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Exploring the Relationship between Air Pollution and Housing Prices in Owner-occupied and Rental Housing in the United States of America

by

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ABSTRACT

According to American Lung Association, over 40% of the American population resides in areas where pollutant levels exceed recommended thresholds, posing a significant health risk. For this reason, this study focuses on understanding the relationship between air pollution and housing prices, specifically how the relationship between owner-occupied and rental housing differs. Current academic literature found that air pollution had a negative relationship with the house value of owner-occupied housing, but limited research has been performed on rental housing. This thesis conducts cross-sectional and longitudinal studies by performing linear and polynomial regressions in each study. The study finds that the relationship between air pollution and housing prices for owner-occupied and rental housing is not linear. At the low and high levels of $PM_{2.5}$, the relationship with housing (rental) prices is negative. However, in the mid-level of $PM_{2.5}$, the relationship tends to be positive. In addition, as $PM_{2.5}$ increases or decreases within a specific range, there are corresponding increased in house values and rents. In conclusion, this study reveals a complex relationship between air pollution and housing prices in the United States, indicating potential socioeconomic disparities.

Keywords: *air pollution*, *particulate matter 2.5*, *owner-occupied*, *rental*, *United States*

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PREFACE

This master thesis titled "Exploring the Relationship between Air Pollution and Housing Prices for Owner-occupied and Rental Housings in the United States of America" represents the culmination of my academic journey and research in real estate studies. Air pollution and its relationship with housing prices have emerged as critical study topics in recent years. This thesis aims to investigate the complex relationship between air pollution levels and housing prices for owner-occupied and rental housing across different regions of the United States. Throughout this thesis, I have delved into extensive literature, analyzed large datasets, and applied rigorous statistic techniques to uncover intricate dynamics.

I am grateful to my advisor, Sarah L. Mawhorter, for her invaluable guidance, expertise, and unwavering support throughout this research. Her mentorship has played a pivotal role in shaping the direction and quality of this thesis. Furthermore, I would like to acknowledge the support and encouragement of my family and friends, who have stood by me during the ups and downs of this academic pursuit. Their belief in my abilities has been a constant source of motivation. Lastly, I appreciate the academic community and fellow researchers who have paved the way in studying real estate and its intersection with environmental factors. Their pioneering work laid the foundation for this thesis, and I hope my research contributes to the existing body of knowledge.

I hope this thesis provides valuable insights into the relationship between air pollution and housing prices, shedding light on the implications for owner-occupied and rental housing in the United States. It may catalyze further research and policy discussions to foster healthier, more sustainable urban environments.

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I. INTRODUCTION

1.1. Motivation

Most countries are currently grappling with the significant problem of air pollution. According to the World Health Organization (WHO), it poses a crucial threat to health and climate. WHO data shows that nearly the entire global population is exposed to air with elevated levels of pollutants, surpassing the organization's recommended limits. Based on the Air Quality and Health by WHO, several types of contaminants pose significant public health risks, such as particulate matter (PM), ground-level ozone, lead (Pb), carbon monoxide (CO), nitrogen dioxide (NO_2), and sulfur dioxide (SO_2). Although the report shows the most polluted area at the city level, WHO mentions that the presence of these pollutants depends on its location and can vary in each location; hence air pollution can be localized at the neighbourhood level. Transportation, the most significant source of air pollution, becomes localized in particularly dense traffic areas such as roads in and around cities (Robinson, 2018). Other than that, industrial facilities developed to increase economic growth in one localized area have a trade-off to the environmental quality, including increased air pollution (Nataraj et al., 2013). Additionally, the report mentions residential, wildfires, natural, and agricultural sources as the other origins of air pollution after transportation and industrial facilities. Nevertheless, countries worldwide have been trying to reduce air pollution and improve air quality through several policies implemented nationally.

According to the United States Environmental Protection Agency (EPA), the United States of America is one of the developed countries that has experienced an improvement in terms of air quality since 1980. Although significant strides have been made in enhancing air quality, in the report called State of the Air 2022, Harold Wimmer, the President and CEO of the American Lung Association (ALA), stated, "shows that an unacceptable number of Americans are still living in areas with poor air quality that could impact their health.". The report shows that 40% of Americans, over 137 million people, reside in areas with unhealthy particle pollution levels or ozone. According to the report, exposure to particle and ozone pollution can cause various health risks, such as increased risk of premature death, respiratory problems, cardiovascular problems, developmental and reproductive harm, and chronic diseases, such as cancer and diabetes. Consequently, air pollution is related to consumer decision-making, including the decisions related to where to live (Liu, 2022). People may avoid areas with high levels of air pollution due to concerns about their health and may be willing to pay higher to live in areas with cleaner air (Bayer, 2009; Lang, 2015). However, that is not always the case.

Based on the report, some groups of people are especially vulnerable to illness and death caused by air pollution. These groups are people of colour, people experiencing poverty, children and older adults, and people with underlying health conditions, such as asthma, chronic obstructive pulmonary disease, lung cancer, cardiovascular disease, and pregnancy. Low-income populations and communities of colour, such as African American and Hispanic, are disproportionately exposed to air pollution compared to their affluent and White counterparts (Miranda et al., 2011; Banzhaf, 2019). According to the State of the Air 2022, 72% of the 18 million residents in the counties with the lowest air quality are people of colour. This disproportionate exposure can result in adverse health outcomes, reduced property values, and lower economic opportunities (Banzhaf, 2019). In conclusion, even though some people are exposed to a certain level of air pollution, their ability to decide where to live is still based on their ability to pay and their ethnic background.

For these reasons, this research focuses on understanding the relationship between air pollution and housing prices. RICS mentions that pollution can decrease the residential property value by up to 15% compared to a similar property in a less contaminated region. Despite the potential bidirectional causality between the two variables, this research specified the relationship in only one direction: how air pollution is related to housing prices, not vice versa,

1.2. Academic Relevance

According to the motivation, this research focuses on how air pollution is related to housing prices. Several studies have been done regarding this relationship, and they found air pollution has a negative association with housing (rental) prices which means a high level of air pollution indicates low housing (rental) prices (Anderson and Crocker, 1971; Chay and Greenstone, 2005; Liu, 2022). The study by Chay and Greenstone (2005) found that localized decreases in particulate matter pollution and other air pollutants significantly increase housing prices. Since air pollution has a negative relationship with housing prices, it can be said that air quality has a positive relationship with housing prices, suggesting that individuals are willing to spend extra money to reside in areas that have less polluted air (Bayer, 2009; Lang, 2015). However, as explained previously, that is not always the case because even though individuals may face a particular degree of air pollution, their capacity to choose their place to live still depends on other factors, including their ability to pay.

Environmental injustice is evident in the intricate interplay between people's economic capacities and air quality. It is assumed that low-income individuals often confront limited housing options, compelling them to reside in areas with poorer air quality due to reduced financial flexibility for relocation. This phenomenon is suggested to be pronounced in the rental housing market, where tenants may have fewer resources to select healthier environments, exacerbating their vulnerability to the adverse health effects of air pollution. Additionally, in terms of the owner-occupied housing sector, although homeowners might have relatively greater autonomy in choosing their location, financial constraints can still restrict their options, leading to air quality compromises for those with lower income and reinforcing socioeconomic disparities. Based on the research, the proposition that a negative relationship exists between air pollution and property values or rentals appears to be confirmed (Anderson and Crocker, 1971). The presence of air pollution significantly reduces housing prices, and the impact is more pronounced for properties for sale rather than those for rent (Anderson and Crocker, 1971; Grainger, 2012; Bento et al., 2014). This condition may be because renters have less choice in terms of housing quality and location, hence may be more willing to tolerate air pollution to secure affordable housing.

Furthermore, air pollution exposure also has a strong relationship with socioeconomic disparities (Miranda et al., 2011; Hajat et al., 2015; Banzhaf, 2019; Colmer, 2020). Socioeconomic status shapes individuals' vulnerability to air pollution exposure, forging a profound link between economic realities and environmental quality. Low-income and minority communities are experiencing higher levels of pollution compared to the higher-income and non-minority communities; a pattern often referred to as "environmental injustice" or "environmental racism", which has been documented in many cities and regions across the United States (Hajat et al., 2015). This situation leads them to settle in areas with inferior air quality due to limited capacity for relocation. Therefore, it exposes them to air pollutants that can significantly compromise residents' health and well-being, accentuating the environmental injustice inherent in such situations. Miranda et al. (2011) developed an Environmental Justice (EJ) score that evaluates the degree to which environmental risks are distributed unequally across different communities in the United States. The studies found that low-income and non-White communities are more likely to be exposed to multiple sources of pollution, one of them being air pollution, compared to high-income and White communities (Miranda et al., 2011; Colmer, 2020). In addition, Hajat et al. (2015) also found that these disparities are most pronounced in urban areas and regions with high levels of industrial activity.

Prior research has examined how air pollution is related to housing prices. As the next step, further research is required to investigate the broader scope of geographical locations and recent periods and the distribution of housing tenure based on people's ability to pay and decide where to live regarding environmental justice. The study by Anderson and Crocker (1971) only focuses on Washington, Kansas City, and St. Louis and only examines data up to the 1960s. Moreover, the study by Chay and Greenstone (2005) only uses data from 988 counties in the United States and only examines data from 1970 – 1980. The purpose of this further investigation is to see the similarities if the prior research study can be generalized to a larger scale and to more recent periods since air pollution is dynamic and the United States have experienced an improvement in air quality since 1970. Therefore, the current periods and more observations in a country scale of the United States of America will be taken as the evidence of this research.

1.3. Research Problem Statement

This study aims to understand the relationship between air pollution and housing prices in the United States of America within recent periods. Therefore, the central research question is "What is the relationship between air pollution and housing prices for both owner-occupied and rental housing in the United States of America?" the following sub-questions can elaborate that:

1. What is the relationship between air pollution ($PM_{2.5}$) and the house value of owner-occupied housing in the United States of America?
2. What is the relationship between air pollution ($PM_{2.5}$) and the rent of rental housing in the United States of America?
3. What is the relationship between changes in air pollution ($PM_{2.5}$) and housing prices for owner-occupied and rental housing in the United States of America?

