2015

The Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Health at Birth

Rhea Ann Bhatta
Lehigh University

The Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Health at Birth

by
Rhea Ann Bhatta

Presented to the Graduate and Research Committee
of Lehigh University
in Candidacy for the Degree of
Doctor of Philosophy
in
Business and Economics

Lehigh University
August 2015

Dissertation Approval Page

Approved and recommended for acceptance as a dissertation in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Business and Economics.

Date

(Signature)

Dissertation Advisor: Shin-Yi Chou

Accepted Date

Committee members:

(Signature)

Shin-Yi Chou, Co-chair

(Signature)

Muzhe Yang, Co-chair

(Signature)

Alberto Lamadrid

(Signature)

Anca Cotet-Grecu

Acknowledgements

I would like to thank each of my committee members as well as several other individuals for their countless time, effort, and patience expended toward helping me to finish this project and achieve my goals.

I begin with a special thanks to Dr. Shin-Yi Chou for her unmatched patience and support over the last few years. Without her empathy and guidance, I would never have made it to this point. I am forever grateful for the time and effort that she has put forward for our research endeavors and incalculable meeting hours. In the future, I can only hope that I will have the opportunity to pay it forward by advising students with the level of attention and care that Shin-Yi has provided for me.

I would also like to give a special thanks to Dr. Muzhe Yang, without whom I would never have finished this project. Thank you for pushing this work forward while I was unable. While I may have expressed impatience, and perhaps even ignorance at times, in response to his persistence, I always have and will recognize that he has been trying to help me to achieve my full potential. Though I may not have achieved my full potential while in graduate school, through his guidance, Muzhe has provided me with the tools necessary to try to further reach this goal in the future.

Additionally, I would like to thank my committee members, Dr. Alberto Lamadrid and Dr. Anca Cotet-Grecu. Alberto and Anca have been tirelessly patient and understanding, and they have worked very hard to help me to finish my project in a timely manner. Thank you for the wise words and for your constructive comments throughout this process.

Aside from committee members, I would also like to thank Dr. Chad Meyerhoefer for his service as director of the Ph.D. program. His efforts have provided constant support, from both a professional and financial standpoint, throughout this entire process. Without it, this endeavor would never have been possible. In addition, I would like to thank Mary Gulick, Director of CBE Graduate Student Affairs, whom I constantly pestered over the last several years. Still, she has always been patient, and she always has the answers. Also in the Graduate Programs Office, I would like to thank Megan Van Voorhis, who always took care of her graduate students and made sure that we had everything we needed (especially coffee!) to work in a comfortable environment.

Warranting a special thanks is Rene Hollinger for her unprecedented level of service to the Department of Economics. Without her, we simply would not function. In addition to her fantastic sense of humor that never failed to provide emotional relief, she has always been so patient with all of us. Not to mention that she knows all of the right people and always has an answer.

Last, but not least, I would like to thank all of my friends and family for their patience and support over the last several years. You helped me to push through, even during the most challenging times (which these past few years have been, without a doubt), and without your persistence, I would never have seen this through to the end.

To each and every one of you... Thank you, and thank you, again! I am forever grateful and indebted to all of you.

Contents

1 Introduction **3**

2 Literature & Background **7**

2.1 Birth Outcomes 7

2.2 Potential Mechanisms 9

2.3 Sulfur Dioxide 13

2.4 Institutional Setting 15

3 Data **16**

3.1 Data Sources 16

3.1.1 Air Quality System 16

3.1.2 Air Markets Program Data 17

3.1.3 NCDC Integrated Surface Data 17

3.1.4 New Jersey Healthcare Cost and Utilization Project 18

3.1.5 New Jersey Birth Certificates 19

3.2 Sample Selection 20

3.2.1 Using the HCUP Data 20

3.2.2 Using New Jersey Birth Certificates 21

4 Empirical Specifications **23**

4.1 Identification Strategy 23

4.2 Construction of the Instrumental Variable 25
4.3 Regression Models using HCUP 27
4.4 Robustness Checks and Additional Regressions 29
4.5 Regression Models using Birth Certificates 31

5 Results **33**
5.1 Summary Statistics 33
5.1.1 PGS, Pollution, and Weather Variables 33
5.1.2 Outcome and Demographic Variables 36
5.2 Impact of PGS Emissions on SO_2 Concentrations in New Jersey 38
5.3 Impact of Prenatal Exposure to SO_2 on Infant Birth Weight and Related Outcomes 41
5.3.1 Exposure During the Birth Month 42
5.3.2 Exposure During the Months Prior to and Including the Birth Month 43

6 Robustness Checks **47**
6.1 Additional Estimation Samples 47
6.1.1 Impact of Prenatal Exposure to SO_2 During the Birth Month on Infant Birth Weight and Related Outcomes 47
6.1.2 Impact of Prenatal Exposure During the Months Prior to and Including the Birth Month on Infant Birth Weight and Related Outcomes . 51
6.1.3 In Summary 57
6.2 Using a Radius of 25 Miles 60
6.2.1 Impact of PGS Emissions on SO_2 Concentrations in New Jersey Zip Codes 61
6.2.2 Impact of SO_2 Exposure During the Birth Month on Infant Birth Weight and Related Outcomes 62

7 Results Using New Jersey Birth Certificates **67**

7.1 Summary Statistics 67

7.2 Impact of Prenatal Exposure to SO_2 During the Birth Month on Infant Health at Birth 73

7.2.1 Birth Weight 73

7.2.2 Prematurity 79

7.2.3 APGAR Scores 82

7.3 In Summary 86

7.3.1 Discrepancies Between HCUP and Birth Certificate Results 88

8 Conclusion **90**

8.1 Conclusions 90

8.2 Limitations and Extensions 92

List of Tables

5.1 Summary Statistics, Part I . . . 35

5.2 Summary Statistics, Part II . . . 37

5.3 Impact of PGS SO_2 Emissions on SO_2 Concentrations Near NJ Zip Codes . . 39

5.4 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon and Morris Counties) 42

5.5 OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon and Morris Counties) . . . 44

5.6 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon and Morris Counties) . . . 46

6.1 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties) . . . 48

6.2 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties) . . . 49

6.3 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Warren County) . . . 50

6.4 OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, and Sussex Counties) . . . 52

6.5 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, and Sussex Counties) 54
6.6 OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, Sussex, and Warren Counties) 55
6.7 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, Sussex, and Warren Counties) . . . 56
6.8 OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Warren County) 58
6.9 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Warren County) 59
6.10 Impact of PGS SO_2 Emissions on SO_2 Concentrations Near NJ Zip Codes, Using a 25-mile Radius 62
6.11 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon and Morris Counties) 63
6.12 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties) 64
6.13 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties) 65
6.14 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Warren County) 66

7.1 Summary Statistics, Part IIIa 69
7.2 Summary Statistics, Part IIIb 72

7.3 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon and Morris Counties) 74

7.4 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties) 76

7.5 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties) 77

7.6 Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Warren County) 78

7.7 Effect of SO_2 Exposure During Birth Month on Prematurity$^{\diamond}$, OLS and 2SLS Estimates (Hunterdon and Morris Counties) 79

7.8 Effect of SO_2 Exposure During Birth Month on Prematurity$^{\diamond}$, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties) 81

7.9 Effect of SO_2 Exposure During Birth Month on Prematurity$^{\diamond}$, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties) 82

7.10 Effect of SO_2 Exposure During Birth Month on Prematurity$^{\diamond}$, OLS and 2SLS Estimates (Warren County) 83

7.11 Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon and Morris Counties) 84

7.12 Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties) 85

7.13 Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties) 86

7.14 Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Warren County) 87

List of Figures

2.1 How Air Pollution May Affect Infant Health 10
2.2 Map of Region 15
4.1 Azimuth: A Visual Example 26

Abstract

According to the fetal origins hypothesis, adverse events that occur while a fetus is in-utero may have lasting impacts throughout the duration of the individual's lifetime. Therefore, from a policy standpoint, understanding the factors that affect prenatal health are of utmost importance. The purpose of this study is to examine how prenatal exposure to sulfur dioxide (SO_2), one of six criteria pollutants monitored by the U.S. EPA, affects infant health at birth. In particular, we consider outcomes related to birth weight, prematurity, and APGAR scores.

For this study, we integrate data from several different sources. Pollution and emissions data come from the EPA's Air Quality System and Air Markets Program Data, respectively. Weather and wind data are obtained from the National Climactic Data Center Integrated Surface Data. For infant health outcomes, we utilize two data sets–discharge abstracts from the Healthcare Cost and Utilization Project (HCUP) State Inpatient Database for New Jersey and birth certificate records obtained from the New Jersey Department of Health.

Our identification strategy follows Yang and Chou (2015), a setting under which SO_2 emitted from a power plant in Pennsylvania travels to New Jersey by way of the prevailing wind. We construct an IV for zip-code-level SO_2 exposure that adjusts plant-level SO_2 emissions using wind direction from the emission source to the mother's zip code of residence. Using the HCUP data, we uncover strong first- and second-stage results; exposure to SO_2 during pregnancy can increase the likelihood of an LBW birth by 0.5 percentage points and VLBW birth by 0.4 percentage points. Unfortunately, we find mixed results using the birth certificates, but further investigation will be necessary using these records.

Nonetheless, even at today's relatively low levels of SO_2, thanks largely to the passage of the Clean Air Act of 1970, our estimates indicate that the benefit of pollution abatement can be significant, even for an affluent region, as in our study, which already has excellent access to health care.

Chapter 1

Introduction

Air pollution, along with other kinds of pollution, such as industrial wastewater and toxic releases, is a by-product of many basic economic activities that are essential to our society's survival. Environmental policies directed towards pollution abatement seek to protect, and even improve, the health and welfare of society and its members. While complete eradication of air pollution is impractical from both financial and social standpoints, environmental policies can be designed so as to appropriately balance the private and social costs and benefits of abatement. In order for environmental policies to develop and determine "optimal" levels of pollution and reduction, empirical evidence with causal interpretation is of critical importance to policymakers.

One crucial aspect that environmental policymakers must consider is how polices affect certain population groups. For this study, we consider infants, who are among society's most vulnerable members and adversely affected by policy, yet have no voice (for obvious reason) in social and political decision-making. In particular, our study considers infant health at birth, which is highly associated with early and later health and life outcomes. If, for instance, infants who are born premature or with low birth weight are more likely to develop certain types of diseases, whose treatments result in higher private and social costs, then the need to understand the factors that affect these potential birth outcomes is justified. The specific purpose of our study is to examine how prenatal exposure to air pollution affects infant health at birth.

Our analysis considers the impact of sulfur dioxide, which is a colorless, pungent gas emitted from various industrial processes, including the generation of coal-powered electricity. Since the early 1970s, sulfur dioxide has been highly scrutinized by the U.S. Environmental Protection Agency (EPA) under two programs, its nationwide Air Quality System and its Acid Rain Program, evidence that, to date, extensive resources have been devoted to its reduction. This emphasis, however, is seemingly warranted. For instance, short-term exposures to sulfur dioxide, ranging from 5 minutes to 24 hours, are associated with a variety of adverse respiratory and cardiovascular effects;[1] exposure during pregnancy has also been linked to pre-term birth ([Shah and Balkhair, 2011]).

Given data restrictions, our primary analysis focuses on outcomes related to birth weight, including the likelihood of low birth weight (< 2,500 grams) and very low birth weight (< 1,500 grams). Birth weight, and related measures, are commonly used indicators for infant health at birth. However, we expect that prenatal exposure to air pollution, including sulfur dioxide, most adversely affects fetal development during the first few months of pregnancy, and thus, might expect to find a stronger relationship with direct outcomes, such as the likelihood of prematurity or intrauterine growth retardation, than with indirect outcomes, such as birth weight. Results from our primary analysis indicate an unusual, but compelling, result: sulfur dioxide exposure in the birth month most strongly affects the likelihood of low birth weight.

Additional data provide the opportunity to explore alternative measures of infant health at birth. In addition to birth weight, we explore the impact of sulfur dioxide on prematurity; this exploration is warranted since premature births are frequently associated with higher costs of care. We also examine APGAR scores, which provide a "quick" summary of an infant's physical condition at birth.

[1]Source: `http://www.epa.gov/airquality/sulfurdioxide/health.html`

For our study, we use the identification strategy developed by Yang and Chou (2015), which exploits a unique empirical situation in which sulfur dioxide emitted from a coal-fired power plant in Pennsylvania blows into regions of New Jersey. As a consequence, these regions are in violation of the EPA's primary standards for sulfur dioxide concentrations. Since sulfur dioxide concentrations experienced by a mother during her pregnancy are likely to be endogenous, we utilize Yang and Chou's IV estimation strategy in which direction-adjusted sulfur dioxide emissions from the Pennsylvania plant instrument for sulfur dioxide concentrations in New Jersey. Using one data set, we find strong first- and second-stage results, although the second data set yields confusing results.

Several data sets are brought together for this study. Air pollution data are obtained from the U.S. EPA's Air Quality System and Air Markets Program Data. Weather and related information are gathered from the National Climactic Data Center (of the National Oceanic and Atmospheric Administration) Integrated Surface Data. Birth-related information come from the Healthcare Cost and Utilization Project (HCUP) for the State of New Jersey. In supplemental analyses, birth certificate records, obtained from the New Jersey Department of Health, are used.

Through this study, we attempt to address several environmental-policy-relevant questions. First, we seek to answer whether or not prenatal exposure to sulfur dioxide affects infant health at birth. Second, if exposure affects birth outcomes, at what points during pregnancy is a fetus most vulnerable? Third, does exposure affect the fetus directly or indirectly? In other words, what birth outcomes are most adversely affected by exposure? Lastly, even at today's relatively low levels of pollution, are further reductions in air pollution beneficial from a cost-benefit perspective?

The remainder of this study is structured as follows. Chapter 2 summarizes relevant literature, background on EPA air pollution policies, and the institutional setting used in our empirical analyses. Chapter 3 provides an overview of our data sources and sample selection. Chapter 4 contains empirical specifications, including validity checks, as well as construction of the instrumental variable following Yang and Chou (2015). In Chapters 5 and 6, we review summary statistics and results from our empirical specifications using the HCUP data. In Chapter 7, we provide summary statistics and results using the birth certificate records. Chapter 8 concludes with a summary of our findings as well as the limitations and potential extensions to the study.

Chapter 2

Literature & Background

To study the impact of prenatal exposure to air pollution on infant health at birth, we bring together several different streams of literature, extending beyond economics to also include studies in the fields of biology, medicine, and environmental science. In the proceeding sections (2.1 and 2.2), we examine literature regarding the importance of studying infant health and consider the potential biological mechanisms for how infant health may be affected by exposure to air pollution while in-utero. In Section 2.3, we discuss the properties of sulfur dioxide (SO_2) and its regulation by the U.S. EPA. Section 2.4 makes note of the institutional setting used in our analysis.

2.1 Birth Outcomes

The Barker hypothesis, commonly known as the fetal origins hypothesis, posits that "fetal growth retardation consequent to malnutrition has long-term structural and physiologic impacts that predispose an individual to chronic diseases in adulthood" ([Barker, 1998]). In other words, individuals who have experienced adverse events while in-utero are more likely to experience adverse or worsened outcomes throughout their lifetimes, even into adulthood. If we believe the fetal origins hypothesis to be true, then understanding the factors that affect fetal health is of utmost importance from health- and social-policy standpoints. An infant has no control over his intrauterine environment, yet what he experiences may have long-term impacts throughout the duration of his life. Perinatal outcomes are affected by a number of different factors, including nutrition and health, genetics, physiological stressors, and environmental toxicants ([Keen et al., 2003]). Since the direct study of in-utero health is virtually impossible from our standpoint, we examine infant outcomes at birth, which may be representative of an infant's in-utero experiences. Since infant outcomes at birth may be strongly correlated with later-life outcomes, we focus on how prenatal exposure to air pollution, sulfur dioxide (SO_2), in particular, affects birth outcomes.

The focus of our primary study is how exposure to SO_2 affects birth weight, in particular, low birth weight. Infant weight at birth is highly correlated with early and later health and life outcomes and, thus, serves as an important outcome to study. For instance, infants born with low birth weight (LBW) (weighing less than 2,500 grams) are more likely to develop such conditions as high blood pressure, cerebral palsy, and asthma during childhood ([Nelson and Grether, 1997]; [Brooks et al., 2001]; overview in [Almond et al., 2005]). Additionally, infants born LBW have lower educational attainment, poorer self-reported health status, and reduced employment and earnings as adults ([Behrman et al., 1994]; [Currie and Hyson, 1999]; [Behrman and Rosenzweig, 2004]). In addition to the social costs, infants born with LBW impose substantial financial costs as well. According to estimates ([Almond et al., 2005]), the initial costs of care for an infant weighing 1,000 grams (2.2 pounds) at birth can exceed $100,000 (in 2000 dollars); for babies weighing 2,000-2,100 grams (4.4 to 4.6 pounds), an additional pound (454 grams) of weight is associated with a $10,000 difference in hospital charges. Therefore, understanding the factors that affect birth weight is critical from a policy perspective.

LBW is governed by two main factors: (1) short gestation (i.e. prematurity); and (2) slow prenatal growth, or intrauterine growth retardation (IUGR) ([Kannan et al., 2006]). Factors (1) and (2) may be affected by congenital or chromosomal abnormalities, placental problems, infections during pregnancy, and maternal risk factors, such as multiple pregnancies, previous

LBW infants, poor nutrition, heart disease or hypertension, smoking, drug or alcohol abuse, insufficient prenatal care, and exposure to lead and air pollution. Based on this information, our examination of the impacts of prenatal exposure to SO_2 on birth weight and LBW considers a potentially indirect relationship. In order to identify a direct relationship, we need to consider how prenatal exposure to SO_2 affects prematurity and IUGR. While data limitations at present will not permit the study of IUGR, we attempt to the examine the more direct relationship between prenatal exposure to SO_2 and prematurity.

In addition to birth weight and prematurity, other early life indicators may be affected by prenatal exposure to SO_2. Another outcome we consider is an infant's APGAR score. The APGAR score was invented to quickly summarize an infant's physical health at 1-minute and 5-minutes after birth ([Apgar, 1953]). It contains five components (**A**ppearance, **P**ulse, **G**rimace, **A**ctivity, **R**espiration), each of which are scored on a scale of 0 to 2. While the highest possible score is 10, very few infants actually score a perfect 10. APGAR scores greater than or equal to 7 are considered normal, while scores between 4 and 6 are fairly low, and scores less than or equal to 3 are critically low. While a low 1-minute score may suggest the need for immediate medical attention, it is not necessarily indicative of a long-term health problem ([Casey et al., 2001]). Though controversy exists as to whether APGAR scores are indicative of potential neurological problems, it is still an important measure since it is used to predict survival during the neonatal period.

2.2 Potential Mechanisms

Figure 2.1 demonstrates how prenatal exposure to air pollution may affect infant health: either directly by affecting the fetus or indirectly by compromising the mother's health. While some may argue that any impact on the fetus is indirect, we make the following distinction: an *indirect* effect first compromises maternal health, which, in turn, compromises fetal health; whereas a *direct* effect does not affect maternal health but does, in fact, affect fetal health. The direct impacts of air pollution exposure on the fetus may translate through outcomes such as gestation length, prematurity, IUGR, and fetal death. The indirect impacts of air pollution exposure on the fetus may occur through reduced birth weight, low or very low birth weight, and reduced APGAR scores. In addition to birth outcomes themselves, the point in time at which a fetus is exposed to air pollution may also have a direct or indirect impact on these outcomes. For instance, one possibility is that direct exposure during the early months of pregnancy more adversely affect the fetus and yield worse birth outcomes. Alternatively, indirect exposure during the later months of pregnancy may cause the mother to become ill and thus indirectly impact the fetus and birth outcomes.

$$
\begin{tikzcd}
\text{mother's health} \arrow[r] & \text{fetus} \arrow[r] & \text{infant health} \\
& \text{air pollution exposure} \arrow[ul, "\text{indirect}"] \arrow[u, "\text{direct}"'] &
\end{tikzcd}
$$

Figure 2.1: How Air Pollution May Affect Infant Health

Though the exact biological mechanisms through which air pollution affects infant health are not well understood, several theories exist in the biological literature. One possibility is that pollution exposure may increase the incidence of maternal infection and illness ([Gibbs et al., 1992]). Another explanation posits that exposure may increase blood viscosity, which, in turn, may affect placental blood flow ([Peters et al., 1997]; [Zondervan et al., 1987]). Air pollution may also affect DNA transcription, which can interfere with fetal growth ([Perera et al., 1992], [Perera et al., 1988]). One pollutant, benzopyrene, is believed to affect uterine and fetal growth through anti-estrogenic effects ([Bui et al., 1986]). Another set of compounds, polycyclic aromatic hydrocarbons (PAHs), binds to receptors for placental growth factors ([Dejmek et al., 2000]); this binding may reduce the exchange of oxygen and nutrients across the placenta. From an environmental policy perspective, we need to understand the levels of pollution exposure that are necessary to induce negative effects as well as the points in time during development that the fetus is most vulnerable to exposure. In the rest of this section, we review studies of specific air pollutants (includin, but not limited to SO_2) and their suspected biological mechanisms in order to understand their impacts on fetal and infant health.

According to one study, prenatal exposure to SO_2 may lead to developmental and functional toxicities ([Singh, 1989]). In this study, pregnant mice were exposed to three different SO_2 concentrations, 0 parts per million (ppm), 32 ppm, and 65 ppm. The study finds that maternal exposure at the highest concentration reduces the average birth weight of pups. In short, the study suggests that maternal exposure to SO_2 during pregnancy can affect the neuromuscular coordination and may produce deficits in the functional capability of the developing offspring, and these deficits are associated with birth weight.

Another set of studies examines the effects of nitrogen dioxide (NO_2) on fetal development. One study finds that exposure to NO_2 suppresses the human body's antioxidant defense systems ([Tabacova et al., 1998]). In particular, elevated exposure to oxidized nitrogen compounds is associated with increased lipid peroxidation in both maternal and cord blood. In turn, higher blood lipid peroxide concentrations are associated with poor birth outcomes, including birth weight, APGAR scores, and clinical diagnoses. The results of the study indicate that fetal exposure to oxidized nitrogen compounds is not only associated with increased risk of adverse birth outcomes, they also suggest that oxidative damage may play a role in the pathogenic pathway. Another study finds that exposure to NO_2 during pregnancy induces lipid peroxidation in the placenta as well as disturbances in postnatal development ([Tabacova et al., 1985]). In this study, pregnant rats are exposed to various concentrations of NO_2 and then postnatal outcomes of the offspring are examined. Their results indicate neurobehavioral impacts (such as disruptions in neuromotor development, coordination difficulties, retarded locomotion development, and reduced activity and reactivity), even at relatively low levels of prenatal exposure. According to Walters et al. (2001), exposure may lead to inflammatory reactions in the lungs, which cause the release of cytokines that could trigger pre-term birth. Prenatal exposure to NO_2 may also have direct toxic effects on the fetus ([Maroziene and Grazuleviciene, 2002]); specifically, a 10 $\mu g/m^3$ increase in NO_2 exposure increases the likelihood of pre-term birth by 25%.

