.6)
Medium (0.704 to 5.776)	3,243	19.4	11.4 (25.3)	9.0 (11.5)	58.7 (36.3)
High (5.777 to 3188)	21,993	14.8	6.0 (9.5)	4.0 (11.7)	27.4 (43.2)
Do Not Live Near an Airport					
Low (0 to 0.704)	163,464	18.7	7.7 (14.8)	5.5 (23.3)	39.2 (42.3)
Medium (0.704 to 5.776)	162,145	16.9	8.2 (15.1)	6.6 (22.2)	33.3 (41.4)
High (5.777 to 3188)	142,694	18.3	11.7 (18.4)	7.5 (19.7)	45.0 (40.2)

Univariate logistic regression models were used to assess the relationship between elevated blood lead levels ($\geq$ 5 µg/dL) and covariates known to be associated with such levels. The strongest predictor of having elevated blood lead was the state where screening occurred. The odds of having elevated blood lead for children screened in Pennsylvania was 1.806 times larger than the odds of elevated blood lead for children screened in New Jersey ($p < 0.001$). Year of screening was also significant, with the odds of having elevated blood lead 1.756 times

higher for children screened in 2006 than for children screened in 2008 ($p < 0.001$). Being male, child's age in months, and census level variables for poverty, percent black and percent housing build before 1950 were also significant predictors. In this un-weighted analysis, living near an airport was associated with 17.1% reduction in the odds of elevated blood lead compared to children living farther away from an airport. Being exposed to medium or high industrial levels of exposure was also significantly associated with elevated blood lead levels prior to adjustment (Table 7-4).

Table 7-4. Univariate logistic regression models for the likelihood of being a case (blood lead level ≥ 5 µg/dL) for covariates of interest.

	OR	95% CI		p-value
% pre50	1.023	1.022	1.023	<0.001
% black	1.017	1.016	1.018	<0.001
% poverty	1.043	1.041	1.044	<0.001
male	1.081	1.066	1.097	<0.001
year 2007 v. 2008	1.458	1.431	1.485	<0.001
year 2006 v. 2008	1.756	1.725	1.789	<0.001
PA v. NJ	1.806	1.780	1.833	<0.001
age in months	1.051	1.050	1.052	<0.001
Medium industry v. Low Industry	1.337	1.311	1.363	<0.001
High Industry v. Low Industry	1.280	1.258	1.302	<0.001
Airport Y v. N	0.829	0.800	0.858	<0.001

Multivariable logistic regression models were assessed to determine how covariate associations changed after adjustment. The first model did not include environmental variables or the indicator variable for living within close proximity to an airport, just the covariates of interest. All covariates remained significant predictors of elevated blood lead ($p < 0.001$). The

results for the full multilevel logistic regression model are shown in Table 7-5. There was no significant difference in the odds of elevated blood lead level for children exposed to medium (p = 0.305) or high levels (p = 0.425) of average intensity lead emissions in comparison to children exposed to the lowest average intensity lead emissions. Living within close proximity to an airport was not predictive of elevated blood lead either (p = 0.094).

Table 7-5. Adjusted odds ratios for elevated blood lead with the inclusion of industrial lead exposures and a categorical variable indicating living within close proximity to an airport.

	OR	95% CI		p-value
pctpre50	1.0139	1.0131	1.0146	<0.001
pctblack	1.0083	1.0076	1.0091	<0.001
pctpoverty	1.0154	1.0136	1.0171	<0.001
Male	1.0931	1.0761	1.1103	<0.001
year 2007 v. 2008	1.5329	1.5033	1.5631	<0.001
year 2006 v. 2008	1.9040	1.8670	1.9418	<0.001
PA v. NJ	1.6960	1.6394	1.7545	<0.001
Age in months	1.0483	1.0473	1.0493	<0.001
Living Near an Airport v. Not Living Near an Airport	0.9548	0.9044	1.0079	0.094
Medium Industry v. Low Industry	1.0205	0.9817	1.0607	0.305
High Industry v. Low Industry	1.0141	0.9798	1.0496	0.425

7.1.5 Discussion

This study was designed to assess if children living within close proximity to an airport were at an increased odds of having elevated blood lead levels for children living in Pennsylvania and New Jersey. Airports annual emissions ranged from less than 1 pound to a maximum emission level of 720 pounds. Living within close proximity to an airport was not associated with an

increased odds of elevated blood lead. The likelihood of elevated blood lead did not differ between average lead intensity exposure categories either.

These results are inconsistent with those found by Miranda et al., for children living near airports in North Carolina [57]. The differences could be due to several factors. The childhood blood lead data in North Carolina were obtained for screenings collected from 1995 to 2003. Blood lead levels have been dropping considerably over time [12]. The age of children ranged from 9 months to 7 years for North Carolina. For the current study, the maximum age of a child was 3 years. The effects observed in the previous study showed a maximum increase in a child's blood lead level of 4%. For the median blood lead level found in our study of 3 µg/dL, the predicted increase in blood lead would be 0.12 µg/dL and such an increase would not result in a child having elevated blood lead. However, due to the propensity of blood lead readings of 0 µg/dL and the skewed nature of the data, simple linear regression using natural log blood lead as the outcome variable was not appropriate. Additional analyses were performed to determine if the significance of living in close proximity to an airport was altered by removing average intensity lead levels. Regardless of the inclusion or exclusion of average lead intensity, residential proximity to an airport was not predictive of elevated blood lead levels.