The first sub-question is answered by performing a cross-sectional study using a polynomial regression model to acknowledge the relationship between air pollution and house values of owner-occupied housing; the existing academic literature supports the basic theory. The second sub-question is answered by performing the same cross-sectional study using a polynomial regression model. Still, to examine the relationship between air pollution and gross rents of rental housing, the basic theory is also supported by existing academic literature. The third sub-question is answered by performing a longitudinal study using a linear regression model to investigate if the change in air pollution (PM2.5) over time relates to changes in housing prices for both owner-occupied and rental housing. This research contributes to fulfilling the last research gap by examining if the earlier findings can be applied to a broader scope and recent times. In addition, while numerous research studies have explored the relationship between air pollution and house prices for owner-occupied housing, there is still a relative scarcity of research focusing on the relationship between air pollution and rental prices. Therefore, this study is conducted better to understand the relationship between air pollution and housing prices by differentiating the relationship between owner-occupied and rental housing.

II. THEORETICAL BACKGROUND & HYPOTHESES

2.1. Air Quality, Health Effects and Housing Market

As mentioned by the United States EPA, the United States has experienced an improvement in terms of air quality since the end of the nineteenth century. The first significant regulation made by Americans is the 1970 Clean Air Act (CAA) which aims to study and set limits on emissions and air pollution. According to EPA, the act defined the National Ambient Air Quality Standards (NAAQS), which set limits on six primary pollutants found in air, such as carbon monoxide, lead, nitrogen dioxide, ozone, sulfur dioxide, and particulate matter (PM). EPA described PM as a complex mixture of small particles and liquid droplets of acids, organic chemicals, metals and dust particles produced by natural and artificial sources. They further explained that artificial PM sources include burning fuels in industrial and mechanical processes, vehicle emissions, and tobacco smoke. In contrast, natural sources include volcanoes, fires, dust storms and aerosolized sea salt.

After two cohort studies conducted in the United States indicated a link between exposure to fine particulate matter in the air and life-shortening, the interest in exploring the health effects of air pollution intensified (Brunekreef and Holgate, 2002). Additionally, when children moved from areas with high pollution to those with lower pollution (or vice versa), their lung function growth was found to change in a way that matched the changes in their exposure to particulate matter (Brunekreef and Holgate, 2002). WHO has evaluated that $PM_{2.5}$ levels are responsible for around 800,000 premature deaths yearly, making it the 13^{th} most significant cause of death globally. The association between particulate matter and decreased lung function growth in children has now been observed in studies.

Several studies have examined the relationship between air pollution and housing (rental) prices. Most studies indicate a negative relationship between air pollution and housing prices, meaning homes in areas with higher pollution levels tend to have lower market values (Anderson and Crocker, 1971; Chay and Greenstone, 2005; Liu, 2022). It is more pronounced for houses closer to pollution sources, such as major roads, highways, industrial sites, and waste disposal sites (Chay and Greenstone, 2005; Hajat, 2015; Chakraborty, 2022). According to Zheng et al. (2014), for every 10% decrease in the pollution that a city imports from its neighbouring areas, there will be an average increase of 0.76% in local housing prices. Another study also mentions that for every 10% increase in $PM_{2.5}$ concentrations in the air, local housing prices decreased by 2.4% (Chen and Jin, 2019). A study was conducted by Chay and Greenstone (2005) to examine the relationship between air pollution and housing prices in 1970 and 1980. As a result, a 1-unit decline in total suspended particulates (TSPs) led to an increase in housing values of around 0.06% in 1970, indicating a negative relationship between these two variables (Chay and Greenstone, 2005). However, a perverse outcome resulted in a 1-unit decline in TSPs, associated with a 0.10% decrease in housing prices in 1980 (Chay and Greenstone, 2005). The study adjusted for nonlinearities and interactions in the covariates, as well as unrestricted region effects, which diminishes the magnitude of the estimation, but the result is still inexplicably signed in the opposite direction (Chay and Greenstone, 2005). Therefore, they concluded that the correlation between TSPs and property value in cross-sectional and fixed effects analysis is weak and very sensitive to the choice of specification (Chay and Greenstone, 2005).

Several factors contribute to the changes in air quality over time. These factors include rapid industrialization and urbanization, increasing energy consumption, transportation emissions, and unfavourable natural conditions (Zhan et al., 2018). The study also found that government policies and measures, such as implementing stricter air quality standards, improving fuel quality, and promoting renewable energy, have positively influenced air quality improvement (Zhan et al., 2018). Chay and Greenstone (2005) compared the TSPs differences in 1970 and 1980, resulting in an estimation that when TSPs are reduced by 1 $\mu g/m^3$, the property values are predicted to increase by 0.2 – 0.4%, indicating an elasticity of -0.20 to -0.35. The study by Lang (2015) shows that declines in PM_{10} cause owner-occupied housing prices to appreciate with the ten-year interval estimate of an elasticity of -0.63, which is similar to other findings such as elasticity of -0.28 by Chay and Greenstone (2005), -0.63 by Bayer et al. (2009); -0.51 by Grainger (2012); and -0.60 by Bento et al. (2014).

Several reasons exist for the relationship between housing prices and air pollution. According to the study by Anderson and Crocker (1971), the fundamental hypothesis is that a portion of air pollution damage is negatively capitalized into land value, meaning the negative effects of air pollution on artefacts and organisms are reflected in lower property values. Furthermore, suppose air pollution negatively affects the utility obtained from other goods. In that case, land rents will vary inversely with air pollutant dosages, implying that higher levels of air pollution lead to lower property values. Air pollutants have been shown to harm physical and biological systems, which could reduce the desirability of residential properties located in areas with high levels of air pollution (Anderson and Crocker, 1971). In addition, based on the research by Chay and Greenstone (2005), the relationship between housing prices and air pollution is primarily driven by the regulation mechanism. The Clean Air Act and other federal regulations impose strict rules on polluters in nonattainment counties, reducing air pollution concentrations. The improvement in air quality induced by the regulations is consistent with preference-based sorting, where individuals tend to self-select into locations based on their preferences for clean air. As a result, areas with lower pollution levels attract individuals who value clean air, leading to higher housing prices in those areas (Chay and Greenstone, 2005).

2.2. Owner-occupied vs Rental Housing

Other than investigating the relationship between air pollution and owner-occupied house value, this study aims to address a research gap by examining the relationship between air pollution and rents of rental housing, which has received limited attention compared to the extensive research focused on owner-occupied house values, particularly in the recent period within the United States (Anderson and Crocker, 1971; Grainger, 2012; Bento et al., 2014). In terms of the offer price elasticity and rents elasticity, there is a marginal capitalized loss of roughly USD 300 to USD 700 per property for owner-occupied housing, while a marginal monthly rental reduction of USD 2 and USD 4 per rental property for rental housing if they are exposed to a certain measure of air pollution (Anderson and Crocker, 1971).

As mentioned earlier about the elasticity of owner-occupied house value, rental housing prices also increase with air quality improvement, as represented by the elasticity of -0.87 at a lag of ten years (Lang, 2015). These findings show that renter elasticities are more significant than owner-occupied elasticities, which is different from the other findings stating that air pollution's effect is more significant for owner-occupied housings. However, this inconsistency could be caused by median values, leading to different results than means, especially if the data distribution is skewed (Lang, 2015). Still, it can be concluded that rental prices respond more slowly to air quality changes than owner-occupied prices, which means that improvements or deterioration in air quality have a relatively delayed impact on rental prices compared to owner-occupied prices (Lang, 2015). On the other hand, a study by Liu (2018) indicates that housing rental prices may be more sensitive to air quality than housing selling prices. This finding suggests that variations in air quality have a more pronounced and immediate effect on rental housing prices than housing prices. The evidence is taken by comparing China's housing rental and selling markets. When the air quality index increases by 0.1, the housing selling and rental prices will decrease by 3.97% and 4.01%, respectively (Liu, 2018). Housing selling prices are frequently influenced by policies and investments (Liu, 2018). Moreover, the cost of capital investment in the housing selling market is relatively high, which affects the consideration of other property characteristics for the housing demand group (Liu, 2018). These factors together result in a lower sensitivity of housing selling prices to the effects of pollution (Liu, 2018). On the other hand, the rental housing market is affected by human factors, with a demand group that has low and flexible capital investments, which indicates that variations in rental prices are more responsive, hence making the effects of pollution more apparent on housing rental prices (Liu, 2018).

Despite the evidence from owner-occupied housing and rental housing, people's decision on where to live may still depend on their ability to pay and other demographic characteristics since air pollution is closely related to socioeconomics disparities (Miranda et al., 2011; Hajat et al. 2015; Banzhaf, 2019; Colmer, 2020). Based on the study by Chakraborty (2022), the residents of public housing, one example of rental housing developments, are more likely to be exposed to higher levels of air pollution than those living in privately owned housing since public housing is usually rented by low-income households, the elderly and people with disabilities. According to the studies by Miranda et al. (2011) and Colmer (2020), there are significant disparities in $PM_{2.5}$ air pollution across racial and socioeconomic lines, with non-White and low-income households experiencing higher exposure to $PM_{2.5}$ than White and high-income households. These disparities are not simply due to differences in population density or other demographic factors but are linked to socioeconomic factors, including poverty, income inequality, and residential segregation (Colmer, 2020). Other than that, systemic racism and historical patterns of residential segregation may play a role in the disproportionate exposure of certain racial and ethnic groups to air pollution (Colmer, 2020).

2.3. Housing Market Indicators

Although this study mainly focuses on the relationship between air pollution and housing prices, several housing market indicators also contribute to housing prices. According to the study by Miles (2012), the relationship between population density and housing prices is positive in areas with high population density. In such densely populated regions, the increase in real estate prices would probably surpass the growth in average income (Miles, 2012). Other than that, according to the study by Davidoff (2006), housing prices and homeownership rates are closely related. Higher housing prices make it more difficult for individuals to afford a home, especially for low and moderate-income earners; hence this can lower homeownership rates as fewer people can purchase houses (Davidoff, 2006).

On the other hand, lower housing prices can make homeownership more accessible to a broader range of individuals, leading to higher homeownership rates (Davidoff, 2006). Also, housing prices strongly correlate negatively with housing vacancy rates (Igarashi, 1991). As housing prices increase, housing demand decreases, which can lead to higher vacancy rates. In contrast, as housing prices fall, housing demand increases, which can lead to lower vacancy rates (Igarashi, 1991).