Another commonly studied air pollutant and its relationship with fetal health is carbon monoxide (CO). According to one study, the presence of CO obstructs oxygen delivery to the fetus by displacing oxygen from the hemoglobin ([Longo, 1977]). In another study examining fetal outcomes for mothers who have accidentally suffered from CO poisoning, the findings suggest that exposure to very high concentrations of CO can result in adverse fetal outcomes, including stillbirths and cerebral palsy ([Koren et al., 1991]). These impacts on fetuses are likely attributable to the fact that CO is eliminated from the body at a slower rate in the fetus than the mother, thus resulting in higher levels of accumulation in the fetus. A third study finds CO poisoning can cause hypoxic stress[1] by interfering with oxygen transport to cells and impairing electron transport ([Hardy and Thom, 1994]). It also finds that CO may affect leukocytes, platelets, and the endothelium, all of which can lead to oxidative injury.[2]

Particulate matter (PM) is a by-product of many industrial and utility activities. A fetus exposed to PM during the early stages of development may result in altered trophoblast formation and placental issues, including abnormal implantation and increased placental mass ([Roberts et al., 1991]). Once PM enters the lungs, it may be absorbed into the blood stream and transported to other organs; since it is relatively small in size, PM is not captured through phagocytosis ([Ritz et al., 2007]). If PM is able to enter the body by way of the blood stream, it may lead to oxidative inflammation in the lungs, other organs, and the placenta, which increases the likelihood of pre-term birth ([Liu et al., 2003]).

[1] This refers to a condition in which the body or certain parts of the body suffer from inadequate oxygen flow.

[2] Oxidative injury refers to the reduction in a system's ability to detoxify or repair any cell damage. When oxidative injury occurs, the body may experience toxic effects through the production of peroxides and free radicals that can damage a cell's various components.

When PAHs are absorbed, DNA adducts[3] may form ([Parker et al., 2005]; [Perera et al., 1999]). Several studies show correlations between high levels of DNA adducts and reduced gestational length ([Liu et al., 2003]; [Perera et al., 1999]; [Perera et al., 1988]), and a correlation between DNA adduct levels in the mother's and newborn's blood also exists ([Topinka et al., 2009]). Additionally, high levels of PAHs may increase blood viscosity and reduce blood flow to the placenta and uterus, thereby interfering with the proper nourishment of the fetus ([Liu et al., 2003]; [Ritz et al., 2000]).

2.3 Sulfur Dioxide

Sulfur dioxide (SO_2), a major group of the broader class of sulfur oxides, is a colorless, pungent gas that is highly reactive. In the presence of other compounds, it can react to form acid rain as well as small, atmospheric particulates that are hazardous to human health. Sulfur compounds are found in coal and petroleum, whose combustion emits SO_2 unless the compounds are removed prior to the fuel-burning process. According to the U.S. Environmental Protection Agency (EPA), the main sources of SO_2 emissions include fossil-fuel combustion at power plants and at other industrial facilities, accounting for 73% and 20%, respectively, of total SO_2 emissions.[4] Other smaller sources of emissions include industrial processes, such as extracting metal from ore, and the burning of high-sulfur-containing fuels by "locomotives, large ships, and non-road equipment".

Established under the Clean Air Act (CAA) of 1970, the EPA's Air Quality System (AQS) monitors ambient concentrations of six criteria pollutants, one of which is SO_2, across the nation. For each of these criteria pollutants, the EPA sets primary standards, which seek to protect public health, as well as secondary standards, which seek to protect public welfare; these are also known as the National Ambient Air Quality Standards (NAAQS). According to the primary standards instituted under the CAA, 24-hour SO_2 concentrations could not

[3] DNA adducts occur when a piece of DNA is covalently bonded to a carcinogenic chemical.
[4] Source: `http://www.epa.gov/air/sulfurdioxide/`

exceed 140 parts per billion (ppb) and the annual average could not exceed 30 ppb. In 2010, the EPA revised the primary standards for SO_2 by revoking the two primary standards set under the CAA and creating a new one-hour standard that concentrations cannot exceed 75 ppb. Secondary standards are assessed with respect to a given three-hour period, during which SO_2 concentrations cannot exceed 500 ppb. If an area violates these standards, the state government must propose a maintenance plan, which first must be approved by the EPA, and then implemented. As of 2010, nine areas, one of which was Warren County, New Jersey, located on the northeastern border with Pennsylvania along the Delaware River, across the U.S. were in violation of the primary standards.

As a precursor to acid rain, SO_2 has also been the target of the EPA's Acid Rain Program, which was developed under Title IV of the Clean Air Act Amendments of 1990. Implemented over two phases, the Program has tightened restrictions on fossil-fuel burning power plants by means of traditional and market-based approaches to pollution reduction. Phase I, beginning in 1995, affected coal-burning electric utility plants located in 21 eastern and Midwestern states. Phase II, beginning in 2000, tightened restrictions on annual emissions of larger, higher-emitting plants and also set restrictions on smaller, cleaner plants powered by coal, oil, and gas. At least in part due to the CAA of 1970 and the Acid Rain Program, SO_2 concentrations, measured as the 99th percentile of one-hour daily maximum averages, decreased from about 147.3 ppb in 1980 to 32.7 ppb in 2012, a roughly 78% reduction across the United States.[5]

For this study, we utilize a specific property of SO_2–its transportability through the air. One important consequence of SO_2 emissions is that prevailing winds can transport SO_2 over a long distance through the air, sometimes over hundreds of miles. According to one study, SO_2 emissions occurring in the Kola Peninsula, located in the far northwest of Russia, traveled to regions of Finland and Norway without substantial dilution ([Tuovinen et al., 1993]). For our study, we examine a particular case in which SO_2 emissions from a plant located in

[5]Source: `http://www.epa.gov/air/airtrends/sulfur.html`

Pennsylvania travel by way of the prevailing wind into neighboring locations in New Jersey.

2.4 Institutional Setting

Our study utilizes the institutional setting employed by Yang and Chou (2015). Under this setting, SO_2 emissions from a power plant located in Eastern Pennsylvania (Portland Generating Station, or PGS) travels through the prevailing wind (the westerly wind, blowing eastward) across the Delaware River into neighboring regions of New Jersey. The affected New Jersey counties include Hunterdon, Morris, Sussex, and Warren. This setting serves as the basis for the instrumental variable approach to examine the impact of prenatal exposure to SO_2 on infant health at birth.[6] Figure 2.2 shows a county-level map of the region under consideration, with a red star denoting the location of the power plant.

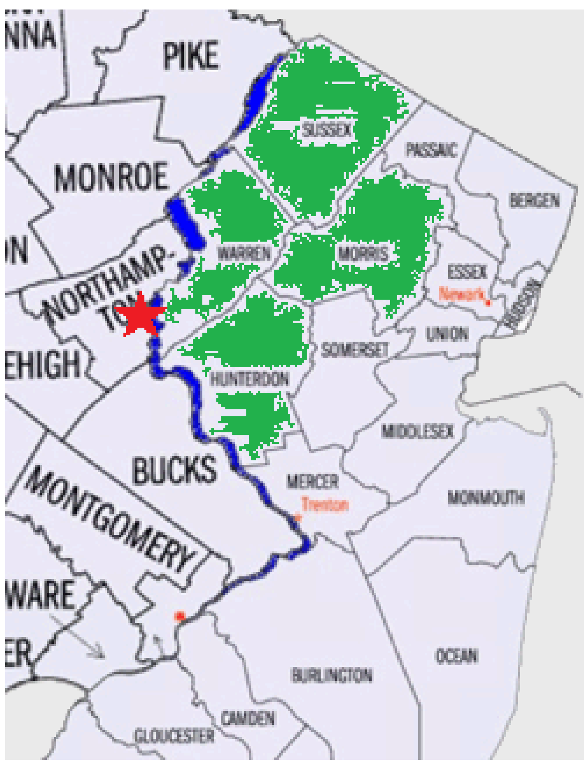

Figure 2.2: Map of Region

[6]For more information regarding this institutional setting, please see Yang and Chou (2015).

Chapter 3

Data

This chapter provides an overview of the data sources (Section 3.1) as well as the selection of the birth samples (Section 3.2) that are used in our analyses.

3.1 Data Sources

Data for this analysis comes from several different sources: the U.S. EPA's Air Quality System (AQS) and Air Markets Program Data (AMPD); the National Oceanic and Atmospheric Administration's (NOAA) National Climactic Data Center (NCDC) Integrated Surface Data (ISD); the Health Care Cost and Utilization Project (HCUP) State Inpatient Database (SID) for New Jersey; and birth certificate records from the New Jersey Department of Health.

3.1.1 Air Quality System

The EPA's AQS Data Mart[1] is a web-based query tool from which we retrieve monitor-level, daily maximum SO_2 measurements (of one-hour readings) for all monitoring sites located in New Jersey, New York, and Pennsylvania for the years 1989 to 2006.[2] We choose the daily maximum values since exposure to these levels are more likely to induce adverse health

[1]See: `http://www.epa.gov/ttn/airs/aqsdatamart/access/interface.htm`

[2]Since these three states are in close geographic proximity, monitor data from New York and Pennsylvania are required to construct zip-code-level SO_2 measures.

effects. Using the daily maximum values, we construct monthly SO_2 measures for each zip code in New Jersey. First, we compute a simple monthly average for each monitor using the daily maximum values. Next, using the monitors' latitudinal and longitudinal coordinates, we calculate the geodetic distance between each monitor and each zip code centroid in New Jersey.[3] We select only monitors located within a 20-mile radius; for robustness checks, we also use a 25-mile radius. Then, for each zip code, we create a monthly weighted-average, using the inverse of distance from the monitor as the weight. The constructed SO_2 measures vary by month and zip code. Our use of the inverse-distance weighting method, as well as our chosen radius of 20 miles, follows Currie and Neidell (2005).

3.1.2 Air Markets Program Data

Using the EPA's AMPD web-based query interface,[4] we obtain total monthly SO_2, NO_X (oxides of nitrogen), and CO_2 (carbon dioxide) emissions (in tons) from PGS's coal-fired generating units for the time period from January 1995 to December 2006. Our analysis only uses emissions of SO_2. PGS has two coal-fired generating units, vintage 1958 and 1962; to find total monthly SO_2 emissions from PGS, we simply add together emissions from each generating unit for every month-year of our sample period. Because the AMPD has no information for PGS prior to January 1995, our subsequent analysis encompasses a shorter time horizon (January 1995 to December 2006) than would be indicated by the available birth data.[5]

3.1.3 NCDC Integrated Surface Data

NCDC ISD provides station-level measurements of various climate variables. The raw data files contain hourly readings of several climate variables for a given station in a given year.

[3] Geodetic distance approximates the length of the shortest curve between two points on the earth's surface.

[4] See: `http://ampd.epa.gov/ampd/`

[5] Our available HCUP data spans from January 1990 to December 2006, and our available New Jersey birth certificate data spans from January 1989 to December 2010.

For our analysis, we retrieve monthly summary data from the NOAA (for all stations in New Jersey for the period from January 1994 to December 2006) for the following variables: mean maximum temperature; mean minimum temperature; mean temperature; total rainfall; and total snowfall.[6] In order to obtain monthly, zip-code-level measures for each of these five variables, we employ a procedure similar to our construction of the SO_2 measures. First, we use latitudinal and longitudinal coordinates to compute the geodetic distance between each zip code centroid and weather monitor. We subset to monitors located within a 20-mile radius of the zip code centroid.[7] Then, using inverse-distance as the weight, we create a weighted, monthly average measure for each zip code.

In addition to temperature and precipitation, the ISD also provides hourly wind speed and wind direction data. We obtain this information for two weather stations, with complete data for the period from January 1994 to December 2006, located in Pennsylvania.[8] The two included weather stations, one of which is located in Allentown (southwest of PGS) and the other in Wilkes-Barre (northwest of PGS), are the closest stations to PGS. For our analysis, and the construction of the instrumental variable, we use wind direction, which is a continuous variable measured in degrees and takes on a value from 0 to 360. Using the hourly wind direction data, we compute a simple monthly average wind direction for each station; then, using the two stations' monthly averages, we construct a single monthly average for wind direction, which is used to approximate monthly wind direction near PGS.

3.1.4 New Jersey Healthcare Cost and Utilization Project

HCUP SID contains inpatient discharge abstracts for nearly all general, acute care hospitals in the state of New Jersey for the years 1990 to 2006.[9] The abstracts contain information on the month and year of admission, type of admission, demographics, insurance status, zip

[6] See: `http://www.ncdc.noaa.gov/cdo-web/search?datasetid=GHCNDMS`

[7] For analyses that utilize a 25-mile radius in construction of the SO_2 measures, we also use a 25-mile radius in constructing these weather variables.

[8] Though we obtained wind speed, it is not included in our current analysis.

[9] While a greater number of years are available, these are the years to which we have access.

code of residence, and any associated diagnostic or procedural codes. For our analysis, we subset to all newborn admissions[10] with a zip code of residence in New Jersey.[11] Though the data do not have the infant's exact birth date, it contains the month and year of birth as well as his birth weight. Unfortunately, the data do not allow the linkage of mothers with their newborns, so our analysis using the HCUP data is unable to control for any maternal characteristics. Nonetheless, we create indicators for the infant's sex, race, and insurance status (Medicare, Medicaid, private insurance, or self-pay). We also create indicators for birth weight (if birth weight is non-missing): if birth weight is less than 2,500 grams, then an indicator for low birth (LBW) equals 1; if birth weight is less than 1,500 grams, then an indicator for very low birth weight (VLBW) equals 1. Additionally, the data do not contain any information on several important birth characteristics, such as gestational age, fetal malnutrition, and intrauterine growth retardation. In order to, at least in part, address the issue of missing this critical information, we construct a dummy variable for extreme immaturity related to short gestation using available ICD-9 codes. If any diagnosis code equal to 765.0 or 765.1 is present, then this dummy variable takes on a value of 1; otherwise it equals 0.[12]

3.1.5 New Jersey Birth Certificates

In supplemental analyses, we use birth certificate records obtained from the New Jersey Department of Health. This data spans from January 1989 through December 2010. While these records contain geo-coded information related to a mother's residence, for the purpose of this study, we limit our analysis to the use of the mother's geo-coded zip code of residence in order to remain consistent with the HCUP analysis. We include only mothers with a geo-coded zip code of residence in New Jersey. This data fills in many of the gaps present in the HCUP data; it contains information regarding prenatal care (number of visits, month of

[10]Newborn admissions are indicated by a variable for admission type (ATYPE) equal to 4.

[11]This is actually the mother's primary zip code of residence which the hospital assigns to the newborn.

[12]In theory, based on the definitions of the ICD-9 codes 765.0 and 765.1, this dummy variable should capture the vast majority of premature births (i.e. birth occurred prior to 37 weeks of gestation).

first visit, date of last menses period, etc.), maternal characteristics (race, ethnicity, marital status, smoking status, and age), and paternal characteristics (race, ethnicity, and age). With regard to prenatal care utilization, we create category dummies based on the number of prenatal visits during pregnancy: no visits; 1 to 9 visits; 10 to 18 visits; 19 to 27 visits; and 37 or more visits. For smoking status, we create a dummy variable equal to 1 if the mother smoked at any point during the pregnancy.

In addition to birth weight (and indicators for LBW and VLBW, constructed using birth weight), the data also contains 1-minute and 5-minute APGAR scores as well as clinical estimation of gestational length (in weeks). We create indicators for normal APGAR scores at 1-minute and 5-minutes; these dummies take on a value of 1 if the respective APGAR score is greater than or equal to 7 and take on a value of 0 otherwise (unless missing). Using gestational length, we also create an indicator for pre-term birth (if gestation length is non-missing): if estimated gestational length is fewer than 37 weeks, the pre-term variable takes on a value of 1; for gestation length greater than or equal to 37 weeks, it takes on a value of 0. The data also provide information regarding the place of birth as well as birth order, in the case of multiple births; we create indicators for hospital births as well as singleton, twin, and multiple (twins, triplets, quadruplets, quintuplets or greater) births. Unfortunately, no payment-related or insurance status information is available. Nonetheless, the birth certificate records permits examination of a greater number of outcome variables as well as the use of a richer set of control variables related to maternal characteristics.

3.2 Sample Selection

3.2.1 Using the HCUP Data

Although we have birth information dating back to January 1990, we are limited by the AMPD, which begins January 1995. Therefore, our New Jersey birth sample spans the period from January 1995 to December 2006. The AQS and NCDC data are from January

1994 to December 2006. By starting our birth sample in 1995, we can assign pollution exposure in the months prior; for instance, an infant born in January 1995 can have sulfur dioxide exposure assigned for each of the nine months prior, dating back to 1994. For the IV estimations that examine the impact of prenatal exposure during the months prior to birth, our sample of births begins in September 1995 since we cannot assign pollution any further back for births occurring earlier than September 1995 due to the AMPD.

Because of data limitations in the HCUP, our study of the impact of prenatal exposure to sulfur dioxide on infant birth weight focuses on a sample of full-term births. Since the HCUP do not contain any information on gestational age, we construct a dummy variable for extreme immaturity due to short gestation, as mentioned previously. This dummy takes on a value of 1 if the newborn has a diagnosis containing the ICD-9 codes of 765.0 or 765.1,[13] and a value of 0 otherwise. For our analysis sample, we exclude infants for which this dummy variable equals 1, which eliminates definitively pre-term births. Consequently, our estimation sample is more likely to include only full-term births.

Additionally, we subset to singleton births since infants born in a multiple birth (twins, triplets, etc.) are likely to have different characteristics. We also drop infants whose birth weight is less than 500 grams (or 1.1 pounds) from our sample. The likelihood of survival for an infant born weighing fewer than 500 grams is extremely low.[14]

3.2.2 Using New Jersey Birth Certificates

In order to remain consistent with our analysis using the HCUP data, we limit our sample using the birth certificate records to include births that occurred between January 1995 and December 2006. All of our analysis samples will focus on singleton births since birth characteristics tend to differ for those born in multiple births. The primary analysis sample using this data will include births that are full-term, live, and in-hospital, and we drop infants whose birth weight is less than 500 grams. In order to examine the impact on pre-

[13] The ICD-9 codes 765.0 and 765.1 indicate gestation of fewer than 37 weeks.

[14] http://en.wikipedia.org/wiki/Fetal_viability

term births, we retain births that are pre-term but still subset to live, in-hospital births (with birth weight exceeding 500 grams) with non-missing information.

Chapter 4

Empirical Specifications

4.1 Identification Strategy

Estimation of a causal relationship between prenatal SO_2 exposure and infant health at birth poses a substantial challenge due to the endogeneity of pollution exposure. Since pregnant mothers can choose where to live, residential choice may be correlated with factors such as income, education, and health care utilization. Mothers may live in areas with high levels of economic activity and, consequently, higher pollution levels. However, these mothers may have higher incomes (due to greater economic activity) and, thus, greater health care utilization. If this is the case, then an ordinary least squares (OLS) estimator of the impact of prenatal exposure to SO_2 will be underestimated. In order to address this endogeneity problem, we employ an instrumental variables (IV) approach. Following Yang and Chou (2015), we use direction-adjusted SO_2 emissions from PGS as an instrument for SO_2 concentrations in New Jersey.

As described in Yang and Chou (2015), the empirical setting, substantiated by the NJDEP's petitions and the EPA's ruling, provides the basis for the use of an IV estimator. Sulfur dioxide emissions from PGS blow eastward, across state lines into New Jersey. The IV, which is direction-adjusted emissions from PGS, instruments for SO_2 concentrations in New Jersey. Arguably, this IV provides exogenous variation in individuals' exposure to SO_2 both temporally and geographically by way of emissions from PGS and wind direction near the plant (and where a particular zip code is located relative to the plant).

Similar to Yang and Chou (2015), our main analysis sample includes Hunterdon and Morris Counties in New Jersey. We expect the instrument to be strongest for these counties, given their locations relative to PGS. For robustness checks, we also add Sussex County and then Warren County to the samples. Finally, we conduct separate analyses for Warren County, for which IV exogeneity is likely to be violated.

According to the Census 2000 from the U.S. Census Bureau,[1] median household income was \$79,888 in Hunterdon County, \$77,340 in Morris County, \$65,266 in Sussex County, and \$56,100 in Warren County.[2] All four counties exceeded median household income in the state of New Jersey (\$55,146) and the entire country (\$41,994). Additionally, the percentage of the population aged 25 or older who obtained bachelor's degrees or higher was 41.8% in Hunterdon County, 44.1% in Morris County, 27.2% in Sussex County, and 24.4% in Warren County. Hunterdon and Morris Counties exceeded the New Jersey statewide proportion of 29.8%, and all but Warren County exceeded the national average of 24.4%. These numbers indicate that the four counties in our analysis are relatively wealthy and well-educated, particularly Hunterdon and Morris Counties, when compared to the rest of the state and the country.[3] If income and education are positively correlated with the utilization of health care (for instance, individuals with higher education may tend to have higher incomes and, consequently, greater access to health care), then our inability to control for health care utilization would result in underestimation of the effect of prenatal exposure to SO_2 on infant health at birth.

With the addition of the birth certificate records, we are also able to perform an additional

[1] We choose to use information from the 2000 Census since this is the time period of interest in our analysis.

[2] Source: U.S. Census Bureau, Census 2000 Summary Files. Retrieved from `http://factfinder.census.gov/faces/nav/jsf/pages/index.xhtml`. (Accessed 14 July 2015).

[3] More recent estimates of median household income indicate that Hunterdon, Morris, and Sussex Counties are among the top 25 richest counties in the country (2012 American Community Survey).

set of analyses that include a richer set of control variables. In particular, the birth certificates provide information related to a mother's prenatal care utilization, including the number of visits during pregnancy, and smoking habits. While they may not paint a complete picture about a mother's health habits during pregnancy, the inclusion of these control variables are likely to provide some degree of information about her overall health habits. Furthermore, the inclusion of a richer set of control variables potentially reduces the downward-bias incurred by an OLS estimator, and we expect that the inclusion of these control variables will reduce the magnitudes of the estimates of the impact of prenatal exposure to SO_2 on infant health at birth.

4.2 Construction of the Instrumental Variable

Following Yang and Chou's identification strategy (2015), we instrument for SO_2 concentrations using direction-adjusted emissions from PGS based on where a particular New Jersey zip code is located relative to PGS. In order to construct our IV, we use the following four-step procedure.[4]

First, we approximate monthly wind direction near PGS, as outlined in Section 3.1.3. We select two NCDC weather stations, one located in Allentown (southwest of PGS) and the other in Wilkes-Barre (northwest of PGS), with complete data on hourly wind direction for the period from January 1994 to December 2006. Using the hourly data, we compute a monthly average for each of the two stations, and then calculate a single monthly average using the two stations' averages for each month. This single average approximates monthly wind direction near PGS.