This study expanded on the research conducted by Miranda et al. [57]. Instead of just 6 counties for one state, all airports between two contiguous states were used. Industrial activity accounts for over 28% of lead air emissions in the U.S.[98]. Due to the long industrial history in both PA and NJ, all models were adjusted for the average intensity of lead emitted from industrial and airport facilities in an effort to account for other non-residential lead exposures. However, some of the most important covariates associated with childhood blood lead levels were only available at the census tract level: percentage of homes built before 1950, percent

black and percent poverty. For census tracts located near metropolitan areas, the area under consideration is relatively small, but in rural regions of PA the census tract could be quite large resulting in one census level value being attributed to children who do not live within close proximity to one another. Ideally, one would have individual level data regarding race and poverty income ratio to ensure proper adjustment of blood lead levels. In addition, NEI data is an annual estimate determined every three years. There is no way to adjust for changes in airport traffic flow or to determine length of residency for each child which could result in exposure misclassification for children in the study.

There are two occupational studies which demonstrate a dose response relationship between blood lead levels and exposure to exhaust from tetraethyl lead fuel combustion. Until 2008 NASCAR used leaded fuel [51]. Prior to the transition to ethanol, O'Neil et al. conducted a pilot study on 47 members of Nextel Cup Teams. Team members with the highest relative risk of elevated blood lead were exposed to exhaust, followed by those who worked on brakes. The median blood lead for all team members was 9.4 µg/dL and ranged from 1 to 22 µg/dL [52]. Park et al. conducted a study on 256 aviation maintenance men, conducted in Korea between March 2012 and July 2012, investigated differences in men who worked exclusively with Avgas (type not specified) versus those who worked exclusively with jet propellant. Men working with Avgas had higher blood lead levels than those using jet propellant (4.2 µg/dL v. 3.57 µg/dL) ($p < 0.001$). Those who working within 200 m of the runway had significantly higher blood lead levels than those working more than 200 m away ($p = 0.045$), and men working longer hours had significantly higher levels than those working shorter hours ($p = 0.017$) [53].

Occupational exposure is different from residential exposure due to much higher concentrations for longer periods of time at much closer distances to the source. This study does

not definitively determine if aviation fuel does or does not contribute to elevated blood lead levels. None of the airports in NJ and PA are associated with exceeding air quality standards of 0.15 ug/m^3 [95], and only 7 airports emitted more than 400 pounds of lead according to the 2008 NEI. However, the Environmental Protection Agency released a report indicating that several airports in California have lead emissions that exceed the AQS standard of 0.15 ug/m^3 [96]. A 2008 report on lead emission through the use of Avgas in the U.S. showed that these airports released at least 1000 pounds of lead annually [97]. Investigations in locations where there are air monitors for lead, as well higher ambient air lead emissions might provide more insight into how ambient air lead concentrations due to the combustion of aviation fuel impact childhood blood lead levels.

8.0 SOCIODEMOGRAPHIC AND ENVIRONAMTAL DETERMINANTS OF ELEVATED BLOOD LEAD IN NJ AND PA FOR CHILDREN AGED 0 TO 3 YEARS (2003-2008)

8.1.1 Abstract

Objective: To determine the spatial distribution of elevated blood lead level at the census tract level for children living in Pennsylvania and New Jersey by considering both sociodemographic and environmental factors.

Methods: Individual de-identified data were obtained for 855,291 children between 0 and 3 years of age who lived in Pennsylvania and New Jersey and received a blood lead screening between 2003 and 2008. Children with blood lead levels ≥ 5 µg/dL were considered to have elevated blood lead levels. Counts of children tested and children with elevated blood lead level were aggregated to the census tract level. In addition to census tract level variables for percent housing built before 1950, percent black, percent poverty and percent male, four levels indicating urban/rural status for each tract were employed: urban, sub-urban, large rural town, and small town/isolated rural. Finally, ArcGIS was used to estimate lead emissions for each census tract based on National Emissions Inventory reports for 2005 and 2008. Spatial lag regression was used to determine the distribution of elevated blood lead level based on urban/rural designations.

Results: Median percentage of children with elevated blood lead was 18.4% in PA (n = 361,758), 11.6% in NJ (n = 493,533) and 15.5% for the entire sample. Prior to adjustment

approximately 20% of children living in large rural towns and isolated towns had elevated blood lead whereas only 15% of children living in urban and suburban areas had elevated blood lead. After adjusting for industrial lead emissions, percent pre-1950 housing, percent black, percent poverty, and percent male the highest prevalence of elevated blood lead level was found in census tracts designated large rural town followed by children living in tracts designated small town/isolated rural.

Conclusions: Ambient air lead levels have dropped considerably due to the removal of lead in gasoline and progress has been made with inner city lead abatement programs. Current reservoirs of lead may no longer be concentrated in cities with older housing. Future research needs to focus on soil and residential lead dust as potential primary sources of exposure in children.

8.1.2 Introduction

Historically, the Centers for Disease Control and Prevention (CDC) developed their efforts to track elevated blood lead levels in children with a focus on children who lived in city centers and other urban environments. Primary sources of lead exposure were largely found to be older housing in cities due to the use of leaded paint and areas with dense traffic patterns due to the inclusion of tetraethyl lead in gasoline. The tracking effort then intensified to include the study of the presence of elevated blood lead levels in children living in suburban [63] and rural [64] environments. It was discovered that children living in non-urban environments had elevated blood lead levels as evidenced by large tracts of older housing and industries located in rural areas.