Additionally, a particular type of residential property, such as single-family homes, tends to have higher values than other residential properties (Yu, 2007). Single-family homes offer more privacy, space, and control over property than residential properties (Yu, 2007). Lastly, Green and Hendershott (1996) also suggest that house age is an essential factor to consider when examining housing prices. Newer homes tend to have higher values due to the greater availability of modern amenities, better construction techniques, and changing consumer preferences (Green and Hendershott, 1996). Therefore, it is assumed that the neighbourhood with high rates of newly built homes may trigger higher values in the same area. For all these reasons, these factors are considered as the contributing factors that could determine housing prices in this study. Including these variables helps reduce omitted variable bias and isolate the specific impact of the key independent variable on the dependent variable, improving the accuracy, precision, and causal inference of the estimated relationships.

2.4. Hypotheses

Derived from the abovementioned theory, hypotheses are derived to answer the research questions. Based on the main research question, the null hypothesis is "No significant relationship between air pollution and housing prices for owner-occupied and rental housing.". On the other hand, there are two alternative hypotheses, such as:

H1: A negative relationship exists between air pollution and housing prices in the United States for owner-occupied and rental housing.

H2: There is a negative relationship between changes in air pollution ($PM_{2.5}$) and changes in housing prices (both owner-occupied and rental housing) over time in the United States.

The first hypothesis is tested by performing a cross-sectional study using linear regression and polynomial regression models to compare the differences between the predictive value of owner-occupied and rental housing in terms of air pollution. Overall, the study assumes that high air pollution is associated with low housing prices for owner-occupied and rental housing. High levels of air pollution may increase the demand for rental housing, as it may be more affordable than owning a house in a polluted area. Based on the literature review, the distribution of housing tenure could be related to people's ability to pay and capacity to decide on where to live; hence it is assumed that air pollution is more pronounced to the price of housing instead of rents (Anderson and Crocker, 1971; Grainger, 2012; Bento et al., 2014). Nonetheless, housing rental prices may also be more sensitive than the housing selling prices regarding air quality (Liu, 2018). This condition is caused by the rental market, which is influenced by human factors, with low and flexible capital investment among its demand group, implying that alterations in rental prices are more susceptible (Liu, 2018).

The second hypothesis is tested by performing a longitudinal study using linear regression and polynomial regression models, as changes in housing prices for both owner-occupied and rental housings as the dependent variable and changes in air pollution in $PM_{2.5}$ measures as the key independent variable. It is assumed that when there is increased air pollution, the housing prices for both owner-occupied and rental housing decrease and vice versa. Air pollution changes at a localized level over time due to various factors, such as changes in industrial activity, transportation patterns, weather conditions, and government policies (Zhan et al., 2018). It is assumed that it can estimate the relationship between air pollution and housing prices in each housing tenure in the long run.

Derived from the theories and hypotheses, a conceptual model is formed to visualize the framework of this research, which can be seen in Figure 1 below.

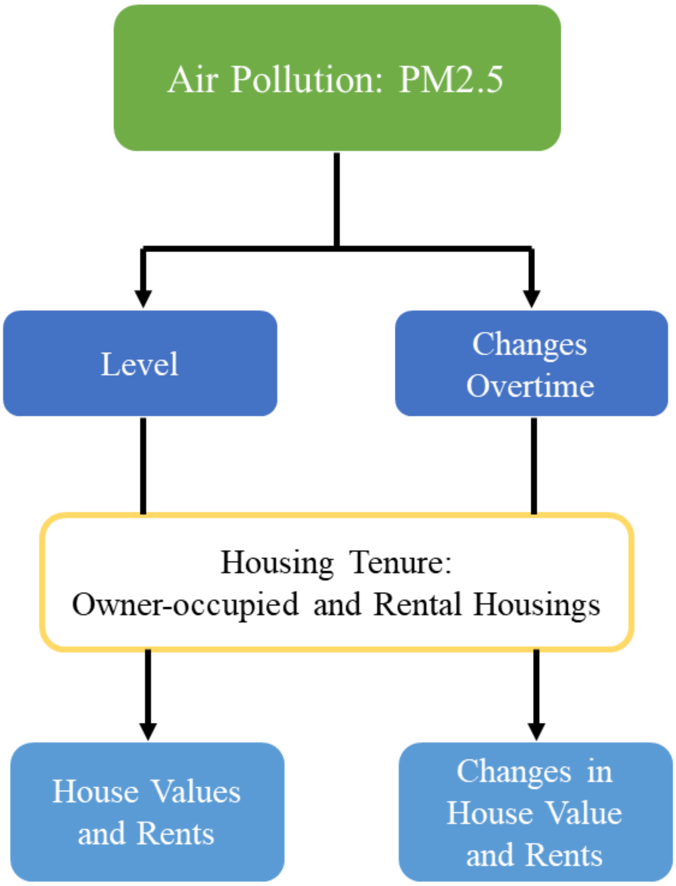

Figure 1 Conceptual Model

The conceptual model starts with the assumption that air pollution is related to housing markets in various ways. Housing (rental) prices represent the dependent variable; air pollution ($PM_{2.5}$) represents the key independent variable; and other control variables that may explain the dependent variable better, such as population density, homeownership rates, vacant units, single-family homes rates, and the recent house built (2010 or later). The first hypothesis assumes that high levels of air pollution may negatively relate to housing prices, as properties in polluted areas have lower prices than properties in cleaner air quality areas. Air pollution is assumed to contribute to the predictive values of owner-occupied and rental housing. For the second hypothesis, the model assumes that housing prices will likely fall if air pollution levels increase in a particular area. In contrast, a decrease in air pollution could lead to an increase in housing prices.

III. DATA & METHODOLOGY

3.1. Dataset Background

The study investigates the relationship between air pollution and housing prices, both owner-occupied and rental housing, and analyses the other factors that might be related to this relationship. Data are assembled from Contextual Data Resource for the Understanding America Study (UAS | CDR) in 2020. The air pollution data is collected from the United States Environmental Protection Agency (EPA) (https://www.epa.gov/hesc/rsig-related-downloadable-data-files), which is called Fused Air Quality Surface Using Downscaling (FAQSD) Files. Particulate Matter 2.5 ($PM_{2.5}$) represents air pollution in this study. The dataset utilizes data from monitoring stations and Community Multiscale Air Quality (CMAQ) output to estimate the average local concentrations of $PM_{2.5}$ throughout the United States. The available data spans from 2002 to 2016, with annual, quarterly and monthly averages provided at the level of census tracts.

On the other hand, the housing prices data is collected from the U.S. Census Bureau (www.socialexplorer.com), called The Decennial Census and American Community Survey (ACS), in the form of house value for owner-occupied housing and gross rent for rental housing. The U.S. Decennial Census and American Community Survey comprise demographic and socioeconomic data on the US population and housing. At the state, county and Core-Based Statistical Area (CBSA) and census tract levels of analysis, the CDR provides Census data for 1990, 2000, and 2010, as well as ACS data for 2005 through 2018. In addition, based on the theoretical background and literature review, the other factors that might affect housing prices can also be found in this dataset, such as population density, homeownership rate, vacant unit rate, single-family homes rate, and recent house-built.

Data from 2016 is used in analyzing the relationship between air pollution ($PM_{2.5}$) and housing prices for owner-occupied and rental housing as the cross-sectional study to answer the first and second sub-question. As for the longitudinal study, the data is utilized from 2007 to 2016 to investigate the relationship between changes in air pollution ($PM_{2.5}$) and housing prices for owner-occupied and rental housing.

3.2. Context

The air pollutant analyzed in this study is Particulate Matter (PM), specifically $PM_{2.5}$. PM can be detailed by its "aerodynamic equivalent diameter" (AED), and usually, it is subdivided into AED fractions which are determined by how the particles are produced and where they accumulate in the respiratory system: PM_{10}, $PM_{2.5}$ and $PM_{0.1}$ (Anderson et al., 2012). Among these fractions, the diameter between 2.5 and 10 µm is defined as "coarse" and dramatically influences the respiratory system (Anderson et al., 2012). $PM_{2.5}$ constitutes a form of air contamination that consists of solid elements and tiny droplets which are not visible to the naked eye (McCormick, 2023). These particles are only 2.5 microns or less in diameter, which means they are significantly smaller than fine beach sand or human hair, measuring dozens of times less (McCormick, 2023). Recent studies indicate that even low concentrations of $PM_{2.5}$ can cause significant health problems, and the threshold for what is considered unsafe varies by organization, with the WHO designating levels above 5 micrograms per cubic meter ($\mu g/m^3$) as hazardous (McCormick, 2023).

The level of air contamination in each part of the country is different; hence this study focuses on the United States of America as the geographical context. California, which is the state with the nation's worst air pollution, recorded levels higher than the current EPA action level of 12 micrograms per cubic meter ($\mu g/m^3$) and conversely, in other regions of the country, the threshold was slightly under the action level, measuring at 11.5 $\mu g/m^3$ (McCormick, 2023). According to the report State of the Air 2022 by ALA, the most polluted cities affected by annual PM are Bakersfield, Fresno-Madera-Hanford, Visalia, San Jose-San Francisco-Oakland, and Los Angeles-Long Beach, ranging from 14 $\mu g/m^3$ to higher than 16 $\mu g/m^3$.

3.3. Operationalising Variables

This study conducts two kinds of analyses: cross-sectional and longitudinal. Each analysis has its own dependent and independent variables. The independent variables remain the same despite the differences in the dependent variable, which depends on owner-occupied or rental housing. The independent variables include control variables such as population density, homeownership rate, vacant units rate, single-family homes rate and recent house-built rate (in 2010 or later) at a census tract level. These control variables are included to reduce omitted variable bias, isolate the effect of the key independent variable, the $PM_{2.5}$, improve model accuracy and precision, and capture interactions and nonlinearities. All variables are in the form of median or average values in a certain neighbourhood. Specifically, the dependent variables are median house value and median gross rent while the independent variable is the annual average of $PM_{2.5}$.

Table 1 Descriptive Statistics for the Cross-sectional Analysis

Variable	Definition	Mean	Std. Dev.	Min	Max
House value	US Dollar	262,712.600	233,320.100	9,999.000	2,000,001.000
Log house value	Logarithmic	12.202	0.726	9.210	14.509
Gross rent	US Dollar	1,123.603	463.367	189.000	3,501.000
Log gross rent	Logarithmic	6.951	0.375	5.242	8.161
$PM_{2.5}$	$\mu g/m^3$	8.345	1.525	3.103	14.908
Population Density	Num of pop /$miles^2$	5,607.252	11,084.690	0.547	263,992.600
Homeownership	Percentage	0.623	0.215	0.012	0.987
Vacant Units	Percentage	0.110	0.094	0.000	0.914
Single-family Homes	Percentage	0.611	0.262	0.000	1.000
House-built in 2010 or later	Percentage	0.034	0.054	0.000	0.839
Observations	61,715				

Notes: Numbers are rounded to three decimals. The total observations are 61,715. The dependent variables are the log house value for the owner-occupied housing and the gross rent for the rental housing. The key independent variable is $PM_{2.5.}$ The geographical area of this data is at a census tract level.