In the next step, we use latitudinal and longitudinal coordinates to calculate the direction in which each New Jersey zip code centroid is located relative to PGS. As a measure of direction, we use azimuth, which takes into account the curvature of the earth's surface. An

[4]To construct the instrumental variable, we use the Stata code created by Yang and Chou. Please see Yang and Chou (2015) for more details.

azimuth is an angle between two points in a spherical coordinate system (see Figure 4.1). To calculate the azimuth of point B (e.g. a zip code centroid) from point A (e.g. PGS), we project vector $\overrightarrow{AB}$ onto a horizontal plane. The reference vector on this plane is due North, is used for point A (the origin), and has an azimuth of either 0° or 360°. Moving clockwise along a 360° circle, any point that is due East of point A will have an azimuth of 90°, any point due South of point A will have an azimuth of 180°, and any point due West of point A will have an azimuth of 270°. Then, the azimuth of B from A is the angle between the projected vector $\overrightarrow{AB}$ and the reference vector (highlighted in red in Figure 4.1).[5]

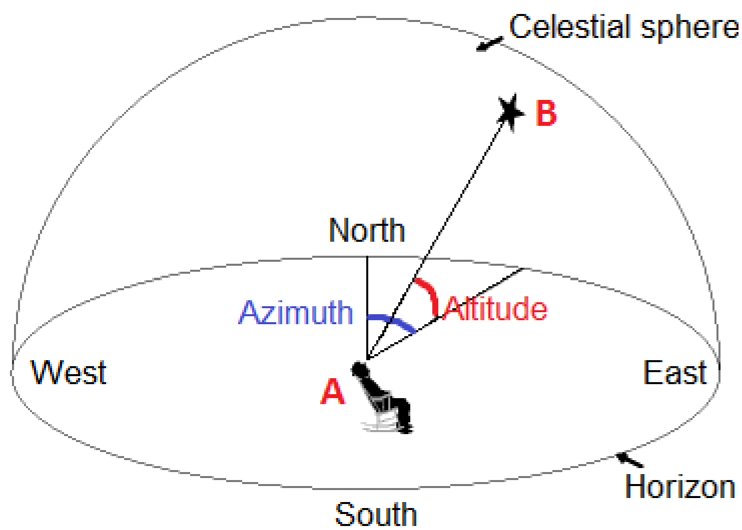

Figure 4.1: Azimuth: A Visual Example

The NCDC data measures wind direction using the meteorological definition: the direction *from which* the wind is blowing. Using this definition, the prevailing wind in the eastern Pennsylvania-western New Jersey region is the westerly wind. In contrast, the wind vector azimuth gives us the direction *toward which* the wind is blowing; using this definition, the prevailing wind in the region is the eastward wind. In order to remain consistent with the measurement of the direction between PGS and a zip code centroid, we will use wind vector

[5]The azimuth of A from B is given by the angle between projected vector $\overrightarrow{BA}$ and the reference vector. It differs from the azimuth of B from A by 180°.

azimuth throughout our study. To convert the meteorological direction to wind vector azimuth, we subtract 180° from the former; if the subtraction results in a negative value, we add 360° to obtain a positive value.

In the third step, we obtain an adjustment factor, which takes on a numerical value between -1 and 1, and varies by month and zip code. The construction of this adjustment factor, which uses the cosine function of the difference between PGS's wind vector azimuth and the azimuth of each New Jersey zip code centroid from PGS, is explained in Yang and Chou (2015). When the adjustment factor takes on the maximum possible value of 1, it indicates that the pollution impact will be largest for zip code centroids located perfectly downwind of PGS. Conversely, if the adjustment factor takes on the minimum possible value of -1, the pollution impact is minimized for zip codes located perfectly upwind of the plant.

As the final step, we multiply the adjustment factor by monthly emissions from PGS. The obtained product serves as our IV, so the instrument is direction-adjusted, varies monthly, and is unique to each New Jersey zip code. Our IV uses two sources of pollution variation that are arguably exogenous to pollution levels in New Jersey: monthly SO_2 emissions from PGS and wind direction near the power plant. One argument in favor of IV exogeneity is that mothers are unaware of the plant's presence unless they live within sight of it (and most residents of New Jersey do not).

4.3 Regression Models using HCUP

In order to estimate the impact of prenatal exposure to SO_2 on infant birth weight, we begin with the following estimation equation:

$$BW_{i,jt} = \alpha_0 Poll_{jt} + \mathbf{x}'_{i,jt}\beta_0 + \mathbf{w}'_{jt}\gamma_0 + z_j + m_t + \varepsilon_{i,jt} \tag{4.1}$$

where $BW_{i,jt}$ represents birth outcomes (birth weight and indicators for LBW and VLBW) for infant i who was born in month-year t and whose mother resides in zip code j. Since the data are cross-sectional, we use the subscript notation of "i,jt", with the inclusion of a comma between i and jt to indicate that there are no repeated observations for infant i across zip codes (indexed by j) and over time (indexed by t). $Poll_{jt}$ is the concentration of SO_2 in month-year t in zip code j; this is constructed according to the four-step procedure mentioned in Section 3.1.1 (including all monitors within a 20-mile radius of j's centroid). α_0 is the OLS estimator of the impact of prenatal exposure to SO_2 during the birth month on the outcome of interest. The vector of control variables, $\mathbf{x}_{i,jt}$, includes the infant's sex, race, and insurance status. Weather variables (monthly mean maximum temperature, monthly mean minimum temperature, monthly mean temperature, monthly total rainfall, and monthly total snowfall) are included in vector $\mathbf{w}_{jt}$. We also include zip code and month-year fixed effects (z_j and m_t, respectively).

However, as explained in Section 4.1, the OLS estimator in equation (4.1) is likely to suffer from downward-bias due to the endogeneity of pollution exposure. Therefore, we apply a two-stage least squares (2SLS) estimator to find the impact of prenatal exposure to SO_2 during the birth month:

$$BW_{i,jt} = \varphi_0 Poll_{jt} + \mathbf{x}'_{i,jt}\beta_0 + \mathbf{w}'_{jt}\gamma_0 + z_j + m_t + u_{i,jt} \tag{4.2}$$

$$Poll_{jt} = \pi_0 IV_{jt} + \mathbf{x}'_{i,jt}\pi_1 + \mathbf{w}'_{jt}\pi_2 + z_j + m_t + v_{jt} \tag{4.3}$$

$$IV_{jt} = emission_t \times \cos(winddir_t - zipdir_j). \tag{4.4}$$

IV_{jt} represents the wind-direction-adjusted SO_2 measure that varies by month and zip code; $emission_t$ represents SO_2 emissions from PGS in month-year t; $winddir_t$ is the wind vector azimuth at PGS in month-year t (i.e. the direction toward which the wind blows near the plant at t); and $zipdir_j$ is the azimuth of zip code j relative to PGS.[6] Equation (4.2) is estimated using 2SLS, and standard errors are clustered at the zip-code-level. Similarly, Currie, Neidell, and Schmieder (2009) compute standard errors clustered at the census-tract-

[6] Azimuth measures the direction in which a zip code j is located relative to PGS.

level.

Since the HCUP data do not contain information about gestational age, we cannot examine the impact of exposure during each of the three trimesters. As a result, the parameter of interest, φ_0, may include the effects of SO_2 exposure prior to and up until the birth month on infant birth weight outcomes. In an attempt to disentangle the effects of exposure during the early stages from the later stages of pregnancy, we estimate a set of equations that includes exposure in the birth month as well as each of the nine months prior to the birth month. We start with an OLS estimator:

$$BW_{i,jt} = \sum_{k=0}^{9} \alpha_k Poll_{j,t-k} + \mathbf{x}'_{i,jt}\beta_0 + \sum_{k=0}^{9} \mathbf{w}'_{j,t-k}\gamma_k + z_j + m_{t-k} + \varepsilon_{i,j,t-k}. \tag{4.5}$$

Again, since the OLS estimator is likely to be downward-biased, we also employ a 2SLS estimator:

$$BW_{i,jt} = \sum_{k=0}^{9} \varphi_k Poll_{j,t-k} + \mathbf{x}'_{i,jt}\beta_0 + \sum_{k=0}^{9} \mathbf{w}'_{j,t-k}\gamma_k + z_j + m_t + u_{i,jt} \tag{4.6}$$

$$Poll_{j,t-k} = \pi_0 IV_{j,t-k} + \mathbf{x}'_{i,jt}\pi_1 + \mathbf{w}'_{j,t-k}\pi_2 + z_j + m_{t-k} + v_{j,t-k} \tag{4.7}$$

$$IV_{j,t-k} = emission_{t-k} \times \cos(winddir_{t-k} - zipdir_j). \tag{4.8}$$

The model defined by equations (4.6)-(4.8) is just-identified, with $IV_{j,t-k}$ as the instrument for $Poll_{j,t-k}$ in order to estimate φ_k (where $k = 0, 1, \ldots, 9$) in equation (4.6). $\sum_{k=0}^{9} \varphi_k$ provides an estimate for the *cumulative* effect of prenatal exposure to SO_2 during pregnancy.

4.4 Robustness Checks and Additional Regressions

As robustness checks, we estimate equations (4.1)-(4.4) and (4.5)-(4.8) using different samples as well as different pollution measures. Our first check includes the addition of Sussex County to the estimation sample. Since Sussex County is located further away from PGS, and since zip codes within the county are less-aligned with wind direction near the plant, we expect that the pollution impact will be smaller for zip codes located in this county. SO_2 that does travel from PGS into Sussex County is more likely to be diluted due to the county's distance and location relative to the plant, so PGS emissions likely have a smaller effect on SO_2 concentrations. As a result, we anticipate that the inclusion of Sussex County to our sample will reduce coefficient magnitudes of the impacts of prenatal exposure to SO_2 on infant health at birth.

Our second check includes only Warren County in the estimation sample. Due to its proximity to PGS, emissions from the plant will most greatly affect zip-code-level SO_2 concentrations in this county as compared to any other county in New Jersey. Therefore, we also expect SO_2 concentrations to be highest in Warren County. However, many residents of Warren County are within eyesight of the power plant, and given its geographic proximity to the plant, many residents can actually smell SO_2 emissions from the plant. As a result, the possibility exists that many residents take precautionary measures to reduce their exposure to ambient SO_2. The case for this type of behavior becomes even stronger for pregnant mothers, who may choose to stay indoors during days of particularly high concentrations. Due to the potential presence of such behaviors, IV exogeneity may be violated, and the IV estimator likely suffers from the same bias as the OLS estimator. Consequently, we expect similarity between OLS and 2SLS estimates and anticipate a zero-effect of prenatal exposure to SO_2 on infant health at birth.

As another check, we include all four counties in the estimation sample. We expect coefficient magnitudes to become smaller and insignificant compared to estimates using the sample that excludes Warren County for the reasons just mentioned. Lastly, we estimate these equations for all other counties in New Jersey; since these counties were not identified according to the institutional setting, we expect to find no effect. These counties are further away from PGS and are not aligned with wind direction near the plant, so we do not expect that SO_2 emissions from PGS traveled into these counties and affected SO_2 concentrations and, consequently, infant health at birth.[7] For additional checks, we also estimate the aforementioned equations using pollution (and weather) measures that are constructed using a 25-mile radius for the various estimation samples outlined above.

4.5 Regression Models using Birth Certificates

In addition to the models outlined in Section 4.3, we estimate another set of models using the New Jersey birth certificate records. Since the dependent and independent variables are different, we make note of the estimation equations. To begin, we estimate the impact of prenatal exposure to SO_2 on birth outcomes using an OLS estimator:

$$O_{i,jt} = \alpha_0 Poll_{jt} + x_{i,jt}\beta_0 + \mathbf{g}'_{i,jt}\delta_0 + s_{i,jt}\eta_0 + \mathbf{w}'_{jt}\gamma_0 + z_j + m_t + \varepsilon_{i,jt}, \tag{4.9}$$

where $O_{i,jt}$ represents birth outcomes (birth weight, LBW and VLBW dummies; 1-minute and 5-minute APGAR scores, dummies for normal 1-minute and 5-minute APGAR scores; pre-term dummy) for infant i who was born in month-year t and whose mother resides in zip code j. Similar to equation (4.1), we use the subscript notation of "i,jt", with the inclusion of a comma between i and jt to indicate that there are no repeated observations for an infant across zip codes and over time. $Poll_{jt}$ is the concentration of SO_2 in month-year t in zip code j; this is constructed according to the aforementioned four-step procedure (including all monitors within a 20-mile radius of j's centroid). α_0 is the OLS estimator of the impact of prenatal exposure to SO_2 during the birth month on the outcome of interest. $x_{i,jt}$ represents the infant's sex. Maternal characteristics included in $\mathbf{g}_{i,jt}$ are the prenatal visit categories (no visits; 1-9; 10-18; 19-27; 27-36; 37+), race (white, black, Asian, other race), and ethnicity (Hispanic or not); $s_{i,jt}$ represents mother's smoking status. Weather variables (monthly mean maximum temperature, monthly mean minimum temperature, monthly mean temperature, monthly total rainfall, and monthly total snowfall) are included in vector $\mathbf{w}_{jt}$. Zip code and

[7] Results from estimations including all other New Jersey counties are not included in subsequent sections. They are available upon request.

month-year fixed effects (z_j and m_t, respectively) are also included.

In addition to the OLS estimator described in equation (4.9), we estimate the impact of prenatal exposure to SO_2 using a 2SLS estimator:

$$O_{i,jt} = \varphi_0 Poll_{jt} + x_{i,jt}\beta_0 + \mathbf{g}'_{i,jt}\delta_0 + s_{i,jt}\eta_0 + \mathbf{w}'_{jt}\gamma_0 + z_j + m_t + u_{i,jt} \tag{4.10}$$

$$Poll_{jt} = \pi_0 IV_{jt} + x_{i,jt}\pi_1 + \mathbf{w}'_{jt}\pi_2 + \mathbf{g}'_{i,jt}\pi_3 + s_{i,jt}\pi_5 + z_j + m_t + v_{jt} \tag{4.11}$$

$$IV_{jt} = emission_t \times \cos(winddir_t - zipdir_j). \tag{4.12}$$

The model defined by equations (4.10)-(4.12) is analogous to the model described by equations (4.2)-(4.4), excepting the differences in dependent and independent variables. The estimation samples used are the same as those outlined in Sections 4.3 and 4.4. The primary sample consists of Hunterdon and Morris Counties. As robustness checks, we add Sussex County, and then Warren County to the samples. We also estimate the models using only Warren County and, finally, for all other counties in New Jersey.[8]

[8] Results for all other New Jersey counties are not included in subsequent sections. They are available upon request.

Chapter 5

Results

This chapter overviews summary statistics and regression results for the primary analysis sample that includes Hunterdon and Morris Counties. In Section 5.1, we provide summary statistics related to PGS, pollution and weather variables, and outcome and demographic variables. Section 5.2 examines the first-stage results of the impact of PGS emissions on SO_2 concentrations in New Jersey. Finally, Section 5.3 reviews results for the impact of prenatal exposure to SO_2 on infant birth weight and related outcomes for Hunterdon and Morris Counties.

5.1 Summary Statistics

5.1.1 PGS, Pollution, and Weather Variables

Table 5.1 shows summary statistics for Portland Generating Station as well as each of the four New Jersey counties included in our analysis for the sample period of January 1995 to December 2006. Panel A shows that SO_2 emissions from PGS averaged over 2,100 tons per month, indicating yearly emissions in excess of 25,000 tons. Direction-adjusted emissions, which average nearly 1,400 tons per month, are uniformly lower due to the downward-adjustment by the cos() function. Unless a zip code is located perfectly downwind of the plant (i.e. the adjustment factor takes on a value of 1), PGS emissions are multiplied by a factor smaller than 1, so direction-adjusted emissions are always smaller than unadjusted emissions. Finally, average wind direction near PGS is approximately 148°, meaning that wind near the plant blows south-southeastwards. While some variation exists in wind direction near the plant, depending on the time of year, the wind direction is generally southeast or south-southeast (not shown).

Next, we focus our attention to Panels B and C of Table 5.1, showing SO_2 concentrations and distance and direction between PGS and each of the four counties in our analysis. As expected, SO_2 concentrations, averaging about 13.8 ppb per month, are highest in Warren County, which is located closest to PGS. Zip codes in this county are, on average, about 10.5 miles away from the plant and located about 134°, or southeast, of the plant. Despite zip codes being located, on average, over 22 miles away from PGS (more than twice the distance of zip codes located in Warren County), Hunterdon County experienced SO_2 concentrations (13.6 ppb) that were nearly as high as those experienced in Warren County. This is likely explained by the fact that zip codes in Hunterdon County are located downwind of the plant; on average, about 155°, or south-southeast of the plant, the same direction toward which the wind blows near PGS. In Morris County, SO_2 concentrations averaged around 11.8 ppb per month; zip codes are located over 30 miles away from the plant; and zip codes are located about 97° relative to the plant, i.e. east. Sussex County, located just over 20 miles away from PGS, averaged monthly SO_2 concentrations of about 10.4 ppb, the lowest of the four counties. This is likely because of the direction in which zip codes are located relative to PGS: 76°, or east-northeast.

Panel D overviews summary statistics for our constructed weather variables (see 3.1.3) for each of the four counties. Since they are located in close geographic proximity, temperatures are very similar across the four counties, ranging from a monthly average minimum of about 40°F to a monthly average maximum of about 60°F. Over the entire sample period, monthly mean temperatures averaged 50°F. In terms of precipitation, Hunterdon and War-

Table 5.1: Summary Statistics, Part I

Panel A: Portland Generating Station (PGS)				
PGS SO_2 monthly emissions (in 1,000 tons)				2.115
				(0.726)
PGS SO_2 monthly emissions (in 1,000 tons), direction-adjusted				1.395
				(0.829)
Wind speed (miles per hour) near PGS				6.941
				(1.275)
Direction towards which the wind near PGS blows[a]				147.652
				(16.991)
# of observations (four New Jersey counties)				10,859
Panel B: SO_2 Pollution, by NJ County				
	Hunterdon	Morris	Sussex	Warren
SO_2 (ppb), zip code level, inverse-distance weighted, monthly average of the one-hour daily maximum concentrations	13.614	11.767	10.365	13.823
	(5.160)	(3.765)	(3.892)	(5.656)
# of SO_2 monitors within a 20-mile radius of zip code centroid	1.698	3.003	1.000	1.768
	(0.649)	(2.380)	(0.000)	(0.853)
# of observations	2,221	6,391	771	1,476
Panel C: Between PGS and NJ Zip Codes, by NJ County				
	Hunterdon	Morris	Sussex	Warren
Distance (miles) between a New Jersey zip code centroid and PGS	22.409	30.888	20.264	10.509
	(5.334)	(6.800)	(3.129)	(3.308)
Direction towards which a New Jersey zip code is located relative to PGS[a]	155.224	96.988	75.902	133.914
	(14.665)	(9.865)	(9.194)	(41.272)
# of observations	2,221	6,391	771	1,476
Panel D: Weather Variables, by NJ County				
	Hunterdon	Morris	Sussex	Warren
monthly mean maximum temperature (°F)	62.011	61.835	60.417	59.643
	(16.018)	(16.436)	(16.407)	(16.095)
monthly mean minimum temperature (°F)	40.734	41.449	39.395	39.351
	(14.903)	(15.079)	(14.945)	(15.256)
monthly mean temperature (°F)	51.370	51.644	49.903	49.498
	(15.394)	(15.710)	(15.628)	(15.601)
monthly total rainfall (inches)	4.316	4.021	3.876	4.315
	(2.535)	(2.102)	(2.189)	(3.251)
monthly total snowfall (inches)	2.392	2.445	3.128	3.159
	(5.210)	(5.054)	(5.855)	(6.085)
# of observations	2,221	6,391	771	1,476

[a] 0° = North, 90° = East, 180° = South, 270° = West

Notes: Standard errors shown in parentheses. Data are from AMPD, AQS, and NCDC. Sample period for this table is January 1995 to December 2006. Please see the following sections for construction of variables: SO_2 concentrations (3.1.1); azimuth of wind and zip code direction (3.1.3 and 4.2); weather variables (3.1.3); and direction-adjusted SO_2 emissions (4.2).

ren Counties experience more rainfall than Sussex County by about 0.5 inches per month; while Sussex and Warren Counties experience more snowfall, about 0.5 inches, on average, per month.

5.1.2 Outcome and Demographic Variables

In Table 5.2, we observe summary statistics for the various birth weight and demographic variables constructed using the HCUP data for Hunterdon, Morris, Sussex, Warren, and all other New Jersey Counties.

Birth weight in the four counties averaged over 3,400 grams (or 7.5 pounds) for the sample period ranging from January 1995 to December 2006. In all other New Jersey counties, birth weight averaged about 100 grams lower (or 0.25 pounds) than these four counties. The proportion of LBW[1] ranged from 3.9% in Hunterdon County to 4.6% in Warren County. For all four counties, the percentage of LBW was lower than all other counties in New Jersey (6.2%). Across the four counties, the percentage of VLBW[2] ranged from 0.6% in Hunterdon County to 1.0% in Sussex County; other counties in New Jersey averaged 1.1% during this period. The proportion of infants born extremely immature due to short gestation[3] ranged from 4.3% in Morris County to 5.9% in Hunterdon County; all four saw proportions lower than other New Jersey counties (6.3%).

Demographically, we observe similarity across the four counties in our analysis sample, but they largely differ from other counties in the state. The only exception is gender–just under one-half of all births were female (∼49%) across all counties in New Jersey. The four counties are largely white, ranging from 80.1% in Morris County to 94.5% in Sussex County; these percentages are substantially greater than the percentage of white in all other New Jersey counties (53.7%). Furthermore, the percentage of blacks is much lower in the four counties (1.7% in Sussex to 2.6% in Morris) than all other New Jersey Counties (16.2%).

[1] An infant is defined as LBW if birth weight is less than 2,500 grams (or about 5.5 pounds).
[2] An infant is defined as VLBW if birth weight is less than 1,500 grams (or about 3.3 pounds).
[3] For construction of this variable, please see 3.1.4.

Table 5.2: Summary Statistics, Part II

	Hunterdon	Morris	Sussex	Warren	Other NJ Counties
Birth weight (grams)	3,453.105	3,422.970	3,458.143	3,432.789	3,337.659
	(539.444)	(562.441)	(563.146)	(559.930)	(584.796)
Low birth weight (1/0):	0.039	0.043	0.042	0.046	0.062
birth weight < 2,500 grams	(0.195)	(0.204)	(0.201)	(0.209)	(0.241)
Very low birth weight (1/0):	0.006	0.009	0.010	0.007	0.011
birth weight < 1,500 grams	(0.077)	(0.095)	(0.100)	(0.085)	(0.104)
Extreme immaturity relating	0.059	0.043	0.049	0.045	0.063
to short gestation (1/0)	(0.235)	(0.203)	(0.217)	(0.207)	(0.243)
Female (1/0)	0.487	0.485	0.491	0.492	0.487
	(0.500)	(0.500)	(0.500)	(0.500)	(0.500)
White (1/0)	0.890	0.801	0.945	0.903	0.537
	(0.313)	(0.399)	(0.227)	(0.296)	(0.499)
Black (1/0)	0.017	0.026	0.012	0.020	0.162
	(0.130)	(0.159)	(0.107)	(0.139)	(0.369)
Hispanic (1/0)	0.047	0.065	0.013	0.034	0.177
	(0.211)	(0.246)	(0.113)	(0.181)	(0.382)
Asian (1/0)	0.022	0.055	0.012	0.016	0.047
	(0.145)	(0.228)	(0.107)	(0.124)	(0.211)
Medicare (1/0)	0.000	0.001	0.001	0.001	0.001
	(0.018)	(0.033)	(0.034)	(0.024)	(0.023)
Medicaid (1/0)	0.037	0.057	0.062	0.074	0.142
	(0.189)	(0.233)	(0.240)	(0.261)	(0.349)
Private insurance (1/0)	0.910	0.872	0.893	0.857	0.755
	(0.286)	(0.334)	(0.310)	(0.350)	(0.430)
Self-pay (1/0)	0.039	0.050	0.028	0.035	0.084
	(0.193)	(0.217)	(0.164)	(0.184)	(0.277)
# of observations	15,809	63,241	18,405	13,646	1,079,491

Notes: Standard errors are shown in parentheses. Data are from the HCUP SID for New Jersey. Sample period includes January 1995 to December 2006. The SID data are released by year and recorded as repeated cross sections. Summary statistics are based on the sample including live singleton births and excluding multiple births.