Norman et al. conducted an observational study, between 1992 and 1993, to compare blood lead levels in urban and rural children living in North Carolina. Urban rural status was designated at the county level. Counties with urban centers, defined as ≥ 400 people per square mile, were considered urban. Rural children were almost 2 times more likely to have elevated blood lead levels than urban children. Assessments of multiple cut points (10 µg/dL, 15 µg/dL, 20 µg/dL) found for each designated blood lead level there was a higher prevalence of elevated blood lead in rural children than in urban children regardless of race. During the time of this study children in rural areas of NC were more likely to be poor and live in pre-1950 housing [65]. Another reason children living in intermediate sized cities or rural locations may have elevated blood lead levels could be due to industrial activity within close proximity to residential communities as well as older housing. A study near the Silver Valley Lead Superfund Site found soil lead, age of the child, cleanliness of the home and parental occupation contributed the most to elevated blood lead levels in 1 to 9 year old children [66]. Blood lead levels of children between 1 and 5 years of age living near the Tar Creek Superfund site, a rural mining community, have also been assessed. For all exposure metrics explored, the odds of elevated blood lead levels were highest for floor dust (OR=8.1, 95%CI: 1.8, 37.8), followed by yard dust (OR=6.4, 95%CI: 1.4, 30.7), then residential proximity (OR=3.4, 95%CI: 1.3, 8.8) and finally interior lead paint (OR=3, 95%CI: 1.2, 7.8) [67]. The children in this study lived in a rural setting, and were exposed to years of lead deposition from the surrounding environment.

Of the studies mentioned above, some provided a definition of urban or rural, but others did not. There are two primary agencies involved with defining rural and urban areas: the U.S. Census Bureau and the U.S. Office of Management and Budget. Often, urban designations are defined in very specific ways, but rural is considered anything that is not urban [76, 77]. Most

designations of urban and rural status occur at the county level because the borders remain relatively constant over time and that is the level at which annual economic statistics are available [78]. The U.S. department of Agriculture has developed definitions of urban and rural status at the census tract level. Rural Urban Commuting Areas (RUCA) have 10 primary classifications based on population counts, and secondary classifications based on the amount of commuting traffic into and out of an area. It also incorporates U.S. Census Bureau definitions of urbanized areas and urban clusters [79].

Pennsylvania and New Jersey have similar industrial histories and are adjacent to each other geographically. Recently the Centers for Disease Control and Prevention lowered the blood lead limit of interest from 10 µg/dL to 5 µg/dL [11]. Few studies have evaluated elevated blood lead level as defined by this new designation. Also, combining these two states permits the assessment of urban/rural status at a more refined level. A 4 tiered variable based on rural urban commuting area (RUCA) definitions is evaluated at the census tract level [79]. The CDC is recommending primary prevention of lead exposure in children because the effects of exposure are irreversible [11] and significant cognitive deficits have been observed down to 2.1 µg/dL [99]. In order to properly implement primary prevention programs, the current reservoir of lead hazards must be known. With the declines in ambient air lead and the remediation of lead paint in residential homes, are inner city children still the most at risk for elevated blood lead levels? The objective of this research is to determine which RUCA level contains the highest proportion of children with elevated blood lead levels and offer reasons as to the major reservoir of lead exposure.

8.1.3 Methods

8.1.3.1 Data

The Centers for Disease Control and Prevention (CDC) has been maintaining a national database on childhood blood lead levels since the mid-1990s [81]. New Jersey and Pennsylvania participate in the Childhood Lead Poisoning Surveillance Program so data for children between 0 and 3 years of age was requested from their respective state health departments. Gender, age in months, blood lead level and geocoded residential location were requested for children who received a blood lead screening between 2003 and 2008. Data from both states were combined into a single dataset. Exact duplicate observations were deleted. If a child received more than one blood lead screening during the years of interest the maximum blood lead level was used in this analysis. Any child with a blood lead level greater than or equal to 5 µg/dL was considered to have an elevated blood lead level. In addition to individual level data, census tract level data were obtained from the U.S. Census American Fact Finder website: percent pre 1950 housing [61], percent black [60], percent below poverty [59] and total population of 0 to 3 year old children [100]. The geospatial coordinates for each child's residence was used to link them to their respective census tract. If a child lived in a tract where the U.S. census was unable to provide an estimate of percent pre-1950 housing, percent black population or percent poverty, they were excluded from the analysis.

A census tract level variable indicating the urban-rural nature of a census tract, from the United States Department of Agriculture Economic Research Service [80], was included in the analysis. There is a 10 level primary category breakdown with secondary delineations for rural urban commuting areas (RUCA). It has been recommended that when using RUCA designations at the census tract level, the 10 level classification system should be collapsed to

four levels [79]. The RUCA 4-tiered classification of urban core, sub-urban, large rural town and small town/isolated rural as delineated by their primary and secondary RUCA codes is shown in Table 8-1.

Table 8-1. Four-tier consolidation of secondary RUCA codes as recommended by WA Health Department.

Class	Tier	Secondary RUCA codes
Urban Core (50,000 +) US Census Urbanized Areas	1	1.0, 1.1
Sub-Urban (metropolitan with high commuting flows to Urban cores (30-49% commute to Urban Cores)	2	2.0, 2.1, 3.0, 4.1, 5.1, 7.1, 8.1, 10.1
Large rural town (10,000 – 49,999) with 10% to urban core and 10 into these towns	3	4.0, 4.2, 5.0, 5.2, 6.0, 6.1
Small town/Isolated Rural (< 10,000 with 1 hour + driving distance to nearest city)	4	7.0, 7.2, 7.3, 7.4, 8.0, 8.2, 8.3, 8.4, 9.0, 9.1, 9.2, 10.0, 10.2, 10.3, 10.4, 10.5, 10.6

National Emissions Inventory (NEI) estimated ambient air lead emissions for 2005 [101] and 2008 [58] were downloaded from the U.S. Environmental Protection Agency for Pennsylvania and New Jersey. The emissions data included tons of lead released annually and the geospatial coordinates of each facility. Emissions were converted from tons of lead to pounds of lead. The NEI emissions from 2005 and 2008 were combined into a single emissions dataset. Empirical Bayesian Kriging, a function in the geostatistical analyst package of Esri ®ArcMap™ 10.1 was used to estimate lead emissions based on 2005 and 2008 combined data sets. If NEI locations were viewed by the program as coincidental sample points the mean of lead emissions was used in the analysis [102]. The raster generated from the kriging process was used to make lead emission predictions for each census tract.