The cross-sectional analysis examines the predictive value of owner-occupied and rental housing in terms of air pollution at a census tract level. The dependent variables of this study are the median house value for owner-occupied housing and the median gross rent for rental housing in 2016. Both of the values have been adjusted with the inflation. The key independent variable of this study is the annual average of $PM_{2.5}$ in 2016 as the representation of air pollution. Additionally, there are control variables, which are also obtained from the Year-2016. The cross-sectional study overlooked the annual average of $PM_{2.5}$ for the most recent period available: 2016. It overlaid demographic data, using U.S. Census data from American Community Survey five-year estimates from 2014 to 2018, using the Year-2016 as the median value. Once the data is merged and cleaned, 61,715 observations occurred, shown in Table 1. The average house value for owner-occupied housing is approximately USD 263,700, while the average gross rent for rental housing is around USD 1,100. As the key independent variable, the annual average of PM2.5 levels is around 8 μg/m^3. Other than that, the other control variables, such as population density, homeownership, vacant units, single-family homes and recent house-built (2010 or later), are in the form of percentages which give the proportion of the data at the census tract level.

Table 2 Descriptive Statistics for the Longitudinal Analysis

Variable	Definition	Mean	Std. Dev.	Min	Max
Changes in house value	US Dollar	60,490.061	115,272.490	3.063	1,385,505.000
Log changes in house value	Logarithmic	10.007	1.518	1.119	14.142
House value in 2007	US Dollar	293,114.240	268,152.350	9,189.330	1,173,223.400
Changes in gross rent	US Dollar	218.557	234.638	0.034	2563.594
Log changes in gross rent	Logarithmic	4.846	1.190	-3.385	7.849
Gross rent in 2007	US Dollar	983.029	410.290	58.075	2,346.447
Changes in $PM_{2.5}$	μg/m^3	-3.616	1.481	-7.572	1.402
$PM_{2.5}$ in 2007	μg/m^3	11.855	2.458	4.328	17.673
Population Density in 2007	Num of pop /miles^2	7,102.250	15,887.099	0.286	217,253.280
Homeownership in 2007	Percentage	0.625	0.225	0.007	1.000
Vacant Units in 2007	Percentage	0.106	0.082	0.000	0.776
Single-family Homes in 2007	Percentage	0.568	0.273	0.000	1.000
Recent house-built (2010 or later) in 2007	Percentage	0.109	0.129	0.000	0.974
Observations	13,032				

Notes: Numbers are rounded to three decimals. The total observations are 13,032. The dependent variables are the log changes in house value for the owner-occupied housing and the gross rent for the rental housing. The key independent variable is the changes in $PM_{2.5.}$ The geographical area of this data is at a census tract level.

On the other hand, the longitudinal analysis examines the relationship between changes in air pollution and house value and gross rent over time changes. The study uses the annual average of $PM_{2.5}$ from 2007 to 2016 while incorporating demographic information from the American Community Survey's five-year median values from the same periods. Control variables are also considered, such as house value, gross rent, level of PM2.5, population density, percentage of homeowners, percentage of vacant housing units, percentage of single-family homes, and percentage of recent house-built (2010 or later), which is from the Year-2007. After combining and refining the data, the same number of observations occurred, which is 13,032. Further information regarding these occurrences is available in Table 2. The average house value increase from 2007 to 2016 is approximately USD 60,490, while the average gross rent increase is around USD 218. As the key independent variable, the average of changes in $PM_{2.5}$ levels is around 3.6 $\mu g/m^3$ decreased.

This study requires checking the data by adjusting and transforming it to the most suitable function form before going further with the analysis. Therefore, density function, scatter plots and correlation matrix need to be addressed. The results can be seen in the Appendix section. There are several variables whose data are not normally distributed; hence natural logarithmic is generated to transform the data to have a normal distribution. These variables are house value and gross rent. Initially, these variables had right-skewed distribution, also known as positively skewed in statistics. Additionally, scatter plots are produced to visualize the distribution of the dependent and independent variables. According to the scatter plots, $PM_{2.5}$ has a more complex relationship with house value for owner-occupied housings and gross rent for rental housings; hence it cannot be initially confirmed that these variables have a linear relationship. According to the correlation matrix, log house value and gross rent have positive relationships with $PM_{2.5}$, even though the weak relationships are represented by 0.004 and 0.050, respectively. This condition indicates that the relationship between air pollution and housing prices is more complex since the theoretical background is found otherwise. In addition, log changes in house value and gross rent also have positive relationships with changes in $PM_{2.5}$, representing a 0.127 correlation for both variables.

3.4. Methodology

There are two studies in this research: cross-sectional and longitudinal. Both of these studies are conducted in separate regression models. Firstly, the cross-sectional study is the one which analyzes the predictive value of owner-occupied housing and rental housing in terms of air pollution in 2016. Secondly, the longitudinal study examines the value of air pollution that changes over time, which might differentiate the relationship between air pollution and house value and gross rent from 2007 to 2016. All of the variables are at the census tract level.

In order to answer the first hypothesis regarding the cross-sectional analysis of the predictive value of owner-occupied housings and rental housings, a linear regression model is initially employed to gauge the relationship between air pollution in the form of particulate matter 2.5 and the house value for owner-occupied housings, as well as the gross rent for rental housings. Furthermore, based on the theoretical background, several housing market indicators could affect house value and rent; hence those indicators are added as control variables to the statistical model. The model can be seen in the equations below.

$$\ln(Y_i) = \alpha + \beta X_i + \gamma_1 Z_{1i} + \gamma_2 Z_{2i} + \gamma_3 Z_{3i} + \gamma_4 Z_{4i} + \gamma_5 Z_{5i} + \delta_i + \varepsilon_i \ldots (1)$$

Both owner-occupied and rental housing regression models use this equation by differentiating the dependent variable into house value for owner-occupied housing and gross rent for rental housing. The models are analyzed separately into two different regression models. Y represents the dependent variable (house value or gross rent) in natural logarithmic form; X represents the measure of air pollution in the form of $PM_{2.5}$ as the key independent variable; α represents the constant or intercept; β represents the coefficient of the key independent variable; Matrix Z encompasses the housing market indicators as the control variables at a census tract level, including population density, homeownership, vacant units, single-family homes, and recent house-built year (in 2010 or later).; i represents state fixed effect at a census tract level; δ represents the coefficient of state fixed effect; γ represents the coefficient of the control variables; and ε defines the error term.

In order to answer the second hypothesis regarding the longitudinal analysis of the air pollution that changes over time, linear regressions are initially conducted to understand the relationship between changes in air pollution and changes in both house value and gross rent, with state fixed effect. The statistical model for this regression analysis can be seen in the equation below.

$$\ln(Y_i) = \alpha + \beta_1 X_i + \mu_1 Z_{6i} + \mu_2 Z_{8i} + \mu_3 Z_{9i} + \mu_4 Z_{10i} + \mu_5 Z_{11i} + \mu_6 Z_{12i} + \mu_7 Z_{13i} + \delta_i + \varepsilon_i \ldots (2)$$

Both owner-occupied and rental housings regression models use this equation, but by differentiating the dependent variable into changes in house value for owner-occupied housings and changes in gross rent for rental housings. The models are analyzed separately into two different regression models. ΔY represents the dependent variable (changes in house value or changes in gross rent) in natural logarithmic form; ΔX represents the changes in air pollution in the form of $PM_{2.5}$ as the key independent variable; Matrix Z represents the control variables in 2007 at a census tract level, including house value, gross rent, $PM_{2.5}$, population density, homeownership, vacant units, single-family homes, and recent house-built (in 2010 or later).; α represents the constant or intercept; i represents the state fixed effect at the census tract level; β represents the coefficient of the key independent variable; μ represents the coefficient of the control variables; δ represents the coefficient of state fixed effect; and ε represents the error term.

Once the relationship between the dependent variables and key independent variables has been addressed, a polynomial regression model is conducted to understand better the potential non-linear relationship between house value, gross rent, and air pollution. Polynomial regression is undertaken for both cross-sectional and longitudinal analysis. Due to the logarithmic nature of the dependent variables, an exponential function is used to transform the coefficient of the independent variables into a percentage, also known as growth rate, for interpretation. θ represents the coefficient of the independent variables.

$$(\exp(\theta) - 1) \times 100$$

3.5. Limitations and Ethical Considerations

The relationship between air pollution and housing prices is a complex phenomenon that various factors may influence. While this study attempts to shed light on this relationship, several limitations should be considered. Firstly, the observational study cannot establish a causality between air pollution and housing prices. Other factors, such as neighbourhood amenities, distance to the city centre and socioeconomic factors, may also affect housing prices. Other than that, endogeneity may occur when the relationship's presumed cause and effect are reversed. Regarding air pollution and housing prices, areas with lower housing prices may attract industries or facilities that generate pollution, resulting in higher pollution levels. In this scenario, housing prices would be causing air pollution rather than vice versa.

When researching this topic, it is important to consider ethical implications. Firstly, the study uses publicly available data, but care should be taken to protect the privacy of individuals and their personal information. In addition, the study examines the relationship between air pollution and housing prices, which may have implications for public policy and individual decision-making. Care should be taken to ensure that the study does not cause harm to vulnerable populations or perpetuate existing inequalities. The author of this study does not own any property herself and writes this thesis from the perspective of an international master's student at the University of Groningen. Ethical considerations should be carefully weighed and addressed to ensure the study is conducted ethically and responsibly.

IV. RESULTS AND DISCUSSION

4.1. Owner-occupied Housing vs Rental Housing

This section presents the empirical analysis examining the relationship between air pollution and housing prices in 2016 at the census tract level. At the start of the analysis, linear regression models are fitted to assess the relationship between air pollution and housing prices for both owner-occupied and rental housing. Once the linear relationships are identified, polynomial regression models are conducted to account for potential non-linear relationships within the observations. This approach helped capture more nuanced patterns and better understand the relationship between air pollution and housing prices. After polynomial regression models have addressed the relationships, it is necessary to conduct diagnostic tests to check the model's quality. Initially, the models indicate heteroscedasticity, which means the variance of the residuals is not consistent across all levels of predictors; hence robust standard errors are conducted to stabilize the variance, which aim is to obtain consistent and efficient estimates of the regression coefficients.