The proportion of Hispanics is also much lower in the four counties (ranging from 1.3% to 6.5%) than the rest of New Jersey (17.7%).

While private insurance serves as the dominant form of insurance across all counties in New Jersey, the percentages of privately insured are higher in the four counties in our analysis sample (85.7% in Warren County to 91.0% in Hunterdon County) than all other counties in the state (75.5%). Since insurance status applies to mothers of newborns, the percentage covered by Medicare is virtually null, as might be expected. However, we notice that the proportion using Medicaid varies; across the four counties, it ranges from a low of 3.7% in Hunterdon to a high of 7.4% in Warren. Still, the use of Medicaid is lower in the four counties than in all other counties in New Jersey (14.2%).

In accordance with our prior discussion of income and educational attainment in the four counties (see Section 4.1), the summary statistics provide evidence supporting the idea of a positive association between birth outcomes and higher incomes. In particular, Hunterdon County, the wealthiest county in our sample, saw the lowest proportions of LBW and VLBW infants (3.9% and 0.6%, respectively) during the sample period. It also had the highest proportion of privately insured (91.0%) and lowest percentage of Medicaid (3.7%).

5.2 Impact of PGS Emissions on SO_2 Concentrations in New Jersey

Table 5.3 shows first-stage results of the impact of SO_2 emissions from PGS on SO_2 concentrations in New Jersey zip codes (equation (4.3)). When the direction in which a zip code is located is aligned with the direction toward which the wind blows near the plant, SO_2 emissions from PGS indeed affect SO_2 concentrations in zip codes located in Hunterdon, Morris, Sussex, and Warren Counties in New Jersey. As expected, the impact of PGS SO_2 emissions is largest in Warren County–a 1,000-ton-increase in emissions increases SO_2 concentrations by about 1.77 ppb (columns (1) and (2)), which translates into a 12.8% increase at the mean concentration (13.823 ppb). We expect the SO_2 emissions impact to be largest for Warren County for two main reasons. First, given its geographic proximity to the plant (with zip codes located, on average, only 10.5 miles away from the plant and some right in the neighborhood of the plant), emissions do not have to travel very far to reach zip codes in Warren County; therefore, the likelihood of dilution or even dissipation of the emitted SO_2 is low. Second, since zip codes in Warren County are located southeast of the plant, and since wind direction near the plant ranges between southeast and south-southeast depending on the time of year, zip codes in this county are frequently aligned with wind direction near the plant. Given that the emissions do not have to travel far and that the wind can blow it easily, the finding that Warren County is most largely affected by SO_2 emissions from PGS is not surprising.

Table 5.3: Impact of PGS SO_2 Emissions on SO_2 Concentrations Near NJ Zip Codes

	Warren		Hunterdon & Morris		Hunterdon, Morris, & Sussex		Hunterdon, Morris, Sussex, & Warren		Other NJ Counties	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PGS SO_2 emissions$^\diamond$	1.769***	1.763***	0.932***	0.931***	0.768***	0.768***	1.041***	1.040***	-0.108	-0.109
	(0.405)	(0.405)	(0.228)	(0.228)	(0.218)	(0.218)	(0.177)	(0.177)	(0.091)	(0.090)
Individual-level demographics	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	77	77	85	85	102	102	495	495
# of observations	11,903	11,903	70,165	70,165	79,776	79,776	91,679	91,679	875,823	875,823

$^\diamond$ PGS SO_2 monthly emissions (in 1,000 tons), direction-adjusted
Notes: Dependent variable in all specifications is the zip-code-level, inverse-distance-weighted, monthly average of SO_2 (in ppb). All specifications include weather variables, year-month (monthly) fixed effects, and zip code fixed effects. Standard errors are shown in parentheses. Standard errors are clustered at the zipcode level. Significance: * 10% level; ** 5% level; *** 1% level.

For zip codes in Hunterdon and Morris Counties (columns (3) and (4)), a 1,000-ton-increase in PGS emissions increases SO_2 concentrations by 0.93 ppb. While we might expect the magnitude to be relatively large for Hunterdon given its location relative to the plant (it is located south-southeast, nearly perfectly aligned with wind direction near the plant), the fact that zip codes are, on average, 22 miles away from the plant means that SO_2 has to travel further, and the chances of emissions reaching zip codes in Hunterdon are lower when compared to Warren County. Keeping this fact in mind about Hunterdon County, the inclusion of Morris County likely reduces the impact estimate since it is located east-southeast of the plant (less aligned with wind direction near the plant, so emissions do not travel as easily into zip codes) and are located further away (over 30 miles, on average). For Hunterdon and Morris Counties, since SO_2 emissions must travel a greater distance (an additional 10 to 20 miles as compared to zip codes in Warren County), and since zip codes in Morris County are less-aligned with wind direction near the plant, the estimates of the impact of PGS SO_2 emissions on zip-code-level concentrations are smaller in magnitude. Unsurprisingly, the addition of Sussex County to the latter sample further reduces the estimate to 0.77 ppb (columns (5) and (6)). This reduction is attributable to the fact that zip codes in Sussex County are least-aligned with wind direction near the plant (located east-southeast of the plant) and are located over 20 miles away, on average. Given the distance and the direction that the PGS emissions need to travel, the likelihood of these emissions reaching zip codes in Sussex County is much lower. Therefore, the PGS emissions impact estimate for the sample including all three counties is smaller.

With the inclusion of all four counties (columns (7) and (8)), a 1,000-ton-increase in PGS emissions results in a 1.04 ppb increase in SO_2 concentrations in zip codes located in these counties. This estimate is smaller than the estimate for Warren County by itself but larger than the estimates for the other two samples (Hunterdon and Morris; Hunterdon, Morris, and Sussex). The results indicate that the impact is very strong in Warren County and likely in Hunterdon County as well; and though Morris and Sussex Counties are significantly affected, their locations and distances relative to the plant reduce the size of the impact estimates when these two counties are added to the sample. As verification, we also estimate the impact of PGS SO_2 emissions on concentrations in all other New Jersey counties (columns (9) and (10)) and find a statistically insignificant effect. In other words, while PGS emissions affected SO_2 concentrations in the four identified counties, they did not affect concentrations in other New Jersey counties that were not identified in the NJDEP's petitions. The first-stage results make a strong case for the use of this empirical setting as our identification strategy ([Yang and Chou, 2015]).

In order for the instrument (direction-adjusted SO_2 emissions) to be truly exogenous, it must be independent of uncontrolled variables that are correlated with birth outcomes and zip-code-level pollution measures. While we cannot directly test for IV independence given our data, we are, however, able to provide some evidence for instrument exogeneity. By estimating the first-stage with the inclusion (even-numbered columns) and without the inclusion (odd-numbered columns) of individual-level demographic variables,[4] we can at least determine if the IV is uncorrelated with individual-level observables. Since estimates with and without the inclusion of these demographic variables are very similar in Table 5.3, the IV is likely to be uncorrelated with these observables. Therefore, we can reasonably say that the IV is perhaps uncorrelated with some important unobserved variables in our data, such as maternal health care utilization, which may be positively correlated with infant health at birth but negatively correlated with ambient air quality.

5.3 Impact of Prenatal Exposure to SO_2 on Infant Birth Weight and Related Outcomes

In the following sections, we examine the impact of prenatal exposure to sulfur dioxide on infant birth weight, the likelihood of low birth weight (LBW), and the likelihood of very low birth birth weight (VLBW). Our primary sample includes infants whose mothers have zip codes of residence in Hunterdon and Morris Counties. In Section 5.3.1, we consider results from equations (4.1) and (4.2)-(4.4); in Section 5.3.2, we consider results from equations (4.5) and (4.6)-(4.8).

[4] Demographic variables include sex, race, and insurance status.

5.3.1 Exposure During the Birth Month

Table 5.4 shows estimates of the impact of prenatal exposure to SO_2 during the month of birth on infant birth weight in Hunterdon and Morris Counties. Panel A reveals that the OLS estimates detect no statistically significant effect of SO_2 exposure on birth weight, LBW, or VLBW. The predicted zero-effect is expected due to the downward-bias incurred by the OLS estimator, as discussed in Section 4.1.

Table 5.4: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon and Morris Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	1.432	1.227	0.000	0.000	0.000***	0.000***
	(1.298)	(1.290)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	77	77	77	77	77	77
# of observations	70,165	70,165	70,165	70,165	70,165	70,165
Panel B: 2SLS Estimates						
X_t	1.780	1.512	0.005*	0.005*	0.004***	0.004***
	(9.599)	(9.378)	(0.003)	(0.003)	(0.002)	(0.002)
First-stage partial F		16.664		16.664		16.664
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	77	77	77	77	77	77
# of observations	70,165	70,165	70,165	70,165	70,165	70,165

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

In Panel B, which includes 2SLS estimates, we find statistically significant effects on LBW and VLBW, though no effect on birth weight. According to the estimates, a 1-ppb increase in prenatal exposure to SO_2 during the birth month increases the likelihood of LBW by 0.5 percentage points and the likelihood of VLBW by 0.4 percentage points. Since the proportions of LBW and VLBW are about 4.2% and 0.84%, respectively, in these two counties, the estimates indicate a 11.9% (= 0.5/4.2) relative increase in LBW and 47.6% (= 0.4/0.84) relative increase in VLBW. Additionally, we observe the first-stage partial F-statistic, which equals 16.66 (columns (2), (4), and (6)). Since this value exceeds 10, the norm used in the detection of a weak instrumental variable, the statistic provides evidence for a relatively strong instrument.

5.3.2 Exposure During the Months Prior to and Including the Birth Month

Table 5.5 shows estimates for equation (4.5), OLS estimates of the impact of prenatal exposure to SO_2 during each of the nine months prior to and including the birth month on infant birth weight and related outcomes. As expected, the estimates are downward-biased–generally opposite-signed and insignificant from zero. For LBW (columns (3) and (4)), the impact in the six month prior to birth is significant and positive; however, this impact becomes negative and significant in the seventh and eighth months prior to the birth month; in the ninth month prior to birth, the impact is once again positive. For the impact on VLBW (columns (5) and (6)), we observe positive and statistically significant coefficient for exposure during the month of birth as well as the fourth and ninth months prior to birth; we observe a negative coefficient in the eighth month prior to birth.

Table 5.6 shows results for equation (4.6), 2SLS estimates of the impact of prenatal exposure to SO_2 during each of the nine months prior to and including the month of birth on infant birth weight and related outcomes. In columns (1) and (2), we observe generally insignificant effects on birth weight, with the exception of the fifth and seventh months prior to birth, where the coefficients actually indicate increases in birth weight. Columns (3) and (4) show the effect of prenatal exposure on LBW. The coefficient for the impact during the birth month is correctly-signed and significant; interestingly, it is now larger (1.6 percentage points) than the previous estimate from Table 5.4, which indicates only a 0.5 percentage point increase in the likelihood of LBW. We also observe a statistically

Table 5.5: OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon and Morris Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight $<$ 2,500g)		Very low birth weight◇ (birth weight $<$ 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	0.762	0.870	0.001	0.001	0.001***	0.001***
	(1.461)	(1.473)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-1}	-0.457	-0.548	0.000	0.000	-0.000	-0.000
	(1.597)	(1.575)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-2}	0.432	0.463	-0.000	-0.000	-0.000	-0.000
	(1.642)	(1.608)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-3}	1.756	1.439	-0.000	-0.000	0.000	0.000
	(1.288)	(1.297)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-4}	-0.954	-1.092	0.000	0.000	0.001***	0.001***
	(1.693)	(1.614)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-5}	1.047	1.321	-0.000	-0.000	-0.000	-0.000
	(1.665)	(1.681)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-6}	-0.518	-0.249	0.001*	0.001*	0.000**	0.000**
	(1.524)	(1.483)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-7}	0.415	0.330	-0.001***	-0.001***	-0.000	-0.000
	(1.402)	(1.411)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-8}	3.021*	2.539	-0.002***	-0.002***	-0.001***	-0.001***
	(1.623)	(1.640)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-9}	-2.820*	-2.654	0.001**	0.001**	0.000***	0.001***
	(1.665)	(1.639)	(0.000)	(0.000)	(0.000)	(0.000)
$X_t + X_{t-1} + \cdots + X_{t-9}$		2.420		-0.001		0.000
		(2.487)		(0.001)		(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	77	77	77	77	77	77
# of observations	69,803	69,803	69,803	69,803	69,803	69,803

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

significant increase in the probability of LBW for exposure during the second month prior to birth. A puzzling result is the negative and significant coefficient for the seventh month prior to birth, although this may be attributable to the fact that we are unable to identify gestational age. Compared to the OLS estimate (-0.1 percentage points), the 2SLS estimate of the cumulative impact is positive and relatively large (0.9 percentage points), though still insignificant. This coefficient translates into a 21.4% (= 0.9/4.2) increase in the occurrence of LBW in Hunterdon and Morris Counties; this is larger than the estimate obtained using the model that only measures exposure during the birth month (see Table 5.4).

In columns (5) and (6), we observe the impact of exposure on VLBW. Again, the estimate for exposure during the birth month is larger (1.0 percentage point) than the original estimate of 0.4 percentage points (see Table 5.4). We also see a positive and statistically significant effect during the second month prior to birth. Interestingly, the coefficients for the fifth and seventh months prior to birth are negative and significant, which, again, may be attributable to our inability to identify gestational age. However, with the inclusion of all months up to and including the birth month, prenatal exposure to SO_2 increases the likelihood of VLBW by 0.7 percentage points, which is 75% larger than the initial estimate of 0.4 percentage points. At the mean proportion of VLBW in Hunterdon and Morris Counties, the estimate translates into an 83.3% (= 0.7/0.84) increase in VLBW.

Table 5.6: 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon and Morris Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	-27.614	-27.029	0.016**	0.016**	0.010**	0.010**
	(22.978)	(22.523)	(0.007)	(0.007)	(0.004)	(0.004)
X_{t-1}	16.186	16.530	0.004	0.004	0.001	0.001
	(20.167)	(19.350)	(0.005)	(0.005)	(0.002)	(0.002)
X_{t-2}	-24.075	-23.131	0.013**	0.013**	0.009**	0.009**
	(16.888)	(17.800)	(0.006)	(0.006)	(0.004)	(0.004)
X_{t-3}	41.508	40.045	-0.005	-0.005	-0.002	-0.002
	(29.640)	(29.467)	(0.007)	(0.007)	(0.004)	(0.004)
X_{t-4}	-10.072	-9.899	0.007	0.007	0.005	0.005
	(20.343)	(19.924)	(0.008)	(0.007)	(0.004)	(0.004)
X_{t-5}	42.998	45.184*	-0.009	-0.010	-0.006*	-0.007*
	(27.011)	(26.790)	(0.007)	(0.007)	(0.003)	(0.004)
X_{t-6}	-61.700	-64.369	0.003	0.003	0.003	0.003
	(51.631)	(50.922)	(0.012)	(0.012)	(0.006)	(0.006)
X_{t-7}	82.584*	81.440*	-0.027**	-0.027**	-0.018**	-0.018**
	(45.156)	(45.593)	(0.013)	(0.013)	(0.008)	(0.008)
X_{t-8}	-89.949	-84.752	0.022	0.021	0.010	0.010
	(75.177)	(74.365)	(0.022)	(0.022)	(0.011)	(0.011)
X_{t-9}	65.036	60.860	-0.016	-0.015	-0.006	-0.006
	(48.739)	(48.504)	(0.015)	(0.015)	(0.008)	(0.008)
$X_t + X_{t-1} + \cdots + X_{t-9}$		34.880		0.009		0.007*
		(28.257)		(0.008)		(0.004)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	77	77	77	77	77	77
# of observations	65,424	65,424	65,424	65,424	65,424	65,424

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Chapter 6

Robustness Checks

In order to supplement our analyses from Chapter 5, we run all models discussed in Section 4.3 using different samples (Section 6.1). First, we add Sussex County to the sample including Hunterdon and Morris; then, we add Warren County. Additionally, we run our estimations including only Warren County in the sample. In the second set of regressions (Section 6.2), we run all of our models using a 25-mile radius in constructing the pollution and weather measures. For all estimation samples and outcomes, we run two sets of models–one that includes no individual-level demographic variables (only controls for weather), and another that includes demographics (infant's race, sex, insurance status).[1]

6.1 Additional Estimation Samples

6.1.1 Impact of Prenatal Exposure to SO_2 During the Birth Month on Infant Birth Weight and Related Outcomes

Hunterdon, Morris, and Sussex Counties

Table 6.1 shows results with the inclusion of Sussex County to our sample. In Panel A, we observe no statistically significant impact of prenatal exposure to SO_2 on infant birth weight

[1]See Sections 4.3 and 4.4 for more details.

or related outcomes, as predicted using the downward-biased OLS estimator. However, Panel B verifies our results from the previous chapter. Exposure to SO_2 during the month of birth increases the likelihood of LBW and VLBW by 0.5 and 0.4 percentage points, respectively. According to these estimates, LBW increases by about 11.9% (= 0.5/4.2) and VLBW increases by about 46.0% (= 0.4/0.87). The first-stage partial F-statistic equals 12.42, providing evidence for a relatively strong instrument.

Table 6.1: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	1.254	1.055	0.000	0.000	0.000***	0.000***
	(1.238)	(1.241)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	85	85	85	85	85	85
# of observations	79,776	79,776	79,776	79,776	79,776	79,776
Panel B: 2SLS Estimates						
X_t	0.274	-0.366	0.005*	0.005*	0.004**	0.004**
	(9.816)	(9.451)	(0.003)	(0.003)	(0.002)	(0.002)
First-stage partial F		12.421		12.421		12.421
p-value for first-stage partial F		0.001		0.001		0.001
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	85	85	85	85	85	85
# of observations	79,776	79,776	79,776	79,776	79,776	79,776

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Hunterdon, Morris, Sussex, and Warren Counties

Table 6.2 estimates equations (4.1) and (4.2) with the addition of Warren County to the estimation sample. Again, as expected, the OLS estimates show a statistically insignificant effect (Panel A). However, in Panel B, we notice that the coefficient for the impact on LBW is now much smaller and insignificant (one-fifth the magnitude of the original estimate) while

Table 6.2: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	0.214	-0.086	0.000	0.000	0.000***	0.000***
	(0.887)	(0.899)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	102	102	102	102	102	102
# of observations	91,679	91,679	91,679	91,679	91,679	91,679
Panel B: 2SLS Estimates						
X_t	-4.291	-4.621	0.001	0.001	0.002***	0.002***
	(5.152)	(4.900)	(0.002)	(0.002)	(0.001)	(0.001)
First-stage partial F		34.660		34.660		34.660
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	102	102	102	102	102	102
# of observations	91,679	91,679	91,679	91,679	91,679	91,679

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

the coefficient for VLBW is one-half of the magnitude (0.2 percentage points) reported using the previous estimation samples that exclude Warren County. At the mean proportion of VLBW in these four counties, the estimate translates into a 23.5% (= 0.2/0.85) increase in VLBW.

Warren County

Finally, we estimate equations (4.1) and (4.2) using only Warren County (Table 6.3). We note a strong divergence from the patterns observed in our previous results (Tables 5.4, 6.1, and 6.2), as might be expected. First, the coefficients for VLBW are insignificant from zero. Second, the 2SLS estimates for LBW are negative and actually smaller than the OLS estimates (-0.3 and 0.1 percentage points, respectively). Lastly, the impact on birth weight is statistically significant and negative; coefficients were previously insignificant from zero.

Table 6.3: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Warren County)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-2.618*	-2.844*	0.001*	0.001*	0.000***	0.000***
	(1.390)	(1.498)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	11,903	11,903	11,903	11,903	11,903	11,903
Panel B: 2SLS Estimates						
X_t	-10.602***	-10.161***	-0.003*	-0.003*	0.001	0.001
	(3.811)	(3.339)	(0.002)	(0.002)	(0.000)	(0.000)
First-stage partial F		18.998		18.998		18.998
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	11,903	11,903	11,903	11,903	11,903	11,903

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

On one the hand, the results in Table 6.3 may explain why coefficient magnitudes shrink with the addition of Warren County to the estimation sample that includes Hunterdon, Morris, and Sussex Counties. At the same time, the results also indicate the potential practice of health protection behaviors by residents of Warren County. Recall that Warren County is located immediately next to PGS, separated only by the Delaware River. In fact, for some residents of Warren County, PGS is within eyesight. Even for residents who cannot see the power plant, they may still be able to smell SO_2 in the air since its pungent odor can be detected at concentrations as low as 3 parts per million ([Singh, 1989]). For residents who can see the plant or who can smell the emissions, the possibility exists that they have taken precautionary measures to mitigate the potential impact of the pollution emitted from the plant. For instance, if residents are able to see or smell higher emissions of SO_2 on a given day, or even a given part of the day, they may choose to stay indoors in order to minimize their exposure to the ambient air; while indoors, they may keep windows and doors closed and run air conditioning so that some of the pollutants are filtered out of the air upon entering the home. If such precautionary measures are effective, particularly among pregnant women, then the impact of prenatal exposure to SO_2 is mitigated, or even eliminated, so that the estimates are reduced to zero or even become negative. Additionally, the possibility remains that pregnant women residing in this county may adjust their health behaviors because of their proximity to the power plant. If this is true, then the IV becomes endogenous since it is now correlated with these health-promoting behaviors that can affect infant birth outcomes. The similarity in the OLS and 2SLS estimates (in Panels A and B, respectively) indicate that both estimators likely suffer from the same bias.

6.1.2 Impact of Prenatal Exposure During the Months Prior to and Including the Birth Month on Infant Birth Weight and Related Outcomes

Hunterdon, Morris, and Sussex Counties

Table 6.4 shows results for equation (4.5) for the sample including Hunterdon, Morris, and Sussex Counties. The addition of Sussex County does not change the estimates. All coefficients for the impact of SO_2 exposure during the months prior to and including the birth month on birth weight are small in magnitude and insignificant. For LBW, we still see significant results for the sixth, seventh, eighth, and ninth months prior to birth; however, the coefficients for exposure during the seventh and eighth months are wrong-signed. For VLBW, coefficients for exposure during the birth month are positive and significant. However, as mentioned before, the OLS estimates are downward-biased, which likely explains why incorrectly-signed results are observed.