8.1.3.2 Statistical Analyses

All regression analyses were performed with GeoDa 1.4.6 [103]. In order to perform regressions all individual level data on elevated and non-elevated blood lead levels were aggregated to counts at the census tract level: total number of children tested, total number of children with elevated blood lead, and percent elevated. If a census tract had 4 or fewer children tested, it was combined with adjacent census tracts with similar characteristics. A total of 22 census tracts had fewer than 5 kids tested and 16 of those tracts had RUCA designations of urban. All tracts where no child was tested were excluded from the analysis. The goal was to use the proportion of children with elevated blood lead levels as the outcome variable with census level variables for percent male, percent black, percent pre-1950 housing, percent poverty and predicted lead emissions as the predictors. However percent elevated is not normally distributed and is not weighted with regards to the population of children between 0 and 3 years of age who live within the census tract. Cressie [104] recommends the following transformation because it accounts for population size as well as tracts with counts less than or equal to 1:

$$Z_i = log\left(\frac{1000(Y_i+1)}{n_i}\right),$$

where Z_i is the transformed proportion, Y_i is the count of elevated blood lead levels in each tract and n_i is the population count of 0 to 3 year old children as estimated by the 2000 census. The newly transformed proportion was normally distributed.

Ordinary least squares regression cannot be applied to data that is spatially autocorrelated due to a lack of independence between adjoining census tract attributes. Characteristics of adjacent tracts are usually more similar to each other than to tracts located further away. Moran's I was used to test for spatial autocorrelation for univariate models as well as for full regression models. In all instances evidence indicated significant spatial autocorrelation so

spatial lag regression models were used to assess which predictors were associated with a higher proportion of children with elevated blood lead levels. The spatial lag regression model is specified as

$$Y = X\beta + \rho WY + \epsilon$$

where Y denotes the vector of response variables, X denotes the matrix of explanatory variables, W denotes the spatial weight matrix, and ϵ denotes the vector of error terms that are independent but not necessarily identically distributed.

8.1.4 Results

A total of 855,291 children between 0 and 3 years of age had blood lead screenings between 2003 and 2008 in PA and NJ. Approximately 42% of the children were screened in PA and 58% were screened in NJ (Table 8-2). The Wilcoxon-Mann-Whitney test was used to compare distributions between the two states. There was no significant difference in the proportion of individuals living in poverty ($p = 0.4331$). New Jersey had a significantly higher proportion of black people than Pennsylvania ($p < 0.001$), but Pennsylvania had more pre-1950 housing ($p < 0.001$), higher proportion of male children ($p = 0.003$) and a higher proportion of children with elevated blood lead levels ($p < 0.001$). After transforming percent elevated by the census tract population of 0 to 3 year olds, the proportion was significantly higher in NJ than in PA ($p < 0.001$), and the estimated lead emissions were higher in NJ than in PA ($p < 0.001$). New Jersey is a more urban state than Pennsylvania with only 5 census tracts in the entire state defined as isolated rural. Only 1.7% of all NJ tracts are defined as isolated rural tracts or large

rural towns, the rest of the state is considered urban and sub-urban. For tracts in PA, 16.6% are designated isolated rural or large rural town.

Table 8-2. Distribution of median and IQR census tract characteristics by Rural Urban Commuting Area.

State		Urban	Sub-urban	Large Rural Town	Small Town Isolated	All
PA	Kids tested (n)	269331	29156	41611	21660	361758
	Tracts (n)	2214	370	335	178	3097
	0 to 3 year olds (n)	2450376	419604	376710	200886	3447576
	% Male	51.3 (7.4)	52.0 (8.0)	51.4 (6.8)	50.2 (6.0)	51.3 (7.9)
	% black	4.12 (15.0)	0.51 (1.5)	0.55 (2.2)	0.38 (1.36)	2.3 (9.0)
	% Poverty	6.0 (12.6)	5.6 (6.5)	7.5 (6.6)	9.3 (5.8)	6.5 (10.3)
	% Pre50	41.7 (48.3)	29.9 (18.8)	36.1 (31.1)	39.6 (18.1)	37.9 (41.6)
	Estimated Lead (lb)	3.3 (16.4)	8.4 (20.4)	6.8 (20.6)	13.0 (27.4)	4.2 (20.4)
	Blood lead (µg/dL)	3 (3)	2.2 (3)	3 (3)	3 (2.9)	3 (3)
	% elevated	17.9 (19.5)	16.7 (11.8)	20.8 (12.5)	21.1 (10.1)	18.4 (16.4)
NJ	Children tested (n)	464285	21840	6683	725	493533
	Tracts (n)	1792	112	28	5	1937
	0 to 3 year olds (n)	2488218	136890	34782	1134	2661024
	% Male	50.9 (4.7)	51.0 (5.7)	51.3 (6.4)	51.5 (9.8)	50.9 (6.7)
	% black	5.64 (15.9)	2.62 (5.6)	12.61 (19.9)	0.0 (29.0)	5.4 (16.0)
	% Poverty	6.2 (10.4)	4.5 (4.0)	8.7 (12.4)	0.0 (0.0)	6.0 (10.0)
	% Pre50	28.6 (38.0)	19.9 (19.8)	20.5 (22.8)	0.0 (0.0)	27.3 (36.9)
	Estimated Lead (lb)	20.9 (26.9)	22.9 (23.8)	24.1 (40.0)	22.7 (6.7)	21.3 (27.2)
	Blood lead (µg/dL)	3 (2)	3 (1)	3 (3)	3 (1)	3 (2)
	% elevated	11.6 (12.4)	11.0 (9.4)	15.0 (13.8)	16.2 (4.8)	11.6 (12.1)
PA and NJ	Children tested (n)	733616	50996	48294	22385	855291
	Tracts (n)	4006	482	363	183	5034
	0 to 3 year olds (n)	4938594	556494	411492	202020	6108600
	% Male	51.1 (5.9)	51.6 (7.5)	51.4 (6.7)	50.5 (6.0)	51.1 (6.1)
	% black	4.7 (16.3)	0.7 (2.6)	0.7 (2.9)	0.4 (1.4)	3.3 (12.2)
	% Poverty	6.1 (11.6)	5.3 (5.1)	7.6 (7.3)	9.2 (6.1)	6.3 (10.2)
	% Pre50	35.0 (44.4)	28.0 (19.6)	34.9 (21.8)	39.1 (18.6)	34.2 (39.6)
	Estimated Lead (lb)	11.8 (28.0)	12.3 (24.7)	7.0 (22.3)	13.9 (27.3)	11.6 (27.8)
	Blood lead (µg/dL)	3 (2)	3 (2)	3 (2.7)	3 (2.7)	3 (2)
	% elevated	14.5 (16.7)	15.6 (12.7)	20.6 (12.8)	21.0 (10.1)	15.5 (16.1)