Furthermore, predictions are conducted to check if the residuals are normally distributed. As a result, the density function of the predicted residuals indicates normal distribution, which is visualized by histograms in the Appendix. Lastly, there is multicollinearity caused by the exponential models of $PM_{2.5}$, but it may not necessarily change the interpretation of the regression models.

Table 3 Estimated Regression Results of the Relationship between Median Owner-occupied House Value and Air Pollution ($PM_{2.5}$)

	Model 1 Log house value	Model 2 Log house value	Model 3 Log house value
$PM_{2.5}$	-0.016*** (0.002)	-0.000 (0.002)	-0.763*** (0.055)
$PM_{2.5}$ x $PM_{2.5}$			0.106*** (0.006)
$PM_{2.5}$ x $PM_{2.5}$ x $PM_{2.5}$			-0.005*** (0.000)
Population Density	0.000*** (0.000)	0.000*** (0.000)	0.000*** (0.000)
Homeownership	1.212*** (0.021)	1.324*** (0.019)	1.306*** (0.019)
Vacant Units	-1.977*** (0.047)	-1.139*** (0.037)	-1.073*** (0.038)
Single-family Homes	-0.712*** (0.020)	-0.639*** (0.018)	-0.608*** (0.018)
Recent House-Built (2010 or later)	1.297*** (0.041)	1.852*** (0.039)	1.863*** (0.039)
Constant	12.074*** (0.021)	11.352*** (0.030)	12.929*** (0.156)
State Fixed Effect	No	Yes	Yes
Number of observations	61715	61715	61715
R-squared	0.233	0.522	0.528

Standard errors in parentheses

* p<0.05, ** p<0.01, *** p<0.001

The results of the linear regressions for the owner-occupied housings are shown in Table 3, especially in Model 1 and Model 2. Model 1 addressed the relationship between air pollution and owner-occupied house value without state fixed effect, while Model 2 included state fixed effect in the estimation. Both models indicate a negative relationship between $PM_{2.5}$ and log house value. However, when the state-fixed effect is considered, the coefficient of $PM_{2.5}$ is no longer significant, while the coefficients of the remaining variables are still significant. Despite that, the R-squared increases quite drastically from 23.3% in Model 1 to 52.2% in Model 2, which means the variance of the dependent variable can be explained better by the independent variables in Model 2. The introduction of the state fixed effect as an additional independent variable in the regression model yielded a substantial increase in the goodness of fit, as indicated by the R-squared value. To better understand a potential non-linear relationship between these two variables, a polynomial regression model with state fixed effect is conducted, which details can be found in Model 3. The independent variables are typically the same as Model 2 but with interaction terms of $PM_{2.5}$ as an addition, resulting $PM_{2.5}{}^3$. Although the R-squared is not different compared to Model 2, the coefficient of $PM_{2.5}$ in Model 3 is statistically significant. The model also indicates negative and positive exponential relationships with log house value. This estimation is similar to the theoretical background that found a negative relationship between air pollution and housing prices (Anderson and Crocker, 1971; Chay and Greenstone, 2005; Liu, 2022). However, a margins plot is conducted to address a more accurate interpretation since the relationship is exponential. The predictive value of owner-occupied housing can be found in Figure 2.

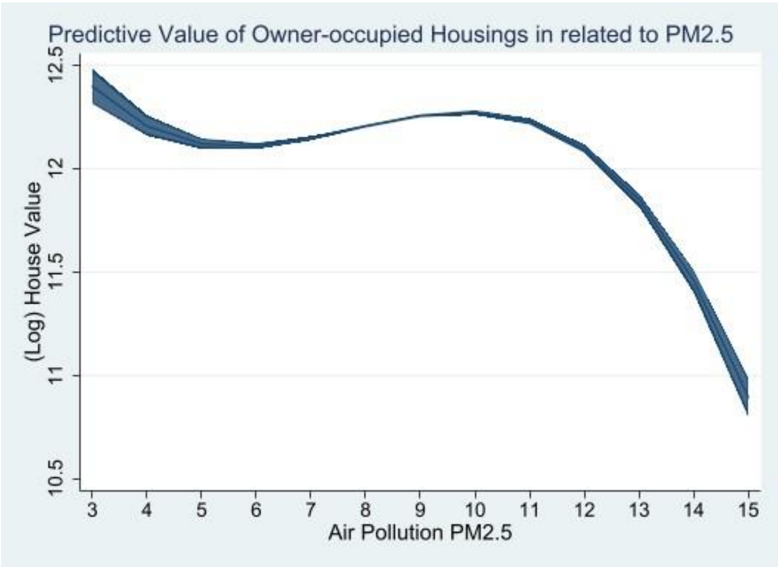

Figure 2 Predictive Value of Owner-occupied Housings in related to Air Pollution ($PM_{2.5}$)

Figure 2 visualizes the predictive value of owner-occupied house value in terms of $PM_{2.5}$ at a census tract level. The y-axis is the house value in the form of natural logarithmic as the dependent variable. As the key independent variable, the x-axis is the air pollution in PM2.5 measures (µg/m3). The margins are calculated to predict owner-occupied house value for all combinations of $PM_{2.5}$, ranging from 3 µg/m^3 to 15 µg/m^3 in increments of 1 µg/m^3. At low and high levels of $PM_{2.5}$, the relationship between $PM_{2.5}$ and house value is negative. However, the relationship with house value becomes slightly positive when the PM2.5 level is in its mid-level, ranging from around 7 µg/m3 to 10 µg/m3. The graph indicates that when the $PM_{2.5}$ level increases from 3 µg/m3 to 6 µg/m3, the estimated average house value decreases from USD 242,166 to USD 181,609. The same negative relationship occurs when PM2.5 levels increase from 11 µg/m^3 to 15 µg/m^3; the estimated average house value decreases drastically from USD 204,471 to USD 53,844. However, when $PM_{2.5}$ is in the mid-level, from 7 µg/m^3 to 10 µg/m^3, the estimated house value, on average, increases from USD 188,411 to USD 213,668. This finding suggests that there might be unobservable variables, resulting in a positive relationship in the mid-level of $PM_{2.5}$. One possible example of an unobservable variable could be the proximity to amenities or desirable features. For instance, houses near parks, schools, or waterfronts might attract higher prices, despite being exposed to slightly higher pollution levels.

Table 4 Estimated Regression Results of the Relationship between Median Rental Gross Income and Air Pollution ($PM_{2.5}$)

	Model 4 Log gross rent	Model 5 Log gross rent	Model 6 Log gross rent
$PM_{2.5}$	0.005*** (0.001)	0.018*** (0.001)	-0.375*** (0.031)
$PM_{2.5}$ x $PM_{2.5}$			0.061*** (0.004)
$PM_{2.5}$ x $PM_{2.5}$ x $PM_{2.5}$			-0.003*** (0.000)
Population Density	0.000*** (0.000)	0.000*** (0.000)	0.000*** (0.000)
Homeownership	0.617*** (0.010)	0.629*** (0.009)	0.615*** (0.009)
Vacant Units	-0.971*** (0.019)	-0.636*** (0.016)	-0.568*** (0.016)
Single-family Homes	-0.252*** (0.009)	-0.172*** (0.008)	-0.147*** (0.008)
Recent House-Built (2010 or later)	0.705*** (0.025)	0.939*** (0.023)	0.945*** (0.022)
Constant	6.703*** (0.011)	6.217*** (0.016)	6.853*** (0.088)
State Fixed Effect	No	Yes	Yes
Number of observations	61715	61715	61715
R-squared	0.202	0.468	0.481

Standard errors in parentheses

* $p<0.05$, ** $p<0.01$, *** $p<0.001$

On the other hand, the results of the linear regressions for the rental housings are shown in Table 4, in Model 4 and Model 5 specifically. The same with Model 1 and Model 2, Model 5 is the one that includes state fixed effect in the estimation, while Model 4 does not. Consequently, the dependent variable is explained better in Model 5, proven by the increased R-squared from 20.2% in Model 4 to

46.8% in Model 5. Furthermore, both models indicate a positive relationship between $PM_{2.5}$ and log gross rent. This estimation does not align with the theoretical background, which mentions the opposite. Despite that, the coefficient of $PM_{2.5}$ in each model is statistically significant; the same thing occurred for the remaining independent variables. Therefore, the polynomial regression model is conducted and presented in Model 6 to understand this relationship better. The R-squared increased from 46.8% in Model 5 to 48.1% in Model 6, which means the variance of the dependent variable can be explained slightly better by the independent variables in Model 6. The same result in Model 3 and Model 6 indicates a negative and positive relationship between $PM_{2.5}$ and gross rent. Therefore, a margins plot is performed to achieve a more precise understanding. The predictive rent of rental housing can be found in Figure 3.