Table 6.5 shows 2SLS estimates for the sample including Hunterdon, Morris, and Sussex Counties. In general, the results are similar to those observed in Table 5.6. Oddly, the impact

Table 6.4: OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, and Sussex Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	0.754	0.802	0.000	0.000	0.001***	0.001***
	(1.375)	(1.404)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-1}	-0.669	-0.741	0.000	0.000	-0.000	-0.000
	(1.554)	(1.528)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-2}	0.252	0.244	-0.000	-0.000	0.000	0.000
	(1.596)	(1.553)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-3}	1.828	1.565	-0.000	-0.000	0.000*	0.000*
	(1.278)	(1.274)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-4}	-0.847	-0.916	0.000	0.000	0.000***	0.000***
	(1.626)	(1.543)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-5}	0.639	0.875	-0.000	-0.000	-0.000	-0.000
	(1.603)	(1.624)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-6}	-0.321	-0.043	0.001*	0.001*	0.000**	0.000**
	(1.435)	(1.407)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-7}	0.452	0.332	-0.001***	-0.001***	-0.000	-0.000
	(1.261)	(1.279)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-8}	2.865*	2.357	-0.002***	-0.002***	-0.001***	-0.001***
	(1.584)	(1.590)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-9}	-2.253	-2.108	0.001*	0.001*	0.000***	0.001***
	(1.539)	(1.509)	(0.000)	(0.000)	(0.000)	(0.000)
$X_t + X_{t-1} + \cdots + X_{t-9}$		2.365		-0.001		0.000
		(2.428)		(0.001)		(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	85	85	85	85	85	85
# of observations	79,414	79,414	79,414	79,414	79,414	79,414

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

on birth weight is positive and significant during the fifth, seventh, and ninth months prior to pregnancy. However, this may be explained by our inability to identify gestational length, so the estimation samples may include births that occurred prior to a full nine months of pregnancy. Exposure during the birth month and the second month prior to birth increase the likelihoods of LBW (1.7 and 1.4 percentage points, respectively) and VLBW (0.8 and 0.7 percentage points, respectively). The coefficients for the impact during the birth month are larger than previously estimated in Panel B of Table 6.1 (1.7 vs. 0.5 percentage points for LBW; 0.8 vs. 0.4 percentage points for VLBW). The cumulative effect indicates that a 1-ppb-increase in prenatal exposure to SO_2 increases the likelihood of LBW by 1.0 percentage point in these three counties (column (4)); this translates into a 23.8% (= 1.0/4.2) increase in LBW at the mean proportion. The same model for the impact on VLBW indicates a 0.6 percentage point increase, or 71.4% (= 0.6/0.84) increase at the mean proportion of VLBW.

Hunterdon, Morris, Sussex, and Warren Counties

Table 6.6 shows results for equation (4.5) for the sample including Hunterdon, Morris, Sussex, and Warren Counties. Generally, coefficient magnitudes are small and insignificant with the inclusion of Warren County to our sample. As mentioned previously, the OLS estimates are downward-biased, which also helps to explain these results.

Table 6.7 shows 2SLS results for the sample including all four counties. As expected, the inclusion of Warren County, where we previously found potential evidence for antipollution health protection behaviors, reduces the magnitudes of the coefficients compared to Table 6.5. The magnitude of the coefficient for exposure during the birth month on VLBW is 0.4 percentage points, which is one-half of the estimate for the sample excluding Warren County. We also observe statistically significant and positive coefficients for exposure during the third month prior to birth on LBW (0.6 percentage points) and VLBW (0.3 percentage points). However, the cumulative impact indicates a zero-effect on LBW and VLBW. These results are consistent with the idea that our IV is not valid for Warren County and for the evidence

Table 6.5: 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, and Sussex Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	-30.888	-30.778	0.017**	0.017**	0.008**	0.008**
	(22.462)	(22.483)	(0.008)	(0.008)	(0.004)	(0.004)
X_{t-1}	9.264	8.939	0.001	0.001	-0.001	-0.001
	(19.660)	(18.985)	(0.007)	(0.006)	(0.003)	(0.003)
X_{t-2}	-25.535	-24.701	0.014***	0.014***	0.007**	0.007**
	(15.535)	(16.647)	(0.005)	(0.005)	(0.003)	(0.003)
X_{t-3}	26.452	26.384	0.003	0.003	0.004	0.004
	(29.457)	(28.718)	(0.011)	(0.011)	(0.005)	(0.005)
X_{t-4}	-22.482	-19.580	0.015	0.014	0.009	0.009
	(22.305)	(21.230)	(0.011)	(0.011)	(0.005)	(0.005)
X_{t-5}	36.048*	38.936*	-0.010*	-0.011*	-0.005*	-0.005*
	(21.794)	(21.508)	(0.006)	(0.006)	(0.003)	(0.003)
X_{t-6}	-26.227	-29.937	0.002	0.002	-0.001	-0.001
	(36.664)	(35.176)	(0.010)	(0.010)	(0.005)	(0.005)
X_{t-7}	60.823***	58.357***	-0.029***	-0.029***	-0.014***	-0.014***
	(19.696)	(20.381)	(0.010)	(0.010)	(0.005)	(0.005)
X_{t-8}	-51.519	-48.284	0.015	0.015	0.004	0.004
	(39.186)	(38.540)	(0.014)	(0.014)	(0.005)	(0.005)
X_{t-9}	43.996*	41.151*	-0.017	-0.017	-0.005	-0.005
	(23.242)	(23.943)	(0.011)	(0.011)	(0.004)	(0.004)
$X_t + X_{t-1} + \cdots + X_{t-9}$		20.487		0.010		0.006
		(21.723)		(0.007)		(0.004)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	85	85	85	85	85	85
# of observations	74,427	74,427	74,427	74,427	74,427	74,427

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Table 6.6: OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, Sussex, and Warren Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	0.868	0.848	0.000	0.000	0.000***	0.000***
	(1.112)	(1.113)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-1}	0.412	0.274	-0.000	-0.000	-0.000	-0.000
	(1.327)	(1.303)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-2}	0.987	0.808	-0.000	-0.001	-0.000	-0.000
	(1.284)	(1.268)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-3}	-0.119	-0.313	0.000	0.000	0.000**	0.000**
	(1.242)	(1.206)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-4}	-0.673	-0.764	0.000	0.000	0.001***	0.001***
	(1.411)	(1.320)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-5}	0.339	0.524	-0.000	-0.000	-0.000	-0.000
	(1.343)	(1.313)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-6}	-1.231	-1.057	0.001*	0.001**	0.000***	0.000***
	(1.281)	(1.237)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-7}	0.776	0.653	-0.001***	-0.001***	-0.000**	-0.000**
	(1.253)	(1.254)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-8}	1.662	1.171	-0.001**	-0.001***	-0.001***	-0.001***
	(1.399)	(1.366)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-9}	-2.269*	-2.268*	0.001***	0.001***	0.000*	0.000*
	(1.234)	(1.179)	(0.000)	(0.000)	(0.000)	(0.000)
$X_t + X_{t-1} + \cdots + X_{t-9}$		-0.124		0.000		0.000
		(2.023)		(0.000)		(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	102	102	102	102	102	102
# of observations	90,469	90,469	90,469	90,469	90,469	90,469

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

of potential health protection behaviors. Therefore, the inclusion of Warren County in our sample eliminates the impacts found using only the other three counties.

Table 6.7: 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Hunterdon, Morris, Sussex, and Warren Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	-8.212	-8.452	0.003	0.003	0.004**	0.004**
	(8.382)	(7.939)	(0.005)	(0.005)	(0.002)	(0.002)
X_{t-1}	16.862**	16.235**	-0.002	-0.002	-0.002*	-0.002*
	(7.789)	(7.711)	(0.002)	(0.002)	(0.001)	(0.001)
X_{t-2}	-9.250	-9.314	0.004	0.004	0.002	0.002
	(6.292)	(6.520)	(0.003)	(0.003)	(0.001)	(0.001)
X_{t-3}	2.053	0.731	0.006**	0.006**	0.003***	0.003***
	(9.533)	(9.514)	(0.003)	(0.003)	(0.001)	(0.001)
X_{t-4}	-19.576**	-18.781**	0.004	0.004	0.004***	0.004***
	(8.212)	(8.091)	(0.004)	(0.004)	(0.001)	(0.001)
X_{t-5}	12.924	13.639*	-0.005**	-0.005**	-0.004***	-0.004***
	(8.205)	(8.014)	(0.002)	(0.002)	(0.001)	(0.001)
X_{t-6}	-8.571	-8.380	-0.001	-0.001	-0.000	-0.000
	(10.857)	(10.775)	(0.002)	(0.002)	(0.001)	(0.001)
X_{t-7}	28.074**	26.371**	-0.012***	-0.012***	-0.007***	-0.007***
	(11.154)	(10.582)	(0.005)	(0.005)	(0.002)	(0.002)
X_{t-8}	-10.757	-9.755	0.004	0.004	0.001	0.001
	(15.256)	(13.778)	(0.004)	(0.004)	(0.001)	(0.001)
X_{t-9}	13.549	12.952	-0.001	-0.001	0.000	0.000
	(10.420)	(9.530)	(0.004)	(0.004)	(0.001)	(0.001)
$X_t + X_{t-1} + \cdots + X_{t-9}$		15.247		0.000		0.000
		(10.841)		(0.004)		(0.002)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	102	102	102	102	102	102
# of observations	84,691	84,691	84,691	84,691	84,691	84,691

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Warren County

Table 6.8 shows OLS estimates for Warren County. Interestingly, the impact of exposure during the third month prior to birth on birth weight is negative and significant, but very small in magnitude (reduces birth weight by about 7.2 grams). The cumulative effect indicates that prenatal exposure to SO_2 reduces birth weight in Warren County by about 5 grams, which, again, is very small in magnitude when evaluated at the mean birth weight. The OLS estimates for the impacts on LBW and VLBW are generally insignificant and sometimes even negative. However, the cumulative impact (column (4)) indicates a 0.2 percentage point increase in LBW (or a 4.3% increase at the mean LBW proportion of 4.6% in the County).

Table 6.9 shows 2SLS estimates for Warren County. As expected, the estimates are similar to the OLS estimates shown in Table 6.8. We observe a larger effect for exposure during the third month prior to birth on birth weight; the estimate indicates a 22-23 gram reduction in birth weight, which is still relatively small when evaluated at the mean birth weight of over 3,400 grams in Warren County. The coefficients for the effects on LBW and VLBW are either insignificant or generally wrong-signed. In fact, the models that include exposure during each of the nine months prior to and including the birth month show negative, though insignificant, effects on LBW and VLBW.

6.1.3 In Summary

Both the OLS and 2SLS results using either model, exposure during the birth month (estimated by equations (4.1) and (4.2)-(4.4)) or exposure during each of the months prior to and including the birth month (equations (4.5) and (4.6)-(4.8)), demonstrate the possibility that residents of Warren County practice health protection behaviors. They help to explain why the estimation samples that include all four counties observe smaller point estimates than the estimation samples that include only Hunterdon, Morris, and Sussex Counties. Nonetheless, IV estimates of the impact on LBW and VLBW appear to be consistent, regardless of the estimation sample (Hunterdon and Morris versus all three counties) and the model used. In fact, the inclusion of exposure during the months prior to and including the birth month increases the size of the point estimates, potentially supporting the idea that exposure at different points during fetal development could have differential impacts.

Table 6.8: OLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Warren County)

	Birth weight (grams)		Low birth weight$^{\diamond}$ (birth weight < 2,500g)		Very low birth weight$^{\diamond}$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	3.475	4.106*	0.000	0.000	0.000	0.000
	(2.465)	(2.365)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-1}	2.588	2.256	-0.001	-0.001	0.000**	0.000**
	(2.536)	(2.453)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-2}	-2.253	-2.912	-0.000	-0.000	-0.001***	-0.001***
	(2.390)	(2.384)	(0.000)	(0.000)	(0.000)	(0.000)
X_{t-3}	-7.223***	-7.367***	0.001	0.002	0.001**	0.001**
	(1.679)	(1.642)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-4}	1.529	1.257	0.000	0.000	0.000	0.000
	(2.719)	(2.588)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-5}	-0.990	-0.580	0.001	0.001	0.000	0.000
	(2.523)	(2.502)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-6}	-0.983	-0.688	0.000	0.000	0.000**	0.000**
	(2.599)	(2.516)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-7}	2.029	2.035	-0.001**	-0.002**	-0.000	-0.000
	(3.645)	(3.555)	(0.001)	(0.001)	(0.000)	(0.000)
X_{t-8}	-0.584	-0.759	0.000	0.000	-0.000**	-0.000**
	(3.339)	(2.900)	(0.000)	(0.001)	(0.000)	(0.000)
X_{t-9}	-2.353	-2.758	0.001***	0.001***	-0.000	-0.000
	(1.936)	(1.741)	(0.000)	(0.000)	(0.000)	(0.000)
$X_t + X_{t-1} + \cdots + X_{t-9}$		-5.410***		0.002**		0.000
		(1.963)		(0.001)		(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	11,055	11,055	11,055	11,055	11,055	11,055

$^{\diamond}$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).

Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Table 6.9: 2SLS Estimates: Effect of SO_2 Exposure in Each Month of Pregnancy on Infant Birth Weight (Warren County)

	Birth weight (grams)		Low birth weight[◇] (birth weight < 2,500g)		Very low birth weight[◇] (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
X_t	5.532	4.559	-0.008*	-0.008*	-0.001	-0.001
	(6.738)	(7.246)	(0.005)	(0.005)	(0.001)	(0.001)
X_{t-1}	6.422	6.446	-0.002	-0.002	-0.002***	-0.002**
	(12.308)	(12.614)	(0.003)	(0.003)	(0.001)	(0.001)
X_{t-2}	-2.842	-4.461	-0.004*	-0.004*	-0.001***	-0.001***
	(5.048)	(4.909)	(0.002)	(0.002)	(0.000)	(0.000)
X_{t-3}	-23.178***	-22.239***	0.003	0.003	0.003***	0.003***
	(8.337)	(7.554)	(0.004)	(0.003)	(0.001)	(0.001)
X_{t-4}	-13.964	-15.018	-0.009***	-0.009***	-0.001	-0.001
	(13.000)	(13.066)	(0.002)	(0.002)	(0.001)	(0.001)
X_{t-5}	-7.820	-7.354	0.002	0.002	-0.002***	-0.002***
	(6.423)	(7.885)	(0.004)	(0.004)	(0.000)	(0.000)
X_{t-6}	-9.954	-8.773	-0.000	-0.000	0.000	0.000
	(12.594)	(12.036)	(0.002)	(0.002)	(0.000)	(0.000)
X_{t-7}	16.805	17.540	0.005	0.004	0.000	0.000
	(11.600)	(10.904)	(0.004)	(0.004)	(0.001)	(0.001)
X_{t-8}	26.353	26.629*	0.002	0.003	0.001	0.001
	(16.996)	(14.542)	(0.003)	(0.003)	(0.001)	(0.001)
X_{t-9}	18.150	16.141	0.009***	0.009***	0.000	0.000
	(14.431)	(12.734)	(0.002)	(0.002)	(0.001)	(0.001)
$X_t + X_{t-1} + \cdots + X_{t-9}$		13.469		-0.003		-0.002
		(22.039)		(0.005)		(0.001)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	10,264	10,264	10,264	10,264	10,264	10,264

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Nonetheless, the significant effects of prenatal SO_2 exposure on VLBW found in Sections 5.3 and 6.1 are somewhat puzzling and warrant discussion. Because extremely premature cases have been eliminated from the estimation samples, the numbers of infants born VLBW are very small; the proportions are well-below 1% in our sample (see Table 5.2). As a result, our finding that prenatal exposure to SO_2 significantly affects VLBW is surprising. One potential explanation is that the use of ICD-9 codes to identify pre-term births may not capture all premature cases due to the possibility of incorrect diagnosis or even inaccurate measurement of gestational length. Therefore, births that are perhaps only one to two weeks premature are not diagnosed as premature and, thus, not eliminated from the sample. According to birth weight tables ([Doublet et al., 1997]), the majority of fetuses surpass the VLBW threshold of 1,500 grams at around 31 weeks of gestation, and rapid growth, in the realm of 100 to 150 grams or more per week, occurs during the final few weeks of gestation. Another possible explanation for our finding is that infants who have not yet passed the VLBW threshold at 37 weeks (the cutoff for premature cases) are particularly vulnerable to SO_2 exposure during the final weeks of gestation and more likely to experience an adverse outcome, such as little further weight gain, as a consequence. Also possible is that the VLBW cases remaining in our sample (after eliminating premature births) have already experienced fetal complications (which may or may not be the cause of why they have not passed the VLBW, or even LBW, threshold) that are exacerbated by SO_2 exposure and inhibit weight gain during the final weeks of gestation.

6.2 Using a Radius of 25 Miles

In this section, we re-create our results from Sections 5.2, 5.3.1, and 6.1.1, except using a 25-mile radius to construct the zip-code-level pollution and weather variables.

6.2.1 Impact of PGS Emissions on SO_2 Concentrations in New Jersey Zip Codes

Table 6.10 shows first-stage results using the zip-code-level, monthly SO_2 measures constructed using a 25-mile radius. Even with the use of a wider radius, the results are still consistent with the NJDEP's findings and EPA's ruling–SO_2 emissions from PGS impact zip-code-level SO_2 concentrations in Hunterdon, Morris, Sussex, and Warren Counties. However, the magnitudes of the impact are different from the magnitudes found using a 20-mile radius.[2] In Warren County (columns (1) and (2)), for zip codes located downwind of the plant, a 1,000-ton-increase in SO_2 emissions increases SO_2 concentrations by 0.79 ppb, which is much smaller than the original estimate of 1.77 ppb. This finding is potentially explained by the idea that the use of a wider radius, which includes pollution monitors located further away from zip code centroids, creates noisier pollution measures. For zip codes located in Hunterdon and Morris Counties (columns (3) and (4)), we now find a larger effect of PGS emissions–a 1.06 ppb increase compared to the original estimate of 0.93 ppb. With the addition of Sussex County to the latter sample (columns (5) and (6)), the impact of a 1,000-ton-increase in PGS SO_2 emissions increases zip-code-level concentrations by 0.84 ppb (compared to the original estimate of 0.77 ppb). When all four counties are included in the sample ((7) and (8)), the estimate translates into 1.01 ppb increase in SO_2 concentrations, which is slightly smaller than the original estimate of 1.04 ppb. As expected, PGS SO_2 emissions do not affect SO_2 concentrations in all other New Jersey counties (columns (9) and (10)).

[2]See Table 5.3.

Table 6.10: Impact of PGS SO_2 Emissions on SO_2 Concentrations Near NJ Zip Codes, Using a 25-mile Radius

	Warren		Hunterdon & Morris		Hunterdon, Morris, & Sussex		Hunterdon, Morris, Sussex, & Warren		Other NJ Counties	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
PGS SO_2 emissions$^\diamond$	0.792***	0.789***	1.064***	1.063***	0.841***	0.841***	1.015***	1.014***	-0.114	-0.115
	(0.214)	(0.213)	(0.163)	(0.164)	(0.180)	(0.180)	(0.161)	(0.161)	(0.080)	(0.080)
Individual-level demographics	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	18	18	82	82	99	99	117	117	533	533
# of observations	13,035	13,035	75,323	75,323	87,185	87,185	100,220	100,220	926,211	926,211

$^\diamond$ PGS SO_2 monthly emissions (in 1,000 tons), direction-adjusted
Notes: Dependent variable in all specifications is the zip-code-level, inverse-distance-weighted, monthly average of SO_2 (in ppb). All specifications include weather variables, year-month (monthly) fixed effects, and zip code fixed effects. Standard errors are shown in parentheses. Standard errors are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

6.2.2 Impact of SO_2 Exposure During the Birth Month on Infant Birth Weight and Related Outcomes

Hunterdon and Morris Counties

In Table 6.11, which includes only Hunterdon and Morris Counties, we show estimates for equations (4.1) and (4.2) using a 25-mile radius to construct the direction-adjusted, zip-code-level SO_2 measures. Compared to the use of a 20-mile radius (see Table 5.4), the use of 25-mile radius produces OLS and 2SLS estimates that are similar in magnitude. As expected, the OLS estimates in Panel A are still downward-biased and small in magnitude. In Panel B, the estimate for the impact on LBW is five times larger than the OLS estimate (columns (3) and (4)), while the estimate for the impact on VLBW is four times larger than the OLS estimate (columns (5) and (6)). The 2SLS estimates for the impact on LBW (0.5 percentage points) and VLBW (0.4 percentage points) are the same in magnitude whether using a 25-mile or 20-mile radius. We also note the large value for the first-stage partial F-statistic, which is 41.67, indicating a strong instrument.

Table 6.11: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon and Morris Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-2.412	-2.240	0.001***	0.001***	0.001***	0.001***
	(1.691)	(1.673)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	82	82	82	82	82	82
# of observations	75,321	75,321	75,321	75,321	75,321	75,321
Panel B: 2SLS Estimates						
X_t	-0.264	-0.363	0.005***	0.005***	0.004***	0.004***
	(6.386)	(6.420)	(0.002)	(0.002)	(0.001)	(0.001)
First-stage partial F		41.666		41.666		41.666
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	82	82	82	82	82	82
# of observations	75,321	75,321	75,321	75,321	75,321	75,321

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Hunterdon, Morris, and Sussex Counties

Table 6.12 shows OLS and 2SLS estimates for Hunterdon, Morris, and Sussex Counties using a 25-mile radius to construct pollution and weather variables. Panel A shows that the OLS estimates are similar to the estimates using a 20-mile radius (see Table 6.1). The coefficient magnitudes for LBW (columns (3) and (4)) and VLBW (columns (5) and (6)) are positive but small. In Panel B, the coefficients for the impacts on birth weight and LBW have become larger when compared to the use of a 20-mile radius. Though insignificant, a 1-ppb-increase in exposure to SO_2 during the birth month reduces birth weight by about 5.5 grams, which is fifteen times larger than the original estimate (-0.37 grams). Furthermore, the impact of increased exposure in the birth month indicates a 0.7 percentage point increase in the likelihood of LBW (compared to the estimate of 0.5 percentage points obtained using a 20-

mile radius). The estimate for VLBW is now smaller, 0.3 percentage points (compared to 0.4 percentage points in the original estimation). Nonetheless, the first-stage partial F-statistic (21.57) indicates a strong instrument.

Table 6.12: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-2.346	-2.151	0.001*	0.001*	0.001***	0.001***
	(1.649)	(1.629)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	99	99	99	99	99	99
# of observations	87,183	87,183	87,183	87,183	87,183	87,183
Panel B: 2SLS Estimates						
X_t	-5.090	-5.490	0.007***	0.007***	0.003***	0.003***
	(6.544)	(6.403)	(0.002)	(0.002)	(0.001)	(0.001)
First-stage partial F		21.567		21.567		21.567
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	99	99	99	99	99	99
# of observations	87,183	87,183	87,183	87,183	87,183	87,183

◇ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Hunterdon, Morris, Sussex, and Warren Counties

Table 6.13 estimates equations (4.1) and (4.2) for Hunterdon, Morris, Sussex, and Warren Counties using a 25-mile radius. Again, in Panel A, we observe that the OLS estimates are downward-biased and generally insignificant from zero, excepting VLBW. Compared to the original estimates (using the 20-mile radius; see Table 6.2), the new 2SLS estimates using the 25-mile radius (shown in Panel B) are very similar for the impact on birth weight and VLBW. However, the impact on LBW (0.3 percentage points) is larger than the original estimate (0.1 percentage points), though still insignificant once demographic variables are included in the regression.

Table 6.13: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties)

	Birth weight (grams)		Low birth weight$^{\diamond}$ (birth weight < 2,500g)		Very low birth weight$^{\diamond}$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-1.388	-1.348	0.000	0.000	0.001***	0.001***
	(1.309)	(1.278)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	117	117	117	117	117	117
# of observations	100,217	100,217	100,217	100,217	100,217	100,217
Panel B: 2SLS Estimates						
X_t	-4.642	-4.520	0.003*	0.003	0.002***	0.002***
	(3.771)	(3.701)	(0.002)	(0.002)	(0.001)	(0.001)
First-stage partial F		39.289		39.289		39.289
p-value for first-stage partial F		0.000		0.000		0.000
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	117	117	117	117	117	117
# of observations	100,217	100,217	100,217	100,217	100,217	100,217

$^{\diamond}$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Warren County

Finally, Table 6.14 shows OLS and 2SLS estimates for Warren County with the use of the 25-mile radius. The OLS estimates, shown in Panel A, are very similar to the estimates obtained by use of the 20-mile radius (see Table 6.3), indicating virtually no effect on birth weight, LBW, or VLBW. In Panel B, however we see a larger impact on birth weight; a 1-ppb-increase in SO_2 exposure during the birth month reduces birth weight by 13.7 grams (column (2)), compared to about 10.2 grams in the previous estimate. The magnitude of the impact on LBW is now smaller, but it is insignificant and still negative (columns (3) and

(4)). Again, these results provide evidence that the instrument is likely not valid for Warren County due to the potential practice of health protection behaviors by residents.