Figure 8-1 shows the level of lead emissions by census tract as predicted with Empirical Bayesian Kriging. Lead emissions range from 1 pound to 99.92 pounds. Nevertheless the majority of census tracts have annual lead emissions less than 10 pounds based on 2005 and 2008 NEI data. As stated previously, NJ is mostly composed of census tracts defined as Urban Core, while northern and centrally located census tracts in PA are designated as large rural towns or small towns. North central PA and southern NJ have census tracts with the highest proportion of children with elevated blood lead levels.

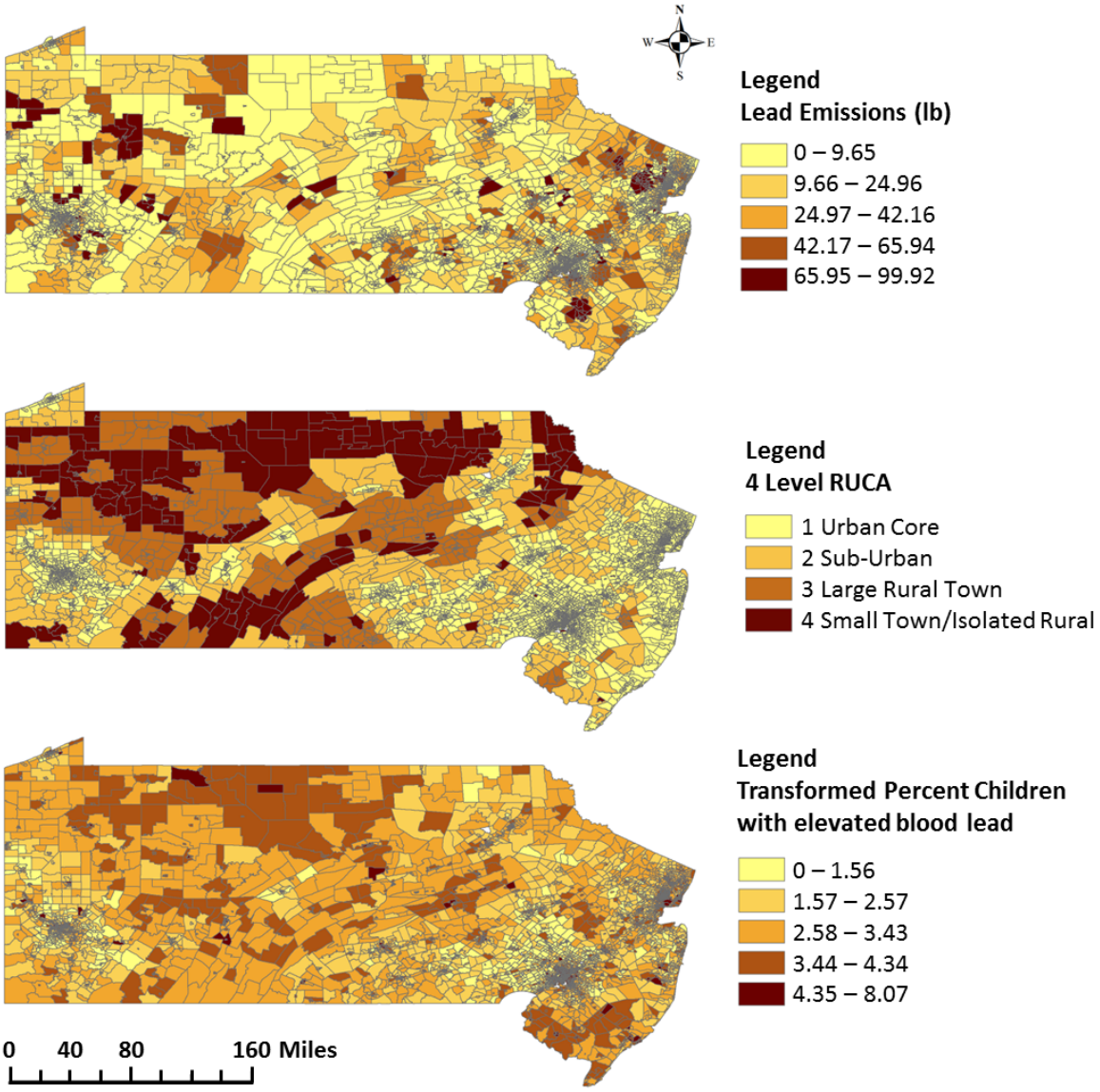

Figure 8-1. Distribution of estimated lead emissions in pounds, RUCA levels and transformed percent elevated by census tracts in PA and NJ.