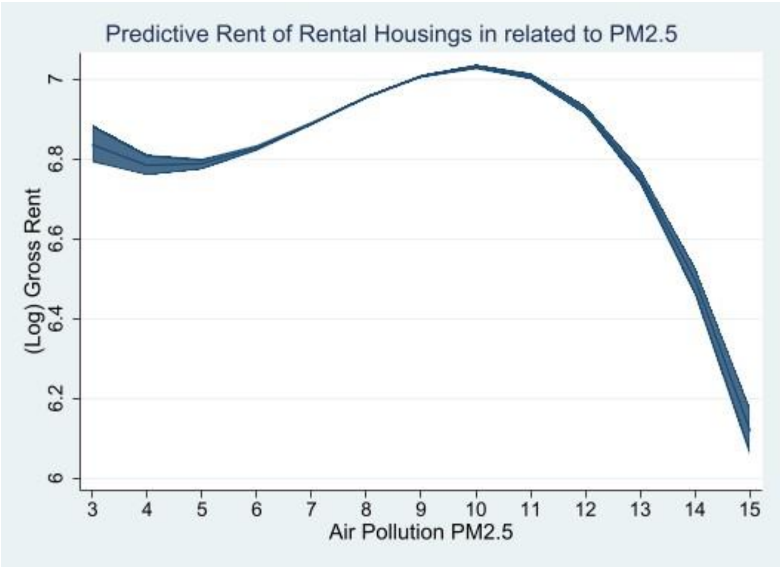

Figure 3 Predictive Rent of Rental Housings in related to Air Pollution ($PM_{2.5}$)

Figure 3 visualizes the predictive rent of rental housing in terms of $PM_{2.5}$ at a census tract level. The y-axis is the gross rent in natural logarithmic as the dependent variable, while the x-axis remains the same as the previous margin plot. The margins are calculated to predict rents for all combinations of $PM_{2.5}$, with the same range as explained in Figure 2. At low and high levels of $PM_{2.5}$, the same negative relationship occurs between $PM_{2.5}$ and gross rent. The graph indicates when $PM_{2.5}$ increases from 3 $\mu g/m^3$ to 4 $\mu g/m^3$; the estimated average gross rent is expected to decrease from USD 932 to USD 884. Furthermore, when the $PM_{2.5}$ level is high, increasing from 11 $\mu g/m^3$ to 15 $\mu g/m^3$, the estimated average gross rent decreases from USD 1,105 to USD 454. However, the relationship becomes somewhat positive when PM2.5 is between 5 µg/m3 and 10 µg/m3. As a result, for every one $\mu g/m^3$ increase of $PM_{2.5}$ in the mid-level, the estimated average gross rent is expected to rise from USD 886 to USD 1,130. The same assumption as interpreting the predictive value of owner-occupied housings, there might be unobservable variables which produce a positive relationship in the mid-level of $PM_{2.5}$. Assuming one of the possible unobservable variables is there are other essential factors that people consider to rent a place to live in. For example, if a business park, which produces high levels of air pollution, is built in an area, many rental housings must be built around the area for the employees. Therefore, the housing does not necessarily have higher rents because the surrounding has a lower level of air pollution but because the location and people who work there are willing to pay rent for a place to live near the business park.

As mentioned earlier, the coefficients of all control variables are statistically significant in both owner-occupied and rental housing. Model 3 and Model 6, as the polynomial regression models for owner-occupied and rental housing, respectively, indicate population density, homeownership and recent house-built (in 2010 or later) to have a positive relationship with housing prices. On the other hand, the remaining control variables, such as vacant units and single-family homes, are negatively related to housing prices. Model 3 indicates that when homeownership and recent house-built are 1% higher at the census tract level, the house value becomes 3.69% and 6.44% higher, respectively. In contrast, when vacant units and single-family homes are 1% higher at the census tract level, the house value becomes 0.34% and 0.54% lower, respectively. Moreover, Model 6 indicates when the rate of homeownership and the proportion of recently built houses are 1% higher at the census tract level, the gross rent is 1.85% and 2.57% higher, respectively. When the proportion of vacant units and single-family homes is 1% higher, the gross rent is 0.57% and 0.86% lower, respectively. Additionally, both models indicate an extremely low coefficient between population density, house value, and gross rent. These interpretations are assumed if the other remaining variables are constant.

4.2. Housing Prices and Air Pollution Change Overtime

This section presents the empirical analysis investigating the relationship between the changes in air pollution and housing prices from 2007 to 2016 at the census tract level. Linear regression models are analyzed to assess this relationship with changes in housing prices for both owner-occupied and rental housing as the dependent variables and changes in $PM_{2.5}$ as the key independent variable. Furthermore, polynomial regression models are conducted to analyze the potential non-linear relationships within the observations. The same diagnostics test are performed as the ones in the previous section. All the models are run with robust standard errors to acquire reliable and effective estimations of regression coefficients.

Table 5 Estimated Regression Results of the Relationship between Changes in Owner-occupied House Value and Changes in Air Pollution ($PM_{2.5}$)

	Model 7 Changes in log house value	Model 8 Changes in log house value
Change in $PM_{2.5}$	-0.084***	-0.171***
	(0.026)	(0.043)
Change in $PM_{2.5}$ x Change in $PM_{2.5}$		-0.014*
		(0.005)
House value in 2007	0.000***	0.000***
	(0.000)	(0.000)
$PM_{2.5}$ in 2007	-0.036**	-0.035*
	(0.014)	(0.014)
Population Density in 2007	0.000	0.000
	(0.000)	(0.000)
Homeownership in 2007	0.003	0.009
	(0.091)	(0.091)
Vacant Units in 2007	0.452**	0.462**
	(0.158)	(0.158)
Single-family Homes in 2007	-0.935***	-0.935***
	(0.082)	(0.082)
Recent House-Built (2010 or later) in 2007	0.611***	0.607***
	(0.093)	(0.093)
Constant	9.594***	9.471***
	(0.158)	(0.165)
State Fixed Effect	Yes	Yes
Number of observations	13032	13032
R-squared	0.328	0.328

Standard errors in parentheses

* p<0.05, ** p<0.01, *** p<0.001

Table 5 presents the regression results of the relationship between the changes in $PM_{2.5}$ and changes in owner-occupied house value. Model 7 shows the linear regression model, while Model 8 presents the polynomial regression model. Both models include state fixed effect, which is proven important while conducting the cross-sectional analysis in the previous section. The R-squared remains the same for both linear and polynomial regressions. Model 7 indicates a significant negative relationship between change in $PM_{2.5}$ and change in log house value, which interpret that every 1 μg/m3 increase of PM2.5 is associated with an 8% decreased owner-occupied house value, assuming the other variables remain constant. Despite that, as indicated in the previous section, the relationship between $PM_{2.5}$ and house value is not linear; hence Model 8 is conducted to examine the exponential relationship. The same result occurs in Model 7; Model 8 indicates a negative relationship between these two variables. The coefficients are significant for normal and quadratic changes in $PM_{2.5}$. Therefore, to better understand, a margins plot is created to visualize the better relationship between the changes in $PM_{2.5}$ and changes in log house value. The margins plot is presented in Figure 4 below.

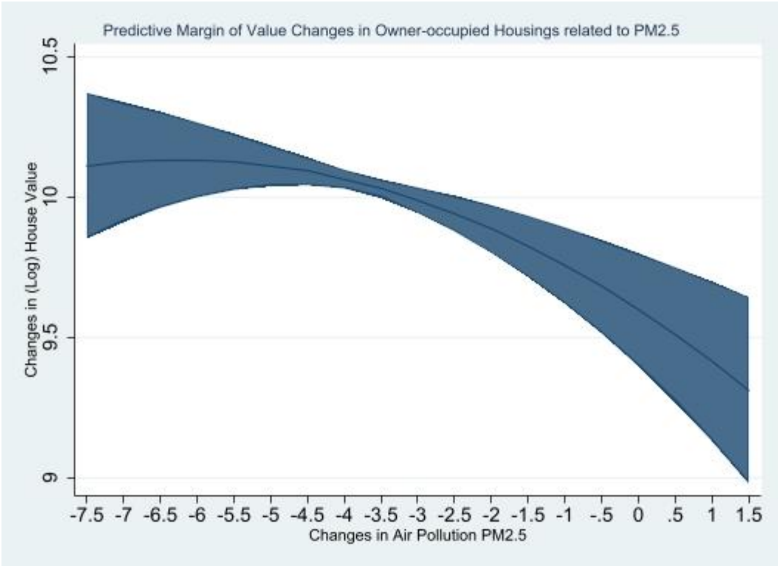

Figure 4 Predictive Margin of Value Changes in Owner-occupied Housings related to Air Pollution ($PM_{2.5}$)

Figure 4 visualizes the predictive value changes of owner-occupied housings in terms of $PM_{2.5}$ at a census tract level. The y-axis is the changes in house value from 2007 to 2016 using natural logarithmic as the dependent variable. On the other hand, the x-axis is the changes in air pollution in $PM_{2.5}$ measures (µg/m^3) as the key independent variable. The margins are analyzed to predict the margin of value changes in owner-occupied housings for all combinations of changes in $PM_{2.5}$, ranging from 7.5 µg/m^3 decreased to 1.5 µg/m^3 increased with the increments of 0.5 µg/m^3. As a result, when a 4.5 µg/m3 to 7.5 µg/m3 is decreased in $PM_{2.5}$, the house value increases in a constant value with an average of USD 24,694. Moreover, when there is a 0.5 µg/m^3 to 3.5 µg/m^3 decrease in $PM_{2.5}$, the house value increases from USD 15,994 to USD 22,669 on average. However, when there is a slight increase of $PM_{2.5}$, ranging from 0.5 µg/m^3 to 1.5 µg/m^3, the house value slightly increased from USD 11,056 to USD 13,481 on average.

Table 6 Estimated Regression Results of the Relationship between Changes in Gross Rent and Changes in Air Pollution ($PM_{2.5}$)

	Model 9 Change in gross log rent.	Model 10 Change in gross log rent.
Change in $PM_{2.5}$	-0.075**	-0.416***
	(0.023)	(0.063)
Change in $PM_{2.5}$ x Change in $PM_{2.5}$		-0.138***
		(0.023)
Change in $PM_{2.5}$ x Change in $PM_{2.5}$ x Change in $PM_{2.5}$		-0.013***
		(0.002)
Gross rent in 2007	0.000***	0.000***
	(0.000)	(0.000)
$PM_{2.5}$ in 2007	-0.043***	-0.007
	(0.012)	(0.014)
Population Density in 2007	0.000***	0.000***
	(0.000)	(0.000)
Homeownership in 2007	0.879***	0.905***
	(0.082)	(0.082)
Vacant Units in 2007	-0.388**	-0.356**
	(0.138)	(0.138)
Single-family Homes in 2007	-0.532***	-0.535***
	(0.073)	(0.073)
Recent House-Built (2010 or later) in 2007	0.832***	0.841***
	(0.082)	(0.082)
Constant	4.020***	3.524***
	(0.144)	(0.167)
State Fixed Effect	Yes	Yes
Number of observations	13032	13032
R-squared	0.163	0.166

Standard errors in parentheses

* p<0.05, ** p<0.01, *** p<0.001

On the other hand, Table 6 presents the regression results of the relationship between the changes in $PM_{2.5}$ and changes in rental housing rents. As well as in Table 5, linear and polynomial regression models are presented in Model 9 and Model 10, respectively. The R-squared slightly increases from 16.3% in Model 9 to 16.6% in Model 10, which means the independent variables' variance is explained slightly better in Model 10. Both models indicate a significant negative relationship between the changes in gross rent and changes in $PM_{2.5}$. Model 9 shows a significant negative relationship between change in $PM_{2.5}$ and change in log house value, which interpret that every 1 µg/m3 increase of $PM_{2.5}$ is associated with a 7% decreased owner-occupied house value, assuming the other variables remain constant. Although overall, the relationship between these two variables is negative, the gross rent increases in a constant value when there is a slight decrease in $PM_{2.5}$; hence it is not necessarily linear. The relationship is explained better in Figure 5.