Table 6.14: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, Using a 25-Mile Radius, OLS and 2SLS Estimates (Warren County)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-1.554	-0.561	0.001	0.001	0.000***	0.000***
	(2.534)	(2.553)	(0.000)	(0.000)	(0.000)	(0.000)
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	18	18	18	18	18	18
# of observations	13,034	13,034	13,034	13,034	13,034	13,034
Panel B: 2SLS Estimates						
X_t	-16.306**	-13.638*	-0.001	-0.001	0.001	0.001
	(6.825)	(7.013)	(0.004)	(0.004)	(0.001)	(0.001)
First-stage partial F		12.865		12.865		12.865
p-value for first-stage partial F		0.002		0.002		0.002
Individual-level demographics	No	Yes	No	Yes	No	Yes
# of zip codes	18	18	18	18	18	18
# of observations	13,034	13,034	13,034	13,034	13,034	13,034

$^\diamond$ Low birth weight and very low birth weight are 1/0 dummy variables (see 3.1.4).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

In general, our estimates are robust to the use of either a 20-mile or 25-mile radius. This may be explained by the fact that the analysis counties are in close geographic proximity. Therefore, regardless of whether a 20- or 25-mile radius is used to construct the pollution and weather variables, we capture the same births, thus yielding similar estimates.

Chapter 7

Results Using New Jersey Birth Certificates

In this chapter, we perform the analyses from Chapters 5 and 6, instead using New Jersey birth certificate records. For all of the subsequent analyses, we use a radius of 20 miles to construct the pollution and weather variables. Section 7.1 overviews summary statistics for relevant variables used from the birth certificate records. For estimation results shown in Section 7.2, we run two sets of models for each outcome variable: one that includes no control variables (except for zip-code-level weather variables) and a second that includes all control variables (infant's sex; prenatal care visits; mother's race and ethnicity characteristics; and maternal smoking status).[1]

7.1 Summary Statistics

In Table 7.1, we observe summary statistics for birth-related information using New Jersey Birth Certificate records. Birth weight (in grams) is very similar to the average in the HCUP data; the mean is over 3,400 grams (or about 7.5 pounds) in the four counties and exceeds the mean in all other New Jersey counties by approximately 100 grams. Interestingly, the

[1]See Section 4.5 for more details.

proportions born LBW are uniformly lower in the birth certificate records across the state, in the realm of 3.4% to 5.5% (compared to 3.9% to 6.2% in the HCUP). Hunterdon County saw the lowest proportion of LBW (3.4%) compared to Morris (3.7%), Sussex (3.6%), and Warren (3.9%), but all four counties were lower than the average proportion in all other New Jersey counties (5.5%) by nearly two percentage points. Additionally, the proportions of VLBW are also lower across the board, in the realm of 0.4% to 0.8%, when compared to the HCUP (where VLBW proportions ranged from 0.6% to 1.1%). Hunterdon County experienced a proportion of 0.4% while Morris, Sussex, and Warren Counties saw proportions of 0.5%; all were lower than other New Jersey counties (0.8%). The uniformly lower proportions of LBW and VLBW found using the birth certificates may be explained by the fact that we are able to identify gestational age and, consequently, better identify full-term births.

Furthermore, the percentage of infants born pre-term (gestational age less than 37 weeks) is greater according to the birth certificate estimates, with the exception of Hunterdon County, where it is one-half percentage point lower than the HCUP estimate (5.2% compared to 5.9%). In the other counties, proportions ranged from 5.4% (Warren County) to 5.6% (Sussex County), and 7.5% in all other New Jersey counties. Nonetheless, these proportions are roughly within 1 percentage point when compared to those suggested using ICD-9 codes to identify cases of "extreme immaturity related to short gestation" in the HCUP. This is likely because the dummy created using ICD-9 codes only includes cases that are extremely immature, but not those cases that are perhaps only a few weeks premature. We also see that average gestational length is around 39 weeks, which is about 1 week short of the average length of pregnancies (40 weeks); the average gestation length in our data is likely reduced by the inclusion of pre-term births and includes births with gestation length as few as 18 weeks.

Lastly, we observe 1- and 5-minute APGAR scores. Average 1-minute scores range from about 8.2 to 8.5 out of a possible 10, and this is within normal range[2]; average 5-minute scores

[2]A normal APGAR score is 7 or greater.

Table 7.1: Summary Statistics, Part IIIa

	Hunterdon	Morris	Sussex	Warren	Other NJ Counties
Birth weight (grams)	3,464.586	3,440.396	3,474.688	3,450.264	3,350.286
	(517.073)	(528.564)	(538.648)	(538.621)	(553.822)
Low birth weight (1/0)	0.034	0.037	0.036	0.039	0.055
	(0.182)	(0.190)	(0.186)	(0.194)	(0.228)
Very low birth weight (1/0)	0.004	0.005	0.005	0.005	0.008
	(0.067)	(0.069)	(0.072)	(0.071)	(0.091)
Pre-term (1/0)	0.052	0.055	0.056	0.054	0.075
	(0.222)	(0.228)	(0.231)	(0.227)	(0.264)
Estimated clinical gestation	39.080	39.016	39.076	39.095	38.851
(in weeks)	(1.660)	(1.669)	(1.716)	(1.712)	(1.891)
APGAR score, 1-minute	8.240	8.499	8.434	8.389	8.443
(0 to 10)	(1.111)	(0.960)	(1.028)	(1.115)	(1.059)
APGAR score, normal,	0.946	0.964	0.956	0.947	0.952
1-minute (1/0)	(0.227)	(0.187)	(0.206)	(0.223)	(0.213)
APGAR score, 5-minute	8.948	9.014	9.081	9.134	8.984
(0 to 10)	(0.425)	(0.476)	(0.555)	(0.619)	(0.493)
APGAR score, normal,	0.995	0.996	0.995	0.994	0.994
5-minute (1/0)	(0.067)	(0.062)	(0.067)	(0.079)	(0.076)
Female (1/0)	0.488	0.485	0.492	0.492	0.487
	(0.500)	(0.500)	(0.500)	(0.500)	(0.500)
# of observations	15,030	62,025	17,731	13,355	1,066,224

Notes: Standard errors are shown in parentheses. Data are from the New Jersey Department of Vital Statistics Birth Certificate records. Sample period includes January 1995 to December 2006. Summary statistics are based on the sample of live, singleton, in-hospital births with non-missing information for the aforementioned variables.

are generally 0.5 points higher than the 1-minute scores, as would be expected, and range from 8.9 to 9.1. Additionally, the proportion of infants with a normal 1-minute APGAR score ranged from 94.6% in Hunterdon County to 96.4% in Morris County; the average was 95.0% in all other New Jersey counties. The proportion of births with normal 5-minute APGAR scores were over 99% in all four counties as well as all other New Jersey counties. The differences between the 1-minute and 5-minute APGAR measures are consistent with the idea that 1-minute scores are not necessarily indicative of long-term health.

Table 7.2 shows information related to prenatal care and maternal characteristics for the birth certificate records. Mothers averaged between 11 to 12 prenatal care visits during pregnancy. The number of visits is slightly higher in Hunterdon and Sussex Counties (12.1 and 12.3, respectively) than Morris and Warren Counties (11.5 and 11.8, respectively). In all other New Jersey counties, mothers made about one fewer prenatal care visit (10.5 visits) than in the four counties. The percentage of mothers who did not have any prenatal care visits was very low in the four counties, between 0.2% and 0.3%, but about one percentage point higher than in all other New Jersey counties (1.2%). While the proportion of mothers with no prenatal care visits is very low, the lack of prenatal care visits may serve as an indication of maternal health behavior during pregnancy; if a mother did not take the time to visit a doctor during pregnancy, a strong possibility exists that she had poorer health habits when compared to mothers who regularly visited a physician during pregnancy. Between 12.2% (Sussex) to 18.6% (Warren) of mothers made between one and nine prenatal visits during pregnancy; these percentages in the four counties are substantially lower than for all other New Jersey counties, where 33.1% of mothers made between one and nine visits to the doctor.[3] The vast majority of mothers made between 10 and 18 prenatal visits during pregnancy; the percentages ranged from 78.2% in Warren County to 84.8% in Sussex County; in all other New Jersey counties, 64.0% mothers had 10 to 18 prenatal care visits.[4]

[3]For a full-term pregnancy, the range of 1-9 visits indicates that a mother had prenatal care visits, on average, once per month or less.

[4]For a full-term pregnancy, the range of 10-18 visits indicates that a mother had prenatal care visits, on average, one to two times per month.

The proportion of mothers who had more than 28 visits was very low, ranging between 0.1% (Morris, all other New Jersey counties) to 0.3% (Hunterdon, Morris, and Sussex). While these proportions are quite small, averaging more than 2 to 3 visits per month is likely indicative of complications during pregnancy.

The percentage of mothers who are married ranged from 80.5% (Warren County) to 91.6% (Hunterdon County), and these percentages are substantially higher in the four counties than in all other counties in New Jersey (68.0%). In terms of ethnicity, the percentage of mothers who are Hispanic ranged from 5.0% in Sussex County to 13.1% in Morris County; the average is much greater in all other counties at 22.8%. Generally, these percentages are greater than those observed in the HCUP. Additionally, the percentage of mothers who are white is much higher in the four counties, ranging from 86.7% in Morris County to 96.3% in Sussex County, in comparison to the rest of New Jersey (70.8%). These averages are greater than the averages observed in the HCUP, particularly in all other New Jersey counties. Mothers who are racial minorities, including black, Asian or Pacific Islander, or other races, constitute a smaller proportion in the four counties as compared to the rest of New Jersey. The notable exception is Morris County, which has a relatively large percentage of mothers who are Asian or Pacific Islander (9.4%), larger even than the rest of New Jersey (8.1%). Also, these averages are generally larger than those observed in the HCUP; this may be explained by how each data set assigns race. In particular, the Asian or Pacific Islander category includes a broader range of racial groups in the birth certificate records than in the HCUP. In general, the differences in race and ethnicity percentages between the birth certificates and the HCUP may be explained by the fact that the birth certificates provide a mother's (and father's) race, whereas the HCUP assigns race to an infant that is presumably based on a mother's race, though not necessarily.

The birth certificates also provide information related to maternal smoking. In the sample, the percentage of mothers who smoked ranged from a low of 5.8% in Morris County to a high of 16.6% in Warren County; the average was about 9.6% in all other New Jer-

Table 7.2: Summary Statistics, Part IIIb

	Hunterdon	Morris	Sussex	Warren	Other NJ Counties
# of prenatal visits	12.108	11.524	12.281	11.765	10.488
	(3.227)	(2.963)	(3.149)	(3.421)	(3.759)
Prenatal visits, none	0.002	0.003	0.002	0.003	0.012
(1/0)	(0.040)	(0.052)	(0.049)	(0.052)	(0.107)
Prenatal visits, 1-9	0.158	0.177	0.122	0.186	0.331
(1/0)	(0.364)	(0.382)	(0.328)	(0.389)	(0.470)
Prenatal visits, 10-18	0.814	0.804	0.848	0.782	0.640
(1/0)	(0.389)	(0.397)	(0.359)	(0.413)	(0.480)
Prenatal visits, 19-27	0.024	0.014	0.025	0.027	0.015
(1/0)	(0.153)	(0.118)	(0.156)	(0.161)	(0.123)
Prenatal visits, 28-36	0.002	0.001	0.002	0.002	0.001
(1/0)	(0.048)	(0.036)	(0.042)	(0.047)	(0.037)
Prenatal visits, 37+	0.001	0.000	0.001	0.001	0.000
(1/0)	(0.026)	(0.020)	(0.023)	(0.026)	(0.022)
Mother, married (1/0)	0.916	0.888	0.866	0.805	0.680
	(0.278)	(0.315)	(0.341)	(0.396)	(0.466)
Mother, hispanic (1/0)	0.051	0.131	0.050	0.069	0.228
	(0.219)	(0.337)	(0.217)	(0.254)	(0.420)
Mother, white (1/0)	0.953	0.867	0.963	0.940	0.708
	(0.211)	(0.339)	(0.189)	(0.237)	(0.455)
Mother, black (1/0)	0.012	0.029	0.014	0.024	0.194
	(0.109)	(0.167)	(0.116)	(0.154)	(0.395)
Mother, Asian or	0.032	0.094	0.021	0.031	0.081
Pacific Islander (1/0)	(0.177)	(0.292)	(0.142)	(0.174)	(0.273)
Mother, other race	0.002	0.010	0.003	0.004	0.017
(1/0)	(0.049)	(0.100)	(0.053)	(0.063)	(0.130)
Smoking status (1/0)	0.086	0.058	0.149	0.166	0.096
	(0.280)	(0.234)	(0.356)	(0.373)	(0.294)
# of observations	15,030	62,025	17,731	13,355	1,066,224

Notes: Standard errors are shown in parentheses. Data are from the New Jersey Department of Vital Statistics Birth Certificate records. Sample period includes January 1995 to December 2006. Summary statistics are based on the sample of live, singleton, in-hospital births with non-missing information for the aforementioned variables.

sey counties. Conditional on smoking status (i.e. having smoked), the average numbers of cigarettes smoked daily ranged from about 10.3 (Morris County) to 12.3 (Warren County), and averaged about 9.6 in all other New Jersey counties (not shown).

7.2 Impact of Prenatal Exposure to SO_2 During the Birth Month on Infant Health at Birth

In this section, we estimate equations (4.9) and (4.10)-(4.12) using the New Jersey birth certificate records. We consider the following outcomes: birth weight, LBW, and VLBW; prematurity; and 1- and 5-minute APGAR scores and the likelihood of normal 1- and 5-minute APGAR scores.[5] An important point to note is that the control variables included in some regressions include maternal smoking as well as prenatal care usage. We include coefficients for the impact of maternal smoking status on infant health because it warrants discussion.

7.2.1 Birth Weight

Table 7.3 shows OLS and 2SLS estimates of the impact of prenatal exposure to SO_2 during the birth month on birth weight and related outcomes for Hunterdon and Morris Counties. Panel A shows OLS estimates, which are similar to the estimates using the HCUP data.[6] We find no effect of SO_2 exposure during the birth month on birth weight, LBW, or VLBW. Interestingly, the 2SLS estimates (shown in Panel B) are now all insignificant and incorrectly-signed. The magnitudes of the effect on LBW (0.2 percentage points versus 0.5 percentage points) and VLBW (0.0 percentage versus 0.4 percentage points) are much smaller than the estimates using the HCUP data (columns (3)-(6)). However, the 2SLS estimate for the impact on birth weight is now larger (9.9 grams versus 1.5 grams), though still insignificant and incorrectly-

[5] An APGAR score of 7 or greater is considered normal.
[6] See Table 5.4.

signed (columns (1) and (2)). The first-stage partial F statistics are slightly smaller than the models using the HCUP, but since they are larger than 10, they are indicative of a relatively strong instrument.

Table 7.3: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon and Morris Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	1.375	1.211	-0.000	-0.000	0.000	0.000
	(0.986)	(1.041)	(0.000)	(0.000)	(0.000)	(0.000)
Smoking status$^\diamond$		-147.346***		0.015***		0.000
		(8.356)		(0.003)		(0.000)
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	76	76	76	76	76	76
# of observations	70,197	67,745	70,197	67,745	70,197	67,745
Panel B: 2SLS Estimates						
X_t	9.122	9.962	-0.001	-0.002	-0.000	-0.000
	(10.200)	(10.371)	(0.002)	(0.002)	(0.000)	(0.000)
Smoking status$^\diamond$		-147.498***		0.015***		0.000
		(8.396)		(0.003)		(0.000)
First-stage partial F	14.339	14.681	14.339	14.681	14.339	14.681
p-value for first-stage partial F	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	76	76	76	76	76	76
# of observations	70,197	67,745	70,197	67,745	70,197	67,745

$^\diamond$ Low birth weight, very low birth weight, and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

A provocative, yet expected result is the significant impact of maternal smoking on both birth weight and LBW. For mothers who smoke relative to those who do not smoke, infant birth weight is reduced by about 148 grams, or 4.3% when evaluated at the mean of roughly 3,440 grams for the two counties (column (2)); the likelihood of LBW is increased by 1.5 percentage points, or about 41.7% at the mean proportion of about 3.6% in the two counties (column (4)). However, we find no impact of smoking on VLBW, as should be the case since premature cases, which make up the majority of VLBW births, have been dropped from the sample.

In Table 7.4, we report OLS and 2SLS estimates with the inclusion of Sussex County to the sample. Again, the OLS estimates shown in Panel A are small and insignificantly different from zero. Additionally, the 2SLS estimates (Panel B) are incorrectly-signed and insignificant.[7] Compared to the previous sample of containing only the two counties, coefficient magnitudes are smaller with the inclusion of Sussex County, which is expected given its location and distance relative to PGS. However, the estimates still contradict our analogous findings using the HCUP data. According to these estimates, exposure to SO_2 during the birth month has no impact on birth weight, LBW, or VLBW. Interestingly, the impacts of maternal smoking on birth weight and LBW are still large and significant. Mothers, residing in these three counties, who smoke had infants that weighed about 146 grams less (column (2)) and had a higher chance of an LBW birth (1.3 percentage points, or nearly 40% increase (column (4))) when compared to mothers that do not smoke.

Table 7.5 shows estimates using all four counties in the sample. Similar to estimates using the HCUP,[8] the OLS estimates are still insignificant and zero (Panel A). However, the 2SLS estimates (shown in Panel B) are now insignificant and zero for the impacts on LBW and VLBW (compared to 0.1 and 0.2 percentage points, respectively, using the HCUP data). The inclusion of Warren County does not change the size of the estimates for LBW and VLBW, but surprisingly, the impact on birth weight is correctly-signed, though still insignificant, with Warren County's inclusion in the sample (columns (1) and (2)). The estimates indicate a 4.2 to 6.0 gram reduction in birth weight; this impact is small when evaluated at the mean birth weight of around 3,450 grams in the four counties. With the exception of birth weight, these results are relatively inconsistent with our findings using the HCUP data.

Another interesting finding in Table 7.6 is the coefficients for the impact of maternal smoking on birth weight and LBW. Mothers, residing in these four counties, who smoke had

[7] For analogous results using the HCUP data, see Table 6.1.
[8] See Table 6.2.

Table 7.4: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties)

	Birth weight (grams)		Low birth weight$^\diamond$ (birth weight < 2,500g)		Very low birth weight$^\diamond$ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	1.227	1.068	-0.000	-0.000	0.000	0.000
	(0.962)	(1.009)	(0.000)	(0.000)	(0.000)	(0.000)
Smoking status$^\diamond$		-146.290***		0.013***		0.000
		(7.735)		(0.002)		(0.000)
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	84	84	84	84	84	84
# of observations	79,912	77,066	79,912	77,066	79,912	77,066
Panel B: 2SLS Estimates						
X_t	2.435	4.124	0.000	-0.000	-0.000	-0.000
	(10.448)	(10.354)	(0.002)	(0.002)	(0.000)	(0.000)
Smoking status$^\diamond$		-146.345***		0.013***		0.000
		(7.764)		(0.002)		(0.000)
First-stage partial F	10.638	10.821	10.638	10.821	10.638	10.821
p-value for first-stage partial F	0.002	0.001	0.002	0.001	0.002	0.001
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	84	84	84	84	84	84
# of observations	79,912	77,066	79,912	77,066	79,912	77,066

$^\diamond$ Low birth weight, very low birth weight, and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

infants that weighed almost 154 grams less (column (2)) and had a 1.5 percentage point higher chance of an LBW birth (column (4)) than mothers who did not smoke. We also find a statistically significant increase of about 0.1 percentage points in the likelihood of VLBW birth for mothers who smoked compared to those that did not smoke (column (6)).

In Table 7.6, the impacts of prenatal exposure to SO_2 during the birth month on birth weight and related outcomes are shown for Warren County. Compared to the estimates using the HCUP,[9] the OLS estimates (Panel A) for birth weight are now smaller and insignificant, though still correctly-signed. The OLS estimates for LBW and VLBW are negative and virtually zero. In Panel B, the 2SLS estimates for the impact on birth weight (columns (1)

[9] See Table 6.3.

Table 7.5: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	0.095	-0.228	-0.000	-0.000	-0.000	-0.000
	(0.801)	(0.841)	(0.000)	(0.000)	(0.000)	(0.000)
Smoking status◇		-153.656***		0.015***		0.001**
		(7.020)		(0.002)		(0.000)
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	101	101	101	101	101	101
# of observations	91,580	88,571	91,580	88,571	91,580	88,571
Panel B: 2SLS Estimates						
X_t	-6.032	-4.242	-0.000	-0.000	-0.000	0.000
	(5.827)	(5.512)	(0.001)	(0.001)	(0.000)	(0.000)
Smoking status◇		-153.689***		0.015***		0.001**
		(7.012)		(0.002)		(0.000)
First-stage partial F	31.709	31.949	31.709	31.949	31.709	31.949
p-value for first-stage partial F	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	101	101	101	101	101	101
# of observations	91,580	88,571	91,580	88,571	91,580	88,571

◇ Low birth weight, very low birth weight, and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

and (2)) are significant and negative. They indicate that increased SO_2 exposure during the birth month reduces birth weight by about 14.0 to 15.7 grams (or about 0.4% at the mean), estimates which are larger than those found using the HCUP data (reductions of about 10.2 grams). For LBW (columns (3) and (4)), the estimates are significant and incorrectly-signed at about 0.3 percentage points, which are similar to estimates using the HCUP (0.2 percentage points). Interestingly, these results for Warren County are relatively consistent with the results using the HCUP data.

A compelling result is magnitudes of the maternal smoking coefficients in Table 7.6. The estimates indicate that mothers, residing in Warren County, who smoke reduced infant birth weight by about 181 grams (or 5.2%), which is 30 to 35 grams larger in magnitude than

Table 7.6: Effect of SO_2 Exposure During Birth Month on Infant Birth Weight and Related Outcomes, OLS and 2SLS Estimates (Warren County)

	Birth weight (grams)		Low birth weight◇ (birth weight < 2,500g)		Very low birth weight◇ (birth weight < 1,500g)	
	(1)	(2)	(3)	(4)	(5)	(6)
Panel A: OLS Estimates						
X_t	-1.614	-1.781	-0.000	-0.000	-0.000***	-0.000**
	(1.551)	(1.383)	(0.000)	(0.000)	(0.000)	(0.000)
Smoking status◇		-180.971***		0.019***		0.001*
		(13.076)		(0.004)		(0.001)
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	11,668	11,505	11,668	11,505	11,668	11,505
Panel B: 2SLS Estimates						
X_t	-15.697***	-14.042***	-0.002**	-0.002*	-0.000	0.000
	(4.212)	(3.126)	(0.001)	(0.001)	(0.000)	(0.000)
Smoking status◇		-181.195***		0.019***		0.001*
		(13.125)		(0.005)		(0.001)
First-stage partial F	21.580	21.360	21.580	21.360	21.580	21.360
p-value for first-stage partial F	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17
# of observations	11,668	11,505	11,668	11,505	11,668	11,505

◇ Low birth weight, very low birth weight, and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

when using the other samples, when compared to non-smokers (column (2)). Furthermore, the likelihood of an LBW birth is 1.9 percentage points higher (or 48.7% at the County's mean proportion), which is roughly one-half percentage point larger than estimates using the other estimation samples (column (4)). As expected due to our sample selection (i.e. the exclusion of premature births), the impact of maternal smoking on VLBW has not changed and indicates an 0.1 percentage point increase in the probability of VLBW, or a 20% increase at the mean (column (6)).