A comparison of the OLS and spatial lag multivariable regression is shown in Table 8-3. Moran's I ranges from -1 (perfect dispersion) to 1 (perfect correlation). A Moran's I of 0 indicates a random spatial pattern. The Moran's I statistic for residuals of the OLS regression has a value of 0.359 ($p < 0.001$) which indicates that spatial lag regression should be considered.

Note that by accounting for the spatial nature of the data Moran's I for the spatial lag model is -0.022 ($p < 0.001$) which demonstrates an improved statistical model. The significance level indicates there is still spatial autocorrelation that has yet to be accounted for in this model. The spatial error model was also assessed but the AIC values for that model were higher than the spatial lag model by more than 100 (not shown) indicating the spatial lag model provides the best fit to this data.

Table 8-3. Transformed percent elevated regressed on tract level characteristics with ordinary least squares regression and spatial lag regression.

	OLS Coefficient (SE)	p-value	Spatial Lag Coefficient (SE)	p-value
Percent Pre-1950 Housing	0.016 (0.0005)	<0.001	0.010 (0.0005)	<0.001
Percent Poverty	0.026 (0.0013)	<0.001	0.139 (0.0012)	<0.001
Percent Black	0.013 (0.0006)	<0.001	0.006 (0.0006)	<0.001
Percent Male	-0.005 (0.0019)	0.005	-0.003 (0.0016)	0.074
NEI Lead (pounds)	0.0008 (0.0005)	0.111	0.0006 (0.0005)	0.224
Suburban	-0.025 (0.0401)	0.526	0.021 (0.0338)	0.527
Large Rural Town	0.311 (0.0455)	<0.001	0.167 (0.0385)	<0.001
Isolated Rural	0.269 (0.0624)	<0.001	0.159 (0.0527)	0.003
Moran's I statistic on Residuals	0.359	<0.001	-0.022	<0.001
AIC	12277		10860	

After adjusting for poverty, percent male, percent black population, percent pre-1950 housing and estimated lead emissions there remains a significant difference in transformed percent elevated between RUCA levels and the baseline level of Urban Core. The transformed proportion elevated in Sub-urban tracts was not statically different than the transformed proportion elevated in Urban tracts ($p = 0.527$). According to this analysis, tracts defined as large rural towns ($p <0.001$) and small towns/isolated rural ($p = 0.003$) have significantly higher

transformed proportion elevated than urban tracts with large rural towns having the highest proportion. Poverty, percentage of pre-1950 housing and percent black were all significant predictors. However, percent male ($p = 0.07$) and estimated lead emissions ($p = 0.22$) were not significant predictors of transformed proportion elevated.

8.1.5 Discussion

Prior to adjustment, a higher proportion of children living in large rural towns and isolated rural towns had elevated blood lead levels (20%) compared with children living in urban or suburban environments (15%). After adjusting for spatial autocorrelation and predictors known to be associated with elevated blood lead levels, a significant difference in proportion of children with elevated blood lead was found between large rural towns and urban tracts as well as isolated towns and urban tracts. The highest proportion of elevated blood lead levels was found for large rural towns. There was no significant difference in the proportion of children with elevated blood lead between urban and sub-urban tracts. Spatial adjustment for environmental data is critical in epidemiological studies because our environment influences our health outcomes.

These results are consistent with previous research showing higher blood lead level in children living in rural areas near smelting and other lead industrial activity [65-67]. One study showed that past industrial activity may still be impacting blood lead levels in children 20 years after shutting down a lead smelter located near El Paso Texas. A higher proportion of children had blood lead levels greater than or equal to 10 µg/dL living within 600 meters of the old facility than children living further away [105]. Haley and Talbot, investigated blood lead levels of 677,122 children throughout NY state from 1994-1997. More children had blood lead levels greater than or equal to 10 µg/dL in upstate cities (Buffalo, Rochester, Syracuse and

Schenectady) than in New York City. In conjunction with a higher proportion of elevated blood lead, upstate cities also had a higher proportion of African Americans, older housing and lower education levels [106].

There are other studies that show children in urban settings having higher rates of elevated blood lead levels. Two studies from the mid-1990s found a higher proportion of elevated blood lead levels in cities, where screening rates were much higher than in suburban and rural settings. In Monroe County, NY, lower home values, housing built before 1950, higher population density, increased poverty and lower education levels were all associated with higher blood lead levels in addition to living in a city [33]. Rifai et al, studied children between 9 and 36 months and found children living in the city were more likely to have blood lead levels greater than 10 µg/dL and 25µg/dL than children living in suburban and rural settings [107]. From a historical cohort standpoint, lead in housing has been declining since the 1978 banning of lead in residential paint. The first Healthy Home Survey assessing lead and allergens across the country was conducted in the 1990s. The results were published in 2001 and they found that 40% of all homes in the U.S. had lead paint and children under the age of 6 lived in 15% of those homes [108]. The most recent Healthy Home survey was published in 2011. Only 35% of all homes in the U.S. have lead based paint somewhere within the building and the percentage of children less than 6 years of age who live in such a structure has fallen to less than 10% [84].