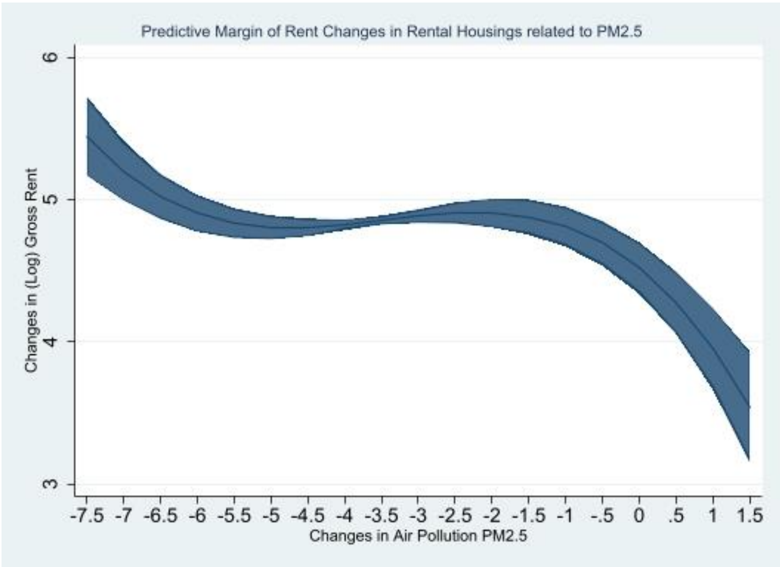

Figure 5 Predictive Margin of Rent Changes in Rental Housings related to Air Pollution ($PM_{2.5}$)

Figure 5 visualizes the predictive rent changes of rental housing in terms of $PM_{2.5}$ at a census tract level. The y-axis is the changes in gross rent in natural logarithmic as the dependent variable, while the x-axis remains the same as the previous margin plot. The margins are calculated to predict rent changes for all combinations of $PM_{2.5}$, with the same range as explained in Figure 4. As a result, when there is a 6.5 µg/m^3 to 7.5 µg/m^3 decrease in $PM_{2.5}$, the gross rent increases from USD 152 to USD 232 on average. However, when there is a slight decrease between 1.5 to 5.5, the gross rent increases in a constant value with an average of USD 128. However, when there is a slight increase of $PM_{2.5}$, ranging from 0.5 µg/m^3 to 1.5 µg/m^3, the gross rent slightly increased from USD 34 to USD 72 on average.

The differential relationship observed between changes in air pollution ($PM_{2.5}$) and changes in house value compared to changes in gross rent may be attributed to several factors. The divergent dynamics of the homeownership and rental markets may play a crucial role. Homeownership, being a long-term investment, may afford individuals greater control and flexibility in housing choices, potentially making them more sensitive to the long-term relation to air pollution. The complex relationship between air pollution and rental housing may occur caused by heterogeneity within the rental market, encompassing various housing types and market segments. However, further research is warranted to comprehensively investigate and validate these potential reasons.

Overall, the empirical analysis of the relationship between air pollution and housing prices at the census tract level reveals complex dynamics with potential implications. The findings suggest a negative relationship between air pollution ($PM_{2.5}$) and housing prices, possibly reflecting health concerns, preferences for improved quality of life, and proximity to desirable amenities. This condition attracts buyers and drives up housing demand, consequently, prices. Additionally, regulatory measures to curb air pollution, such as emissions controls or zoning regulations, could contribute to the observed relationship. Stricter pollution control measures might lead to improved air quality and higher housing prices (Chay and Greenstone, 2005). The difference in the relationship between air pollution and housing prices for owner-occupied and rental housing might reflect the differing motivation and characteristics of these two market segments. Owner-occupied homeowners might be more concerned about long-term impacts on health and quality of life, while factors like proximity to employment centers and transportation links might influence renters. Other than that, supply and demand also play a role. If housing supply is limited in areas with lower air pollution, increased demand due to health and quality of life concerns could drive up prices. Conversely, demand might be lower in areas with higher pollution levels, resulting in lower prices. While these potential reasons provide insights into the relationship between air pollution and housing prices, further research and analysis are needed to gain a better understanding of the relationship.

V. CONCLUSION AND RECOMMENDATION

5.1. Conclusion

This study examines the relationship between air pollution and housing prices for both owner-occupied and rental housing in the United States of America. Several key findings emerged by analyzing the data and addressing the research questions and sub-questions. The study found that air pollution, represented by $PM_{2.5}$ levels, is significantly related to house value and rent.

Previous research has primarily focused on the relationship between air pollution and house prices for owner-occupied housing, and not much further research about the rental market. By considering rental housing, this study sheds light on the potential disparities in exposure to air pollution and associated housing costs across different socioeconomic groups. It highlights the importance of understanding how pollution relates to homeowners and renters, as renters may have fewer choices or resources due to affordability. Individuals with lower incomes may be more likely to reside in areas with higher pollution levels. In comparison, higher-income individuals may have greater resources and options to live in areas with better air quality. The relationship between air pollution and housing prices (house value and rents) is predominantly negative at both low and high levels of $PM_{2.5}$, which aligns with the first hypothesis. However, in the mid-range of $PM_{2.5}$ levels, a slightly positive relationship was observed. This finding suggests that unobservable variables, such as proximity to desirable features or amenities, may offset the negative relationship between air pollution and housing prices. Socioeconomic disparities can arise from these unobservable variables, as certain socioeconomic groups may have more access to desirable amenities or features that counterbalance the negative effects of air pollution. This condition can result in different relationships in housing prices based on socioeconomic status.

Additionally, changes in $PM_{2.5}$ over time have a significant relationship with the changes in housing prices for both owner-occupied and rental housing. As $PM_{2.5}$ increases or decreases within a specific range, there are corresponding changes in house values and rents. These findings align with the second hypothesis, which indicates a negative relationship between changes in air pollution and housing prices for owner-occupied and rental housing. Based on the results, areas with decreased air pollution lead to increased housing prices, indicating that neighbourhoods with poorer air quality may have more affordable housing options. The lower housing prices in these areas might reflect their negative environmental conditions, perpetuating socioeconomic disparities and unequal distribution of environmental benefits and burdens.

5.2. Limitations and Recommendation

By all means, this study is not without limitations. Data limitations and the omission of certain variables may have influenced the results, such as distance to the city centre or amenities and socioeconomic factors. Causality cannot be definitively established, and unobservable variables may affect the observed relationships. In addition, generalizability may be limited, as the findings are specific to the context of the United States and may not be directly applicable to other countries. Based on the results, several recommendations can be made. Policymakers and urban planners should prioritize air quality considerations in housing-related decisions, ensuring that new developments promote good air quality. Efforts should be made to address the socioeconomic disparities associated with air pollution by providing affordable housing options with good air quality in currently polluted areas. Further research is needed to explore the unobservable variables and mechanisms underlying the relationship between air pollution and housing prices. Stronger environmental regulations, public awareness campaigns, and education initiatives can reduce air pollution and promote healthier living environments.

In conclusion, this study underscores the significant relationship between air pollution and housing prices for owner-occupied and rental housing. It highlights the presence of socioeconomic disparities and emphasizes the importance of considering air quality in housing-related decisions. By implementing the recommendations and addressing the limitations, policymakers and communities can work towards reducing the negative relationship of air pollution on housing markets, promoting equitable access to healthier housing options, and mitigating socioeconomic disparities associated with air pollution exposure.

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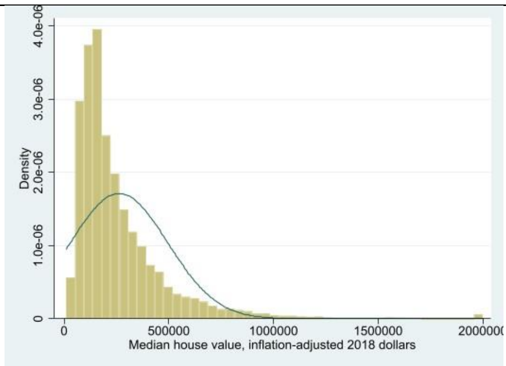
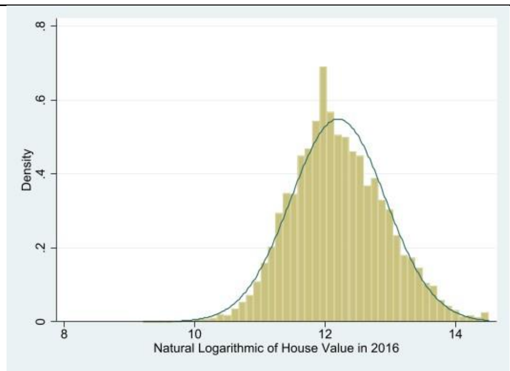
APPENDIX