7.2.2 Prematurity

Table 7.7 shows estimates of the impact of prenatal exposure to SO_2 on the likelihood of pre-term birth for Hunterdon and Morris Counties. We observe an unusual result for both OLS and 2SLS estimates (Panel A and Panel B, respectively). According to these estimates, prenatal exposure to SO_2 during the birth month indicates a reduction in the likelihood of pre-term birth. This result is unexpected, especially for the 2SLS estimates. This may be attributable to the fact that gestational age is the clinical estimation of gestational age, which is not necessarily accurate. Therefore, pre-term, which is constructed using gestational age, and gestation length itself are relatively noisy measures, which could result in unexpectedly signed estimates.

Table 7.7: Effect of SO_2 Exposure During Birth Month on Prematurity$^\diamond$, OLS and 2SLS Estimates (Hunterdon and Morris Counties)

	OLS		2SLS	
	(1)	(2)	(3)	(4)
X_t	-0.001**	-0.001**	-0.003	-0.003
	(0.000)	(0.000)	(0.003)	(0.004)
Smoking status$^\diamond$		0.018***		0.018***
		(0.004)		(0.004)
First-stage partial F			13.915	14.479
p-value for first-stage partial F			0.000	0.000
Control variables	No	Yes	No	Yes
# of zip codes	76	76	76	76
# of observations	74,475	71,698	74,475	71,698

$^\diamond$ Pre-term and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

In the event that the measurement errors in gestational age are correlated with the regressors, we fail to identify the effect of prenatal exposure to SO_2 on the likelihood of pre-term birth. However, if the measurement errors are uncorrelated with the regressors, the size of the standard errors increase, yielding potentially insignificant results. When comparing the standard errors with and without the inclusion of control variables (odd versus even numbered columns), we observe that the standard errors are roughly similar in size. Unfortunately, this suggests that the measurement errors are likely to be correlated with the regressors. As a consequence, we fail to properly identify α_0 in equation (4.9) and φ_0 in equation (4.10), which helps to explain the incorrectly-signed point estimates.

Furthermore, the estimates are muddled by the fact that exposure during the birth month varies depending on how long an infant was in-utero. For infants born premature, SO_2 exposure is measured as early as the third month of pregnancy, and exposure at this point during fetal development could have different effects than exposure during the final month of pregnancy for a full-term infant.[10] Models that measure exposure during each of the months prior to and including the birth month are likely to be more useful and telling than the model indicating exposure only during the month of birth. Unfortunately, this issue arises for all estimation samples when examining the impact of SO_2 exposure during the birth month on prematurity.

Interestingly, though not surprisingly, mothers who smoke increased the likelihood of premature birth by 1.8 percentage points when compared to non-smoking mothers (columns (2) and (4)). At the mean proportion of pre-term births (5.44%) in the two counties, the estimate indicates a 33.1% increase in prematurity.

Table 7.8 shows OLS and 2SLS estimates for the impact of SO_2 exposure during the birth month with the addition of Sussex County to the sample. Again, Panel A and Panel B tell an unexpected story. Regardless of whether we consider OLS or 2SLS, the estimates indicate that exposure reduces the likelihood of pre-term birth. These results are potentially explained by two factors, as mentioned previously. First, since gestational length is a potentially noisy measure, and if the measurement errors are correlated with regressors, we yield insignificant 2SLS estimates. Second, since we are using a sample of births that includes full- and pre-term births, the point in time at which SO_2 exposure during the birth month is measured varies depending on gestation length. Again, the coefficients for maternal smoking are significant, indicating a 1.5 percentage point increase in the likelihood of pre-term birth for mothers who

[10]For pre-term cases in our sample of live, singleton, and in-hospital births, gestation length ranged between 15 and 36 weeks.

smoke (columns (2) and (4)).

Table 7.8: Effect of SO_2 Exposure During Birth Month on Prematurity$^{\diamond}$, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties)

	OLS		2SLS	
	(1)	(2)	(3)	(4)
X_t	-0.001**	-0.001**	-0.005	-0.004
	(0.000)	(0.000)	(0.004)	(0.004)
Smoking status$^{\diamond}$		0.015***		0.015***
		(0.004)		(0.004)
First-stage partial F			10.528	10.712
p-value for first-stage partial F			0.002	0.002
Control variables	No	Yes	No	Yes
# of zip codes	84	84	84	84
# of observations	84,784	81,577	84,784	81,577

$^{\diamond}$ Pre-term and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

Table 7.9 shows estimates for the sample including Hunterdon, Morris, Sussex, and Warren Counties. We observe similar, and unusual, results when compared to the sample that excludes Warren County. Both OLS and 2SLS estimates indicate that SO_2 exposure during the birth month reduces the likelihood of prematurity. Again, we observe the OLS estimates (in Panel A) are significant while the 2SLS estimates (Panel B) are insignificant. The main difference with the inclusion of Warren County in the sample is that magnitudes of the coefficients have become smaller, which is expected, particularly for the 2SLS estimates given that IV exogeneity is likely violated for residents of Warren County. We note that the coefficients for maternal smoking are also smaller in magnitude and indicate a 1.1 percentage point increase in the probability of premature birth for mothers who smoke.

Table 7.10 shows OLS and 2SLS estimates for the sample including only Warren County. Both OLS and 2SLS are insignificant from zero, though the 2SLS estimate with no control variables is correctly-signed (column (3)). Even maternal smoking has no effect on the likelihood of prematurity (columns (2) and (4)). The insignificant results are likely attributable to the fact that Warren County is the smallest of the four counties in terms of population

Table 7.9: Effect of SO_2 Exposure During Birth Month on Prematurity$^\diamond$, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties)

	OLS		2SLS	
	(1)	(2)	(3)	(4)
X_t	-0.001**	-0.001*	-0.002	-0.002
	(0.000)	(0.000)	(0.002)	(0.002)
Smoking status$^\diamond$		0.011***		0.011***
		(0.003)		(0.003)
First-stage partial F			31.565	31.729
p-value for first-stage partial F			0.000	0.000
Control variables	No	Yes	No	Yes
# of zip codes	101	101	101	101
# of observations	97,158	93,754	97,158	93,754

$^\diamond$ Pre-term and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

and, thus, has the fewest number of observations. We are attempting to identify an effect on a small portion of the population (pre-term births) for a sample that is already small; therefore, the insignificant coefficients are unsurprising. Furthermore, the similarity in between the OLS and 2SLS estimates is expected given that IV exogeneity is likely violated for Warren County.

7.2.3 APGAR Scores

Table 7.11 shows OLS and 2SLS estimates for the impact of prenatal exposure to SO_2 during the birth month on 1- and 5-minute APGAR scores as well as the likelihoods of normal 1- and 5-minute APGAR scores for Hunterdon and Morris Counties. OLS estimates (Panel A) are insignificant and positively (incorrectly) signed. However, the 2SLS estimates (Panel B), though insignificant, are correctly (negatively) signed and are larger in magnitude than the OLS coefficients. Since 1-minute APGAR scores are not necessarily indicative of long-term health, and since most infants score higher at the 5-minute recording, the impacts on 5-minute APGAR scores (columns (5)-(8)) are much smaller than the impacts on 1-minute scores (columns (1)-(4)). The likelihood of birth with a normal 1-minute APGAR score is

Table 7.10: Effect of SO_2 Exposure During Birth Month on Prematurity$^\diamond$, OLS and 2SLS Estimates (Warren County)

	OLS		2SLS	
	(1)	(2)	(3)	(4)
X_t	0.000	0.000	0.001	-0.000
	(0.000)	(0.000)	(0.002)	(0.002)
Smoking status$^\diamond$		-0.000		-0.000
		(0.004)		(0.004)
First-stage partial F			21.193	21.025
p-value for first-stage partial F			0.000	0.000
Control variables	No	Yes	No	Yes
# of zip codes	17	17	17	17
# of observations	12,374	12,177	12,374	12,177

$^\diamond$ Pre-term and smoking status are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

reduced by 0.3 percentage points, or about 0.1% at the mean proportion in the two counties. The results for the 5-minute APGAR score measures are likely explained by the fact that little variation exists in the likelihood of a normal 5-minute APGAR score (recall that over 99% were born with a normal 5-minute score). Interestingly, maternal smoking appears to have no or negligible impacts on APGAR scores.

In Table 7.12, we add Sussex County to the estimation sample. Panel A shows OLS estimates, all of which are incorrectly (positively) signed and insignificant from zero. These estimates are similar to those observed in Panel A of Table 7.11. Panel B shows 2SLS estimates, and all coefficients are still insignificant and negative for the impacts on the 1-minute APGAR score measures (columns (1)-(4)). Exposure to SO_2 during the birth month reduces the likelihood of birth with a normal 1-minute APGAR score by 0.4 percentage points, which, again, is negligible at the mean proportion of roughly 96% in the three counties. For 5-minute APGAR scores (columns (5) and (6)), magnitudes have increased with the addition of Sussex County, but the estimates are positively signed. For the likelihood of a normal 5-minute APGAR score, the impact is zero, which is likely attributable to the fact that very little variation exists in the percentage of infants with a normal 5-minute APGAR

Table 7.11: Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon and Morris Counties)

	1-minute APGAR		Normal 1-minute APGAR$^\diamond$		5-minute APGAR		Normal 5-minute APGAR$^\diamond$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: OLS Estimates								
X_t	0.001	0.001	0.000	0.000	0.002	0.002	0.000	0.000
	(0.003)	(0.003)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)
Smoking status$^\diamond$		-0.009		-0.000		0.001		-0.001
		(0.013)		(0.003)		(0.007)		(0.001)
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	76	76	76	76	76	76	76	76
# of observations	70,162	67,713	70,162	67,713	70,175	67,726	70,175	67,726
Panel B: 2SLS Estimates								
X_t	-0.016	-0.016	-0.003	-0.003	0.004	0.001	-0.000	-0.000
	(0.016)	(0.017)	(0.003)	(0.003)	(0.007)	(0.006)	(0.001)	(0.001)
Smoking status$^\diamond$		-0.008		0.000		0.001		-0.001
		(0.013)		(0.003)		(0.007)		(0.001)
First-stage partial F	14.352	14.881	14.352	14.881	14.350	14.880	14.350	14.880
p-value (F)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	76	76	76	76	76	76	76	76
# of observations	70,162	67,713	70,162	67,713	70,175	67,726	70,175	67,726

$^\diamond$ Normal 1-minute and 5-minute APGAR scores are greater than or equal to 7. These, and smoking status, are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

score. Again, we note the insignificant and small point estimates for the impact of maternal smoking on APGAR scores.

Table 7.13 shows estimates with the inclusion of Warren County to the sample. The OLS estimates in Panel A are finally correctly-signed (negative), except for the likelihood of a normal 5-minute score (columns (7) and (8)), for which the coefficients are zero. Panel B, showing 2SLS estimates, demonstrates that prenatal exposure to SO_2 during the month of birth has a significant and negative impact on 1-minute APGAR scores (columns (1) and (2)) as well as the likelihood of a normal 1-minute score (columns (3) and (4)). However, the relative magnitudes are small when evaluated at their respective means; the estimates translate into a 0.022 point reduction in the mean 1-minute APGAR score (which is about

Table 7.12: Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon, Morris, and Sussex Counties)

	1-minute APGAR		Normal 1-minute APGAR$^\diamond$		5-minute APGAR		Normal 5-minute APGAR$^\diamond$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: OLS Estimates								
X_t	0.002	0.002	0.000	0.000	0.002	0.002	0.000	0.000
	(0.003)	(0.003)	(0.000)	(0.000)	(0.001)	(0.001)	(0.000)	(0.000)
Smoking status$^\diamond$		-0.014		-0.002		-0.000		-0.001
		(0.011)		(0.003)		(0.007)		(0.001)
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	84	84	84	84	84	84	84	84
# of observations	79,881	77,038	79,881	77,038	79,895	77,052	79,895	77,052
Panel B: 2SLS Estimates								
X_t	-0.012	-0.015	-0.004	-0.004	0.011	0.008	0.000	0.000
	(0.015)	(0.016)	(0.003)	(0.003)	(0.012)	(0.011)	(0.001)	(0.001)
Smoking status$^\diamond$		-0.013		-0.002		-0.000		-0.001
		(0.011)		(0.002)		(0.007)		(0.001)
First-stage partial F	10.623	10.806	10.623	10.806	10.625	10.809	10.625	10.809
p-value (F)	0.002	0.001	0.002	0.001	0.002	0.001	0.002	0.001
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	84	84	84	84	84	84	84	84
# of observations	79,881	77,038	79,881	77,038	79,895	77,052	79,895	77,052

$^\diamond$ Normal 1-minute and 5-minute APGAR scores are greater than or equal to 7. These, and smoking status, are 1/0 dummy variables (see 3.1.5).
Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

8.4 in the four counties) and a 0.3 percentage point reduction in the likelihood of a normal 1-minute APGAR score (with a mean of about 95%). We also observe negative coefficients for the impact of exposure on the 5-minute APGAR score measures, but, again, the magnitudes are small when evaluated at the mean.

Table 7.14 shows the impact of prenatal exposure to SO_2 during the birth month on APGAR scores for Warren County. Panel A, showing OLS estimates, are all negative and insignificant, excepting for the impact on the 5-minute APGAR score (columns (5) and (6)). Though significant, the point estimate of -0.008 is small in magnitude when evaluated at the mean 5-minute APGAR score in Warren County (9.1 out of 10). In Panel B, the 2SLS estimates are mostly negative but also insignificant. While the magnitudes are small, the

Table 7.13: Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Hunterdon, Morris, Sussex, and Warren Counties)

	1-minute APGAR		Normal 1-minute APGAR$^{\diamond}$		5-minute APGAR		Normal 5-minute APGAR$^{\diamond}$	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: OLS Estimates								
X_t	-0.002	-0.002	-0.000	-0.000	-0.002	-0.002	0.000	0.000
	(0.003)	(0.002)	(0.000)	(0.000)	(0.002)	(0.002)	(0.000)	(0.000)
Smoking status$^{\diamond}$		-0.000		-0.002		0.012		-0.000
		(0.011)		(0.002)		(0.009)		(0.001)
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	101	101	101	101	101	101	101	101
# of observations	91,545	88,539	91,545	88,539	91,559	88,553	91,559	88,553
Panel B: 2SLS Estimates								
X_t	-0.020**	- 0.022**	-0.003*	-0.003*	-0.001	-0.002	-0.001	-0.001
	(0.009)	(0.009)	(0.002)	(0.002)	(0.007)	(0.007)	(0.001)	(0.001)
Smoking status$^{\diamond}$		-0.001		-0.002		0.012		-0.000
		(0.011)		(0.002)		(0.009)		(0.001)
First-stage partial F	31.658	31.902	31.658	31.902	31.657	31.902	31.657	31.902
p-value (F)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	101	101	101	101	101	101	101	101
# of observations	91,545	88,539	91,545	88,539	91,559	88,553	91,559	88,553

$^{\diamond}$ Normal 1-minute and 5-minute APGAR scores are greater than or equal to 7. These, and smoking status, are 1/0 dummy variables (see 3.1.5).

Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

results for Warren County help to explain why the estimation sample containing all four counties see negatively-signed coefficients across the board.

7.3 In Summary

Though largely insignificant, the results for the APGAR score measures are somewhat promising. The insignificant results are likely attributable to the little variation that exists in the APGAR score measures. However, if we create additional groups (APGAR scores ranging from 1 to 3, 4 to 6, 7+), we may observe larger point estimates that provide more meaningful interpretations.

Table 7.14: Effect of SO_2 Exposure During Birth Month on APGAR Scores, OLS and 2SLS Estimates (Warren County)

	1-minute APGAR		Normal 1-minute APGAR◇		5-minute APGAR		Normal 5-minute APGAR◇	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Panel A: OLS Estimates								
X_t	-0.000	-0.000	-0.001	-0.001	-0.008***	-0.008***	-0.000	-0.000
	(0.004)	(0.003)	(0.001)	(0.001)	(0.002)	(0.002)	(0.000)	(0.000)
Smoking status◇		0.040		-0.003		0.049*		0.001
		(0.032)		(0.006)		(0.025)		(0.003)
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17	17	17
# of observations	11,664	11,501	11,664	11,501	11,664	11,501	11,664	11,501
Panel B: 2SLS Estimates								
X_t	0.001	-0.003	0.002	0.001	-0.005	-0.006	-0.001	-0.001
	(0.009)	(0.009)	(0.003)	(0.003)	(0.008)	(0.009)	(0.001)	(0.001)
Smoking status◇		0.040		-0.003		0.049**		0.001
		(0.032)		(0.006)		(0.025)		(0.003)
First-stage partial F	21.535	21.317	21.535	21.317	21.535	21.317	21.535	21.317
p-value (F)	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Control variables	No	Yes	No	Yes	No	Yes	No	Yes
# of zip codes	17	17	17	17	17	17	17	17
# of observations	11,664	11,501	11,664	11,501	11,664	11,501	11,664	11,501

◇ Normal 1-minute and 5-minute APGAR scores are greater than or equal to 7. These, and smoking status, are 1/0 dummy variables (see 3.1.5).

Notes: X_t is zip-code-level, inverse-distance-weighted, monthly average SO_2 (ppb) at time t (t = 01/1995 to 12/2006). All specifications include weather variables, zip code fixed effects, and month-year fixed effects. Control variables include infant's sex, mother's characteristics (race, ethnicity, prenatal care visits), and maternal smoking (see Chapter 4.5). Standard errors (shown in parentheses) are clustered at the zip code level. Significance: * 10% level; ** 5% level; *** 1% level.

For the impact of prenatal exposure to SO_2 during the birth month on prematurity, the estimates are incorrectly-signed and puzzling. However, as mentioned previously, the dummy for pre-term birth is created based on estimated clinical gestational age, which is a potentially noisy measure. Furthermore, SO_2 exposure during the birth month is assigned differently across observations depending on the length of gestation. For instance, an infant born premature during the fourth month of pregnancy is assigned pollution exposure at a different point during fetal development than a full-term infant who is assigned pollution exposure in the final month, when much of the development has already occurred.

7.3.1 Discrepancies Between HCUP and Birth Certificate Results

Unfortunately, the results contained in Section 7.2.1 for the impact of prenatal SO_2 exposure during the birth month on infant birth weight and related outcomes are not entirely consistent with the results obtained using the HCUP data. Generally, the estimates using the birth certificate records are smaller, insignificant, and sometimes unexpectedly signed. Even more troubling is that the results are not strong for the estimation samples including only Hunterdon and Morris Counties as well as Hunterdon, Morris and Sussex Counties, for which we previously observed strong and consistent results using the HCUP data. Oddly, the Warren County sample is the only one for which the birth certificate and HCUP estimates of the impact on birth weight measures are fairly consistent. Also, as might be expected given our sample selection process, the fact that we find insignificant results for the impact on VLBW is somewhat reassuring about our elimination of pre-term cases from our estimation samples.

Nonetheless, the inconsistent findings for birth weight and LBW are particularly troubling since the criteria used for sample selection are similar between the two data sets. Since the HCUP samples include live, singleton births that occurred in hospitals, we subset to live, singleton, in-hospital births for our samples using the birth certificates. Therefore, our estimation samples using the birth certificates should capture the same births as our samples using the HCUP. As a result, estimates using either data set should be very similar; however, they are not (with the exception of Warren County).[11]

One potential explanation for the discrepancies may be the choice of control variables. While the HCUP estimations include controls for an infant's sex, race, and insurance status, the birth certificate estimations include controls for an infant's sex but *mother's* race and ethnicity characteristics as well as prenatal care utilization and smoking status. The inclusion of prenatal care utilization and smoking status likely mitigates some of the downward-bias

[11]We have further verified this notion by checking summary statistics for the pollution and weather variables, which are very similar to those obtained using the HCUP data. These statistics are available upon request.

incurred by an OLS estimator (and the 2SLS estimator in the case of Warren County), but their inclusion also reduces the variation in the birth weight outcomes of interest and, thus, may yield insignificant or incorrectly-signed estimates. However, comparing estimates with and without these control variables are still similar in sign, magnitude, and significance.

Another possibility is that differences exist in the reporting of infant birth-related information across hospitals. For instance, certain hospitals may over-report birth weight while others under-report birth weight; or hospitals may report differentially in their discharge abstracts when compared to the information submitted on the birth certificate forms to the New Jersey Department of Health. If this is the case, then the variables obtained using the birth certificate records will be inconsistent when compared to the HCUP. We can potentially address this problem in the future by including indicators for each hospital.

Since our measurement of prematurity using gestation length (with the birth certificates) is likely more accurate than the use of ICD-9 codes to identify prematurity (with the HCUP data), another possible explanation is that we have eliminated much of the variation in some of the outcome variables related to birth weight. Mean birth weights are slightly greater, by about 10 to 20 grams, in the birth certificate records compared to the HCUP data (see Tables 5.2 and 7.1). Additionally, the mean proportions of LBW and VLBW are approximately one-half percentage point lower across the analysis counties according to the birth certificate records. Furthermore, we note that the size of the standard errors for birth weight, LBW, and VLBW are also smaller in the birth certificates. We are attempting to identify an effect on smaller portions of the population (LBW, VLBW) compared to the HCUP, and these smaller portions also exhibit less variation. Consequently, we are unable to find any significant effects on birth weight and related outcomes.

Chapter 8

Conclusion

In this final chapter, we provide a summary of our study and results (Section 8.1). We also discuss current limitations as well as potential extensions to our study (Section 8.2).

8.1 Conclusions

This study seeks to examine the impact of prenatal exposure to sulfur dioxide (SO_2) on infant health at birth. Understanding the factors that affect fetal health and, consequently, infant health at birth are of utmost importance since health at birth is highly correlated with many early and later life outcomes.[1] From an empirical standpoint, estimation of the impact of prenatal exposure to air pollution poses a challenge due to the possible presence of endogeneity–mothers may choose to reside in an economically vibrant area, which experiences higher levels of pollution because of greater economic activity, but due to higher incomes, mothers may utilize greater quantities of health care. In this event, the true impact of prenatal pollution exposure on infant health at birth would be understated.

In order to address the issue of endogeneity, we apply the institutional setting utilized by Yang and Chou (2015), a setting which is supported by the New Jersey Department of Environmental Protection (NJDEP) and the U.S. Environmental Protection Agency (EPA).

[1] See Chapter 2 for a literature overview.

According to this situation, the NJDEP identified several regions of New Jersey that were affected by Portland Generating Station (PGS), a coal-fired power plant in eastern Pennsylvania. The affected counties include Hunterdon, Morris, Sussex, and Warren. Under this setting, we employ Yang and Chou's instrumental variable approach in which direction-adjusted SO_2 emissions from PGS instrument for SO_2 concentrations in the four identified counties.