Historically, there has been more than one reservoir of lead exposure. Ambient air lead has dropped considerably with the removal of lead from gasoline. From 1960 to 2006 the average ambient air lead for the nation dropped 95% [14]. Soil and dust lead have also been found to contribute to elevated blood lead levels in children. In 1977 ambient air lead and soil lead accounted for 58% of the variance in blood lead levels [66]. A study in Baltimore found that soil

lead was a more important predictor of elevated blood lead than age of housing [1]. An investigation of housing and residential characteristics surrounding a superfund site found that floor dust, followed by soil dust, then interior lead paint were significant predictors of blood lead levels [67]. It has been estimated that for more than 30% of children with elevated blood lead levels no lead paint source is detected and dust is more bioavailable than paint or soil lead [14].

The strength of this current research is the use of geospatial statistics. Environmental lead is dispersed throughout a community with neighbors living near each other sharing similar characteristics than those living further apart. Health risks, available resources and potential exposures are spatially and socially structured [109]. By using spatial statistics and the 4 level RUCA designation from Urban to Rural we hoped to capture contextual information associated with the children being evaluated. Plus, the spatial autocorrelation present for each predictor was accounted for. Some important predictors associated with blood lead levels were not included in the model because census level predictions were not available for all census tracts (Table 8-4). Including them in the model would have resulted in the loss of children from 8 to 500 census tracts depending on the variable of interest. Table 8-4 shows a higher proportion of more educated populations in urban and suburban RUCAs and there was a higher proportion of unemployed and uninsured individuals in the large rural-towns and isolated rural areas. These are all risk factors associated with increased blood lead levels.

Table 8-4. Tract level socioeconomic characteristics for census tracts in which at least 5 children had a blood lead level screening.

	Urban			Sub-urban			Large Rural Town			Small Town Isolated		
Tract SES variable	n	Md	IQR	n	Md	IQR	n	Md	IQR	n	Md	IQR
HS Education plus	3998	89.0	11.9	482	88.4	7.4	363	85.3	7.2	180	85.2	6.0
Bachelor's degree plus	3998	25.7	27.4	482	19.1	14.2	363	15.2	10.2	180	13.5	6.7
% employed	3989	61.5	11.6	482	62.2	9.2	363	57.1	9.2	180	55.4	8.0
% unemployed	3989	6.1	5.2	482	5.5	3.2	363	6.7	4.0	179	6.5	3.1
% uninsured	3506	9.3	9.3	421	8.3	4.8	275	10.0	6.0	113	10.5	4.1
%poverty	4006	6.1	11.6	482	5.3	5.1	363	7.6	7.3	183	9.2	6.1
% black	4006	4.7	16.3	482	0.7	2.6	363	0.7	2.9	183	0.4	1.4
% pre-1950 housing	4006	35.0	44.4	482	28.0	19.6	363	34.9	31.8	183	39.1	18.4

One interesting note was that there was no significant effect of ambient air lead estimates on elevated blood lead levels. This may be due to the dramatic declines in ambient air lead levels over time. It could also be due to the lack of ambient air lead monitors throughout both states leading to exposure misclassification. A more appropriate predictor of blood lead levels may be soil lead. Kansas has a strong history of lead industrial activity including mining and smelting which began in the mid to late 1800s [110]. A recent study conducted by Talbott and Brink (2014) demonstrated a significant inverse relationship between a child's residential proximity to a TRI lead facility and childhood blood lead levels after adjusting for age of the child, percent poverty and percent pre-1950 housing at the census tract level ($p < 0.007$) [111]. Mining waste covers vast acres across the state [110] and proximity to such facilities may serve as proxy measures of exposure from soil lead and residential lead dust. Over 16% of all lead superfund sites across the U.S. are found in Pennsylvania and New Jersey. Future work to determine current reservoirs of lead exposure in the U.S. should consider soil lead. Current and past industrial locations associated with lead may result in residential homes having increased levels of lead dust as well as increased levels of soil dust in the surrounding community.

9.0 SUMMARY AND CONCLUSIONS

This body of work shows that living in areas with a high prevalence of housing built before 1950 and poverty are still significantly associated with elevated blood lead levels whether assessed at the individual or aggregated level of the census tract. Only one study out of the three found a significant association between childhood blood lead levels and ambient air lead as estimated by NATA or through inverse distance weighted exposure as determined by both industrial emissions and proximity to Toxic Release Inventory facilities. The two papers with a specific focus on children living in Pennsylvania and New Jersey (residential proximity to airports and rural urban commuting area prevalence of elevated blood lead level) found no significant association with ambient air lead as reported in NEI after adjusting for age, gender or census level variables related to housing, poverty or proportion black population. Both of these states have long industrial histories associated with lead. The distribution of elevated blood lead level by urban/rural status shows that the highest prevalence occurs in census tracts designated as large rural towns. Children living in these areas may be located near pockets of lead deposition from prior industrial activities resulting in increased exposure to soil lead and residential lead dust. Since the new recommendation by the CDC is primary prevention, research needs to explore areas with known lead industrial activities. If evidence of lead repositories in soils is found, steps can be taken to remediate the area to prevent future exposures in children.