Density Function

<table>
<tr><th>Variable</th><th>Before Log Transformation</th><th>After Log Transformation</th></tr>
<tr><td>House Value in 2016</td><td>
</td><td>
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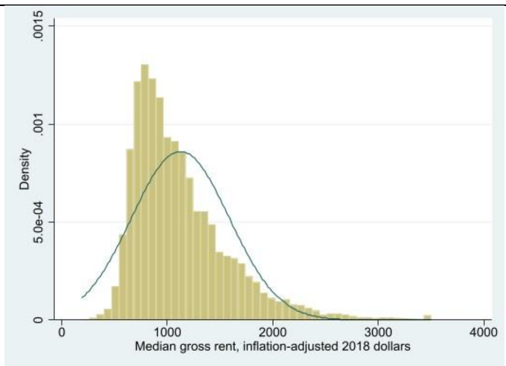
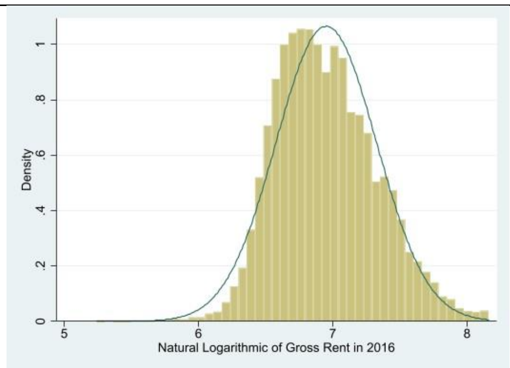
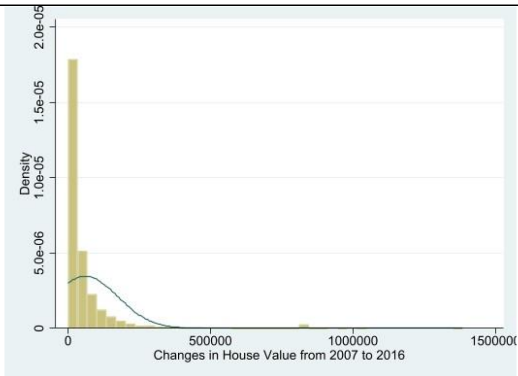
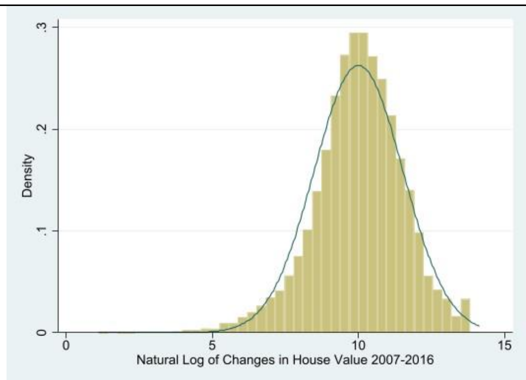
<tr><td>Gross Rent in 2016</td><td>
</td><td>
</td></tr>
<tr><td>Changes in House Value from 2007 to 2016</td><td>
</td><td>
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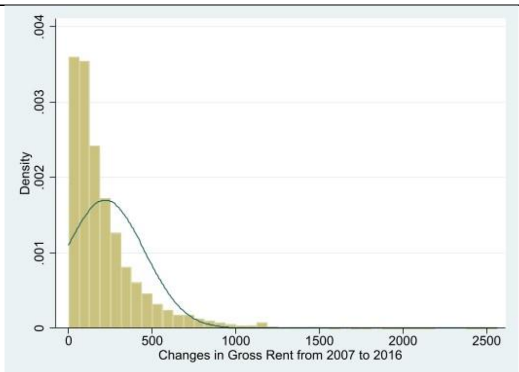
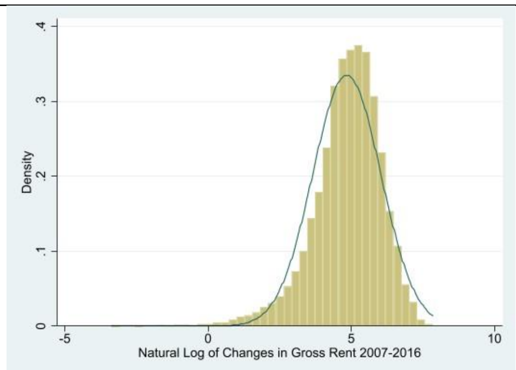
<tr><td>Changes in Gross Rent from 2007 to 2016</td><td>
</td><td>
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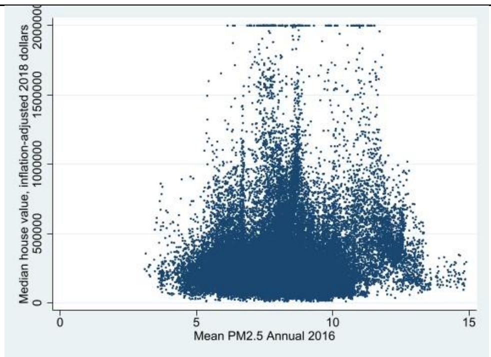
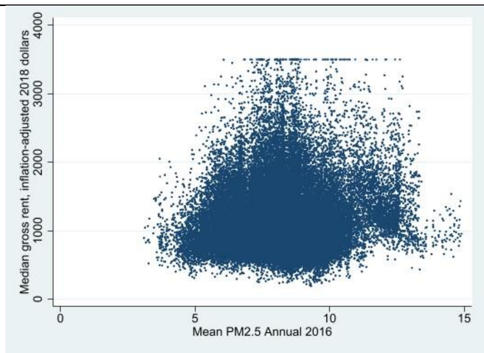
Scatter Plots

	House Value	Gross Rent
$PM_{2.5}$		

Correlation Matrix

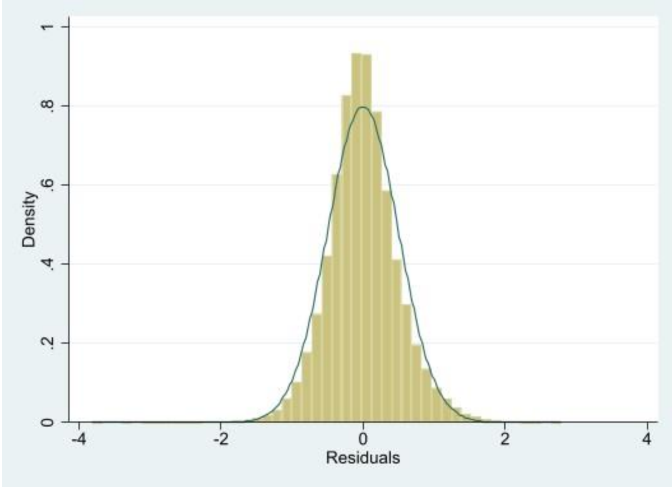
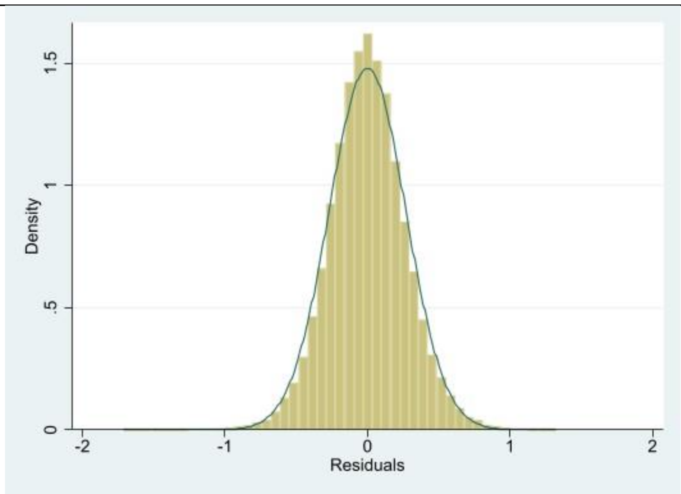
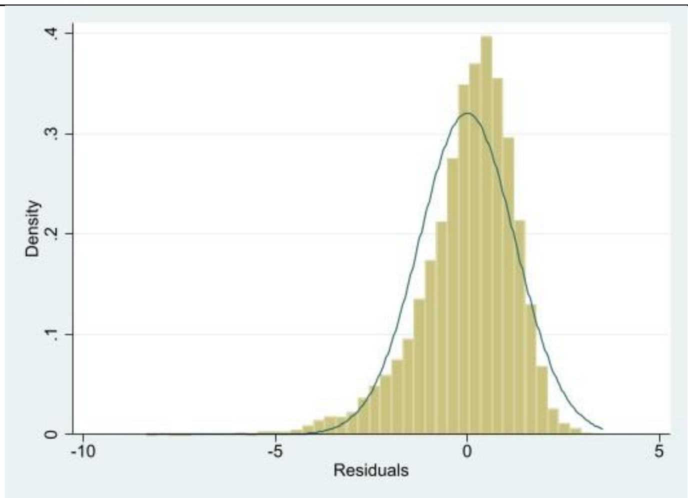
Cross-sectional Analysis

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
(1) housevalue2016	1.000									
(2) loghousevalue16	0.875	1.000								
(3) grossrent2016	0.714	0.728	1.000							
(4) loggrossrent16	0.672	0.742	0.967	1.000						
(5) pm252016	0.042	0.004	0.051	0.050	1.000					
(6) popden2016	0.334	0.304	0.228	0.243	0.122	1.000				
(7) homeowner2016	0.001	0.068	0.142	0.126	-0.156	-0.416	1.000			
(8) vacantunit2016	-0.158	-0.282	-0.257	-0.286	-0.171	-0.079	-0.083	1.000		
(9) singlefamil~2016	-0.134	-0.118	-0.013	-0.032	-0.061	-0.504	0.745	-0.107	1.000	
(10) built0010la2016	0.032	0.093	0.090	0.099	-0.047	-0.104	0.056	-0.039	0.010	1.000

Longitudinal Analysis

Variables	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
(1) housevalue0716	1.000												
(2) loghouseval~0716	0.658	1.000											
(3) grossrent0716	0.352	0.347	1.000										
(4) loggrossrent0716	0.259	0.313	0.768	1.000									
(5) pm250716	0.097	0.127	0.127	0.127	1.000								
(6) housevalue2007	0.614	0.518	0.478	0.393	0.126	1.000							
(7) grossrent2007	0.490	0.447	0.408	0.330	0.150	0.786	1.000						
(8) pm252007	-0.027	-0.068	-0.087	-0.097	-0.856	-0.032	-0.048	1.000					
(9) homeowner2007	-0.148	-0.194	0.059	0.008	0.045	-0.157	-0.033	-0.116	1.000				
(10) singlefami~2007	-0.192	-0.264	-0.033	-0.081	0.082	-0.253	-0.157	-0.128	0.797	1.000			
(11) built0010la2007	-0.069	-0.004	0.087	0.082	0.066	-0.110	0.087	-0.038	0.241	0.188	1.000		
(12) popden2007	0.257	0.264	0.106	0.139	-0.111	0.391	0.293	0.127	-0.455	-0.559	-0.201	1.000	
(13) vacantunit2007	-0.025	-0.055	-0.118	-0.116	-0.007	-0.193	-0.243	-0.028	-0.111	-0.134	-0.054	-0.061	1.000

Normal Distribution of the Residuals

Model 3 Polynomial Regression of $PM_{2.5}$ and owner-occupied house value in 2016	
Model 6 Polynomial Regression of $PM_{2.5}$ and rental housings gross rents in 2016	
Model 8 Polynomial Regression of changes in $PM_{2.5}$ and changes in owner-occupied house value in 2007 – 2016	

Model 10 Polynomial Regression of changes in $PM_{2.5}$ and changes in gross rents in 2007 – 2016