For this study, we bring together several different data sets. Pollution and emissions data come from the EPA's Air Quality System (AQS) and Air Markets Program Data (AMPD). Weather-related variables come from the National Oceanic and Atmospheric Administration's National Climatic Data Center Integrated Surface Data. We combine the weather and pollution variables with two different data sets for birth outcomes–one is the Healthcare Cost and Utilization Project (HCUP) State Inpatient Database (SID) for the state of New Jersey; the other is the New Jersey Department of Health's birth certificate records.

Using the HCUP data, we find strong first- and second-stage results. According to the first-stage estimates, PGS emissions of SO_2 increase zip-code-level SO_2 concentrations in Hunterdon, Morris, Sussex, and Warren Counties but do not affect concentrations in other New Jersey counties. According to our estimates, a 1,000-ton-increase in SO_2 emissions from PGS increases zip-code-level SO_2 concentrations by about 1.78 ppb in Warren County and 1.04 ppb in all four counties combined. In the second-stage, IV estimates indicate that a 1-ppb increase in prenatal exposure to SO_2 during the birth month increases the likelihoods of low birth weight (LBW) by about 0.5 percentage points and very low birth weight (VLBW) by 0.4 percentage points. At their respective mean percentages, around 4% for LBW and 1% for VLBW, the estimates translate into relatively large percentage increases in these proportions. The estimates for the impact on LBW and VLBW are relatively robust to the use of different estimation samples as well as the use of an alternative radius in constructing the zip-code-level pollution and weather measures. With the inclusion of exposure during each of the months prior to and including the birth month, we find even larger point estimates–a 1-ppb increase in prenatal SO_2 exposure increases the likelihoods of LBW and VLBW by roughly 1.0 percentage point and 0.6 percentage points, respectively.

Unfortunately, the use of the New Jersey birth certificate records produces mixed results. With respect to the impacts of exposure during the birth month on birth weight, LBW, and VLBW, the results are inconsistent with those found using the HCUP data. Generally, even the 2SLS estimates are small in magnitude and sometimes wrong-signed. Interestingly, we find a statistically significant decrease in birth weight (about 16 grams) for Warren County. Equally puzzling are the results for the impact of exposure on prematurity. Though largely insignificant, the estimates are incorrectly-signed and indicate that exposure *decreases* the likelihood of pre-term birth, with the exception of Warren County. Lastly, we explore the impact of SO_2 exposure during the birth month on 1-minute and 5-minute APGAR score measures. While we find correctly-signed estimates for 1-minute APGAR measures, they are largely insignificant and very small in magnitude.

Nevertheless, despite today's relatively low levels of pollution, due largely to the Clean Air Act of 1970, the results of our study suggest that further pollution abatement may be beneficial, even for affluent regions, such as Hunterdon, Morris, and Sussex Counties, which already have excellent access to health care.

8.2 Limitations and Extensions

Though we address the issue of endogeneity through the use of an IV estimator as well as an additional data set that allows for various control variables, at present, several limitations to our study exist, for which we address potential solutions.

One major limitation is that we are unable to determine at what points in time during development a fetus is most vulnerable to SO_2 exposure. While we incorporate models measuring exposure during each of the months prior to and including the birth month (with the HCUP data), we are unable to identify gestational age and cannot determine with absolute certainty if the births in our sample are full-term. Nonetheless, we attempt to mitigate this possibility by excluding extremely immature cases due to short gestation in our primary analysis. Additionally, we plan to use the birth certificate data, which includes gestational age, to run models that incorporate prenatal exposure to SO_2 during each of the months prior to and including the birth month. We can also estimate models for exposure during each trimester using this data set. We anticipate that these models may yield more consistent estimates, at least in the sense that they are correctly-signed. Further evidence to support this notion is that, using the HCUP data, we observe larger cumulative effects of prenatal SO_2 exposure as compared to the effect of exposure in a given month.

Although the New Jersey birth certificate records contain gestational age, we use "clinical estimation of gestational age", which is a potentially noisy measure. If the measurement errors in gestational age are uncorrelated with regressors, then the impact of prenatal exposure to SO_2 can be identified but standard errors will increase in size. However, if the measurement errors are correlated with regressors, then we are unable to identify the impact of prenatal exposure to SO_2. Unfortunately, our results suggest that the latter may be the issue. In order to address potential measurement error in gestational age, we check the estimated gestational age with "recalculated" gestational age, which takes into account a mother's last menses. We find that estimated clinical gestational age and the recalculated gestational age are nearly identical.

Another limitation of our study is the use of live births in our analysis samples. Using only live births is likely to incur "fetal selection" bias ([Currie, 2009]). In other words, our findings are relevant for those infants who survived an adverse in-utero event but not for those who died. The use of only these survivors is likely to downward-bias estimates of, and thus, understate, the impact of prenatal exposure to SO_2 on infant health at birth. Unfortunately, in the HCUP, we are only able to identify live births; we have no way to determine a stillbirth. While our analysis using the New Jersey birth certificates is limited to live births, we can extend the sample to include all births, though live births comprise nearly all births (over 99.6%) in the records.

According to biological theory, the causal pathway of the relationship between prenatal exposure to SO_2 and infant birth weight is governed by two main factors, short gestation (premature birth) and slow fetal growth (intrauterine growth retardation). We lack information on both of these factors using the HCUP data. Despite strong and consistent results using this data set, the impact of prenatal exposure to SO_2 on infant birth weight that we have identified is *indirect*, at best. We attempt to address this issue using the New Jersey birth certificates by examining a direct outcome, the likelihood of pre-term birth. While the data do not have direct information on slow fetal growth, we may be able to use birth weight tables to construct an indicator for small-for-gestational-age using gestational age and birth weight at the time of birth. Nonetheless, in subsequent analyses, we seek to explore the impact of exposure on prematurity as well as how it relates to and potentially affects birth weight in hopes to identify a more direct effect.

The possibility also remains that additional pollutants, such as nitrogen dioxide (NO_2) and carbon monoxide (CO), emitted by PGS have also traveled through the air into neighboring counties in New Jersey. Our focus is on SO_2, which is the only pollutant identified by the NJDEP and EPA as having affected the four New Jersey counties. However, if these other potentially correlated pollutants did, in fact, travel by way of the wind into New Jersey, our estimates of the impact of prenatal exposure to SO_2 on infant health at birth are likely to be overstated. Subsequent models and analyses should include NO_2 and CO, and even other air pollutants, in order to evaluate their individual as well as interactive effects with SO_2.

Finally, we can explore alternative ways of constructing pollution measures. Rather than using zip-code-level, monthly pollutant concentrations, the birth certificate records affords the opportunity to construct weekly or even daily pollution measures based on an infant's exact birth date. Geographically speaking, we can more precisely assign pollution based on the latitudinal and longitudinal coordinates of a mother's residential address. With greater temporal and geographic precision, we would create pollution measures that exhibit greater variation, which could potentially yield more meaningful estimates.

Bibliography

[Almond et al., 2005] Almond, D., Chay, K. Y., and Lee, D. S. (2005). "The Costs of Low Birth Weight". *The Quarterly Journal of Economics*, 120(3):1031–1083.

[Apgar, 1953] Apgar, V. (1953). "A Proposal for a New Method of Evaluation of the Newborn Infant". *Current Researches in Anesthesia and Analgesia*, 32(4):260–267.

[Barker, 1998] Barker, D. J. P. (1998). "The Immediate and Long-Term Consequences of Low Birthweight". In *Technical Consultation on Low Birthweight*, New York. UNICEF.

[Behrman and Rosenzweig, 2004] Behrman, J. R. and Rosenzweig, M. R. (2004). "Returns to Birthweight". *The Review of Economics and Statistics*, 86(2):586–601.

[Behrman et al., 1994] Behrman, J. R., Rosenzweig, M. R., and Taubman, P. (1994). "Endowments and the Allocation of Schooling in the Family and in the Marriage Market: The Twins Experiment". *Journal of Political Economy*, 102(6):1131–1174.

[Brooks et al., 2001] Brooks, A.-M., Byrd, R. S., Weitzman, M., Auinger, P., and McBride, J. T. (2001). "Impact of Low Birth Weight on Early Childhood Asthma in the United States". *Archives of Pediatrics & Adolescent Medicine*, 155(3):401–406.

[Bui et al., 1986] Bui, Q. Q., Tran, M. B., and West, W. L. (1986). "A Comparative Study of the Reproductive Effects of Methadone and Benzo[a]pyrene in the Pregnant and Pseudopregnant Rat". *Toxicology*, 42(2-3):195–204.

[Casey et al., 2001] Casey, B. M., McIntire, D. D., and Leveno, K. J. (2001). "The Continuing Value of the Apgar Score for the Assessment of Newborn Infants". *The New England Journal of Medicine*, 344(7):467–471.

[Currie, 2009] Currie, J. (2009). "Healthy, Wealthy, and Wise: Socioeconomic Status, Poor Health in Childhood, and Human Capital Development". *Journal of Economic Literature*, 47(1):87–122.

[Currie and Hyson, 1999] Currie, J. and Hyson, R. (1999). "Is the Impact of Health Shocks Cushioned by Socioeconomic Status? The Case of Low Birthweight". *Papers and Proceedings of the One Hundred Eleventh Annual Meeting of the American Economic Association*, 89(2):245–250.

[Currie and Neidell, 2005] Currie, J. and Neidell, M. (2005). "Air Pollution and Infant Health: What Can We Learn From California's Recent Experience?". *The Quarterly Journal of Economics*, 120(3):1003–1030.

[Currie et al., 2009] Currie, J., Neidell, M., and Schmieder, J. F. (2009). "Air Pollution and Infant Health: Lessons from New Jersey". *Journal of Health Economics*, 28(3):688–703.

[Dejmek et al., 2000] Dejmek, J., Solanskỳ, I., Beneš, I., Lenìček, J., and Šràm, R. J. (2000). "The Impact of Polycyclic Aromatic Hydrocarbons and Fine Particles on Pregnancy Outcome". *Environmental Health Perspectives*, 108(12):1159–1164.

[Doublet et al., 1997] Doublet, P., Benson, C. B., Nadel, A. S., and Ringer, S. A. (1997). "Improved Birth Weight Table for Neonates Developed from Gestations Dated by Ultrasonography". *Journal of Ultrasound Medicine*, 16(4):241–249.

[Gibbs et al., 1992] Gibbs, R. S., Romero, R., Hillier, S. L., Eschenbach, D. A., and Sweet, R. L. (1992). "A Review of Premature Birth and Subclinical Infection". *American Journal of Obstetrics and Gynecology*, 166(5):1515–1528.

[Hardy and Thom, 1994] Hardy, K. R. and Thom, S. R. (1994). “Pathophysiology and Treatment of Carbon Monoxide Poisoning”. *Journal of Toxicology Clinical Toxicology*, 32(6):613–629.

[Kannan et al., 2006] Kannan, S., Misra, D. P., Dvonch, J. T., and Krishnakumar, A. (2006). “Exposures to Airborne Particulate Matter and Adverse Perinatal Outcomes: A Biologically Plausible Mechanistic Framework for Exploring Potential Effect Modification by Nutrition”. *Environmental Health Perspectives*, 114(11):1636–1642.

[Keen et al., 2003] Keen, C. L., Klegg, M., Hanna, L. A., Lanoue, L., Rogers, J. M., Daston, G. P., Oteiza, P., and Uriu-Adams, J. Y. (2003). “The Plausibility of Micronutrient Deficiencies Being a Significant Contributing Factor to the Occurrence of Pregnancy Complications”. *Journal of Nutrition*, 133(5 Suppl 2):1597S–1605S.

[Koren et al., 1991] Koren, G., Sharav, T., Pastuszak, A., Garrettson, L. K., Hill, K., Samson, I., and et al. (1991). “A Multicenter Prospective Study of Fetal Outcome Following Accidental Carbon Monoxide Poisoning During Pregnancy”. *Reproductive Toxicology*, 5(5):397–403.

[Liu et al., 2003] Liu, S., Krewski, D., Shi, Y., Chen, Y., and Burnett, R. T. (2003). “Association Between Gaseous Ambient Air Pollutants and Adverse Pregnancy Outcomes in Vancouver, Canada”. *Environmental Health Perspectives*, 111(14):1773–1778.

[Longo, 1977] Longo, L. D. (1977). “The Biological Effects of Carbon Monoxide on the Pregnant Woman, Fetus, and Newborn Infant”. *American Journal of Obstetrics and Gynecology*, 129(1):69–103.

[Maroziene and Grazuleviciene, 2002] Maroziene, L. and Grazuleviciene, R. (2002). “Maternal Exposure to Low-Level Air Pollution and Pregnancy Outcomes: A Population-Based Study”. *Environmental Health*, 1(1):6.

[Nelson and Grether, 1997] Nelson, K. B. and Grether, J. K. (1997). "Cerebral Palsy in Low-Birthweight Infants: Etiology and Strategies for Prevention". *Mental Retardation and Developmental Disabilities Research Reviews*, 3(2):112–117.

[Parker et al., 2005] Parker, J. D., Woodruff, T. J., Basu, R., and Schoendorf, K. C. (2005). "Air Pollution and Birth Weight Among Term Infants in California". *Pediatrics*, 115(1):121–128.

[Perera et al., 1992] Perera, F. P., Hemminki, K., Gryzbowska, E., Motykiewicz, G., Michalska, J., Santella, R. M., Young, T.-L., Dickey, C., Brandt-Rauf, P., DeVivo, I., and et al. (1992). "Molecular and Genetic Damage in Humans from Environmental Pollution in Poland". *Nature*, 360(6401):256–258.

[Perera et al., 1999] Perera, F. P., Jedrychowski, W., Rauh, V., and Whyatt, R. M. (1999). "Molecular Epidemiologic Research on the Effects of Environmental Pollutants on the Fetus". *Environmental Health Perspectives*, 107(Suppl 3):451–460.

[Perera et al., 1988] Perera, F. P., Whyatt, R. M., Jedrychowski, W., Rauh, V., Manchester, D., Santella, R. M., and Ottman, R. (1988). "Recent Developments in Molecular Epidemiology: A Study of the Effects of Environmental Polycyclic Aromatic Hydrocarbons on Birth Outcomes in Poland". *American Journal of Epidemiology*, 147(3):309–314.

[Peters et al., 1997] Peters, A., Doring, A., Wichmann, H. E., and Koenig, W. (1997). "Increased Plasma Viscosity During an Air Pollution Episode: A Link to Mortality?". *Lancet*, 349(9065):1582–1587.

[Ritz et al., 2007] Ritz, B., Wilhelm, M., Hoggatt, K. J., and Ghosh, J. K. (2007). "Ambient Air Pollution and Preterm Birth in the Environment and Pregnancy Outcomes Study at the University of California, Los Angeles". *American Journal of Epidemiology*, 166(9):1045–1052.

[Ritz et al., 2000] Ritz, B., Yu, F., Chapa, G., and Fruin, S. (2000). "Effect of Air Pollution on Preterm Birth Among Children Born in Southern California Between 1989 and 1993". *Epidemiology*, 11(5):502–511.

[Roberts et al., 1991] Roberts, J. M., Taylor, R. N., and Goldfien, A. (1991). "Clinical and Biochemical Evidence of Endothelial Cell Dysfunction in the Pregnancy Syndrome Preeclampsia". *American Journal of Hypertension*, 4(8):700–708.

[Shah and Balkhair, 2011] Shah, P. S. and Balkhair, T. (2011). "Air Pollution and Birth Outcomes: A Systematic Review". *Environment International*, 37(2):498–516.

[Singh, 1989] Singh, J. (1989). "Neonatal Development Altered By Maternal Sulfur Dioxide Exposure". *Neurotoxicology*, 10(3):523–527.

[Tabacova et al., 1998] Tabacova, S., Baird, D. D., and Balabaeva, L. (1998). "Exposure to Oxidized Nitrogen: Lipid Peroxidation and Neonatal Health Risk". *Archives of Environmental Health*, 53(3):214–221.

[Tabacova et al., 1985] Tabacova, S., Nikiforov, B., and Balabaeva, L. (1985). "Postnatal Effects of Maternal Exposure to Nitrogen Dioxide". *Neurobehavioral Toxicology and Teratology*, 7:785–789.

[Topinka et al., 2009] Topinka, J., Milcova, A., Libalova, H., Novakova, Z., Jr, P. R., Balascak, I., and et al. (2009). "Biomarkers of Exposure to Tobacco Smoke and Environmental Pollutants in Mothers and Their Transplacental Transfer to the Foetus. Part I: Bulky DNA Adducts". *Mutation Research/Fundamental and Molecular Mechanisms of Mutagenesis*, 669:13–19.

[Tuovinen et al., 1993] Tuovinen, J. P., Laurila, T., Lättilä, H., Ryaboshapko, A., Brukhanov, P., and Korolev, S. (1993). "Impact of the Sulphur Dioxide Sources in the Kola Peninsula on Air Quality in Northernmost Europe". *Atmospheric Environment. Part A. General Topics.*, 27(9):1379–1395.

[Walters et al., 2001] Walters, D. M., Breysse, P. N., and Wills-Karp, M. (2001). "Ambient Urban Baltimore Particulate-Induced Airway Hyperresponsiveness and Inflammation in Mice". *American Journal of Respiratory and Critical Care Medicine*, 164(8 pt 1):1438–1443.

[Yang and Chou, 2015] Yang, M. and Chou, S.-Y. (2015). "Impacts of Being Downwind of a Coal-Fired Power Plant on Infant Health at Birth: Evidence from the Precedent-Setting Portland Rule". *Working Paper*.

[Zondervan et al., 1987] Zondervan, H. A., Oosting, J., Hardeman, M. R., Smorenberg-Schoorl, M. E., and Treffers, P. E. (1987). "The Influence of Maternal Whole Blood Viscosity on Fetal Growth". *European Journal of Obstetrics & Gynecology and Reproductive Biology*, 25(3):187–194.

Curriculum Vitae

Rhea A. Bhatta

Department of Economics, Lehigh University
621 Taylor Street, Bethlehem, PA 18015
(732) 991-4201 (mobile)
rab204@lehigh.edu
http://www.lehigh.edu/~rab204

Education

Ph.D.	Economics, Lehigh University, September 2015
M.S.	Economics, Lehigh University, January 2010
B.S.	Economics, Lehigh University, May 2008
B.A.	Spanish (with honors), Lehigh University, May 2008

Dissertation

Title:	The Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Health at Birth
Committee:	Shin-Yi Chou (co-chair), Muzhe Yang (co-chair), Alberto Lamadrid, & Anca Cotet-Grecu

---

Research Papers

Peer-Reviewed Articles & Reports:

1. Margaret Andrews, Rhea Bhatta, and Michele Ver Ploeg, "An Alternative to Developing Stores in Food Deserts: Can Changes in SNAP Benefits Make a Difference?", *Applied Economic Perspectives and Policy*, 35(1): 150–170, December 2012.

2. Steven Zahniser, Marcela Vera Torres, José Alberto Cuéllar Álvarez, Nicolás Fernando López, and Rhea Bhatta, "The U.S. and Mexican Dry Bean Sectors", U.S. Department of Agriculture, Economic Research Service, Electronic Outlook Report VGS-341-01, http://webarchives.cdlib.org/sw12j6951w/http://www.ers.usda.gov/Publications/VGS/2010/10Oct/VGS34101/VGS34101.pdf, December 2010.

Working Papers

1. Rhea Bhatta, Muzhe Yang, Shin-Yi Chou, and Cheng-I Hsieh, "Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Birth Weight: Evidence from a Pennsylvania Power Plant Located Upwind of New Jersey".

2. Rhea Bhatta, Li-San Wang, Shin-Yi Chou, Laura Cantwell, and Gerard Schellenberg, "Alzheimer's Disease and Toxicity Exposure: A Gene-Environment Interactions Analysis".

Research Experience

Consultant: World Bank Group
Editorial revision of Bangladesh Poverty Assessment (02/2013–05/2013)

Intern: University of Pennsylvania, Department of Pathology and Laboratory Medicine
Genetic data analysis (02/2013–05/2013)

Economist: U.S. Department of Agriculture, Economic Research Service (intern)
Food Economics Division (06/2011–08/2011, 07/2010–08/2010)
Markets & Trade Economics Division (05/2009–08/2009)

Research Assistant: Lehigh University, Department of Economics (Spring 2011)

Teaching Experience

Instructor:

Principles of Economics (Fall 2014, Spring 2015), Moravian College
Principles of Economics, online (Summer 2012, 2013, 2014), Lehigh University

Teaching Assistant (Lehigh University):

Money, Banking, & Financial Markets (Spring 2012; Spring 2014)
Principles of Economics (Fall 2009; Spring 2010; Fall 2010; Fall 2011)
Applied Microeconomics, online (Summer 2010)

Graduate Assistant:

Statistical Methods (Fall 2008, Spring 2009), Lehigh University

---

Professional Activities

Conference Presentations

- Western Economic Association International 89th Annual Conference: "Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Birth Weight: Evidence from a Pennsylvania Power Plant Located Upwind of New Jersey", Denver, CO, June 2014.
- Fifth Biennial Conference of the American Society of Health Economists: "Impacts of Prenatal Exposure to Sulfur Dioxide on Infant Birth Weight: Evidence from a Pennsylvania Power Plant Located Upwind of New Jersey", Los Angeles, CA, June 2014.
- Fourth Biennial Conference of the American Society of Health Economists: "The Impact of Prenatal Pollution Exposure on Infant and Child Health Outcomes", Minneapolis, MN, June 2012.
- Eastern Economic Association 38th Annual Meeting: "The Impact of Prenatal Pollution Exposure on Infant and Child Health Outcomes", Boston, MA, March 2012.

Peer-Reviewing Activity: Professional Journals

Maternal and Child Health

Professional Societies and Affiliations

American Economic Association
American Society of Health Economists
Eastern Economic Association
Western Economic Association International

Awards And Honors

Fall 2013	Warren York Fellow, Department of Economics, Lehigh University
Spring 2011	Research Assistantship, Lehigh University
2004–2008	Dean's List, Lehigh University
2006–2008	Phi Eta Sigma Honors Fraternity, Lehigh University
2006–2008	Omicron Delta Epsilon International Economics Honors Society, Lehigh University
2006–2008	Phi Beta Delta International Scholars Society, Lehigh University

Service Activities

Organizations, Lehigh University

Treasurer, U.S. Association of Energy Economics, January 2014–present

Member, Alpha Phi Omega National Service Fraternity, 2004–2008

Sergeant-at-Arms (appointed), Alpha Phi Omega National Service Fraternity, 2007

Vice President of Membership, Alpha Phi Omega National Service Fraternity, 2006

Treasurer, Alpha Phi Omega National Service Fraternity, 2005

Skills

Computer Skills:	Stata, SAS, Maple, LaTeX, MS Office Suite
Language:	English (native), Spanish (fluent), Bengali (conversational)

References

Shin-Yi Chou

Professor, Department of Economics, Lehigh University
Research Associate, National Bureau of Economics Research
621 Taylor Street, Bethlehem, PA 18015
syc2@lehigh.edu, (610) 758-3444

Muzhe Yang

Associate Professor, Department of Economics, Lehigh University
621 Taylor Street, Bethlehem, PA 18015
muzheyang@lehigh.edu, (610) 758-4962

Thomas Hyclak (Teaching)

Professor, Department of Economics, Lehigh University
621 Taylor Street, Bethlehem, PA 18015
tjh7@lehigh.edu, (610) 758-3425