APPENDIX: SUPPLEMENTAL TABLE

Table A-1. NHANES Studies Related to Childhood Blood Lead Levels

Manuscript	Survey Cycles	Sample Size	Age (years)	Statistical Approach	Covariates	Results
Pirkle et al. 1994. JAMA 272(4):284-91	NHANES II (1976-1980) Phase 1 NHANES III (1988-1991) HHANES (1982-1984)	n = 9832 n = 12119 n = 5682	1 to 74 1 to 74 4 to 47	Survey weighted trend analysis of GM BLL using log transformed bll	Age Race Gender PIR Urban status	Median GM bll 1 to 5yrs – 15 µg/dL Decrease in GM bll consistent for age, gender, PIR and Urban status Overall, BLL ↓ of 78% for 1 to 74 yr olds ↓ of 75% for all 1 to 5 yr olds (14.9 to 3.6 µg/dL) ↓ of 77% white kids, ↓ of 72% for black kids ↓ of 60% black, urban, poor kids (24.0 to 9.7 µg/dL) ↓ of 65% Hispanic kids (8.5 to 3.0 µg/dL)

Table A-1 Continued

Bernard & McGeehin. 2003. Pediatrics 112(6):1308-13	NHANES III (1988-1994)	n = 5787 4624 w/ samples	1 to 5	Investigating children 5 ≤ BLL < 10 µg/dL Sample weighted multivariate logistic regression with BLL groups of <5, 5 ≤ BLL < 10, 10 ≤ BLL < 20, 20+ n=2529	Race Age Age of home PIR Medicaid status Refedu Region Smoke in home	BLL ≥ 5 µg/dL for 1 to 5 year olds occurred for 47% of blacks, 28% Hispanic and 19% white. By region 43% NE, 31% Midwest, 22% S, 14% W 65% of kids with BLL ≥ 20 were black Pre 1946 housing, being a toddler, region, PIR, presence of a smoker in the home, being on Medicaid and REFEDU were significant in logistic regression
Jones et al. 2009. Pediatrics 123(3):e376-85	NHANES III (1988-1991) NHANES III (1991-1994) NHANES (1999-2004)	n = 2232 n = 2392 n = 2532	1 to 5 1 to 5 1 to 5	GM BLL Compared GM and proportions of BLL categories across race and housing risk <1, 1 to <2.5, 2.5 to <5, 5 to <7.5, 7.5 to <10 and ≥10 Multivariable logistic and linear regression	Race Age Age of home PIR Medicaid status	BLL ≥ 10 declined from 8.6% to 1.4%. Differences in distribution of BLLS across all BLL categories were sig diff across age, race, PIR, Medicaid and age of home. More black kids over 10 (3.4%) than Hispanic (1.2%) and white (1.2%) Lowest BLLS were for white kids, non-Medicaid, higher PIR All covariates statistically significant including survey cycle.

Table A-1 Continued

Dixon et al. 2009. Env Health Persp 117:468-474	NHANES (1999-2004) Lead dust sub analysis for homes only pre 1978	n = 2155 n = 731	1 to 5	Linear regression and Ln BLL, Logistic regression for BLL > 5 or > 10 Used Taylor Series expansion theory Fit intercept term for each variable with a missing value	Age Race Gender PIR Smoke in home # smoke in home Cigarettes/day USborn	Flood dust sig predicts BLL, as well as uncarpeted floors, windowsill dust, PIR, age, USborn, homes with smokers They also constructed models to predict GM BLL based on the amount of dust in the home.
Scott & Nguyen 2011. Int Arch Occup Env Health 84:513-22	NHANES III (1988-1994) NHANES (1999-2004)	n = 1085 only used kids with complete data on variables of interest	1 to 5	Survey weighted analysis Compared BLL ≥ 10 by region using linear regression and LnBLL	PIR Age of home Race USborn Age Housing charateristics Region of US	Highest GM BLL in northeast and midwest. Biggest decline in northeast and kids 1 to 2 yrs of age in the west 76% decrease in number of kids with BLL ≥ 10 µg/dL between two survey cycles. Factors that effect BLL differed by region NE – gender MidWest – Age of home South – black and Hispanic kids sig higher levels than whites

Table A-1 Continued

Apostolou et al. 2012. Research and Practice 102(4):714-22	NHANES 1999-2004	n = 6830 n = 791 those w/ dust meas.	3 to 19 3 to 5	Survey Weighted analysis Linear regression models on LnBLL	Gender Age Race USborn BMI percentile Survey year Refedu PIR Age of Home Cotinine	BLL ↓ with ↑ age, education, PIR BLL highest in boys, Black and Hispanic kids, those born outside US and those with pre-1950 housing Cotinine ↓ with ↑ age, education, PIR Cotinine highest in black kids, those born outside US, kids overweight or obese, those living in pre50 housing BLL associated with # smokers in home BLL higher for highest quartile of cotinine compared to BLL for those in lowest quartile of cotinine Dust highest for blacks, higher BMI, lower education, lower PIR, older homes, higher BLL, higher cotinine, homes with smokers

Table A-1 Continued

Richmond-Bryant et al. 2013. Science of Tot Env. 461-462: 207-213	NHANES III (1988 to 1994) NHANES (1999-2008)	n = 2743 n = 1818	1 to 60+	Multi-level LME models to assess BLL and monitor lead levels Monitors located within 4km of census block group centroid within which a participant lived 4km buffer reduced sample size	Age Gender Race Country of birth Refedu PIR Household size Milk consumption Mom's age @ birth Cd and Ca levels Yrs living in home Age of Home Source of tap water Employment (current) Employment (longest interval)	Ambient lead for 1 to 5 yr olds decreased from 0.04 to 0.01 ug/m^3 and median BLL decreased from 4.5 to 2.4 µg/dL No significant effect for monitor levels and 1 to 5 yr olds for the most recent survey cycles Were significant associations between BLL and monitor levels across all age groups for NHANES III

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