Valuation of Noise Pollution and Abatement Policy:

Evidence from the Minneapolis-St. Paul International Airport

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Abstract

Aircraft noise pollution has adverse physical and mental health effects that are capitalized in the affected home values. We contribute to the literature estimating these noise discounts by our novel identification strategy that analyzes the "treatment effect" of two local government subsidized soundproofing initiatives near the Minneapolis-Saint Paul international airport. Combining a repeat-sales sample with data on aircraft noise pollution (1990-2014), we find a causal noise discount of around $25,000 per sale of noise-affected, but abatement-ineligible, properties, whereas abatement-eligible homes experience a negligible effect post soundproofing indicating a return on abatement investments as a high as 40% in Minneapolis.

JEL codes: (R2, R3)
Key words: Airport Noise, House Prices, Soundproofing, Abatement Policy

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1 Introduction

Airport-related noise can have detrimental impacts on the health and well-being of residents nearby.[1] Aircraft noise can interrupt sleep patterns and lead to difficulty in hearing and engaging in verbal conversations.[2] This noise is a classic example of an externality for which residents typically have a willingness to pay to avoid. Baumol et al. (1988) describe the typical condition under which a social planner (such as the local government) will choose to undertake mitigation - that is, up to the point where the marginal social cost equals the marginal benefit. One way in which it is possible to measure the valuation of noise and noise mitigation is through a hedonic housing price analysis, originally popularized by Rosen (1974) and more recently by Banzhaf (2018) among others.[3] The idea is that house prices can be broken up into the value of individual property characteristics and local fundamentals. Among these fundamentals are externalities, such as airport noise. Since noise is expected to have adverse health effects and interrupt sleep and concentration, such properties typically sell for less than similar houses without noise.[4]

Baumol et al. (1988), for example, suggest that homeowners can take defensive actions to avert the externality. In the case of airport noise, this option could entail soundproofing of individual homes, for which there are several examples across various locations in the U.S., including Atlanta, Boston, Minneapolis, and others.[5] But the benefits of such defensive action are typically experienced over many years while the costs of soundproofing, for instance, are usually borne upfront. Even if the benefits of soundproofing exceed the costs, liquidity constraints of homeowners can lead to a suboptimal level of soundproofing. In such a situation, some intervention by the local government can help encourage the optimal level of insulation. This soundproofing can reduce noise experienced by homeowners and in turn, raise house prices. Thus, it would be of interest to determine the return to this government intervention (or "treatment effect"). While a hedonic house price approach is often used in the airport noise literature (as in Cohen and Coughlin (2008)), a repeat sales approach can enable a "treatment" effect to be estimated for a set of properties that have sold twice - once before and once after a soundproofing initiative sponsored by the local government.

Due to the unavailability of data on the precise implementation of these abatement policies, however, there has been a lack of attention to this issue in the airport noise impacts on house prices literature.[6] Instead, much of the previous research on airport noise, such as Cohen and Coughlin (2008, 2009), Salvi (2008), and others, address the impacts of airport noise but do not implement a careful identification strategy. Issues of endogeneity, such as the potential for reverse causality between noise pollution and home values affect much of the previous research and have resulted in a wide range of imprecise estimates of the impacts of noise on house values, which, when used for policy purposes, may be undesirable. One of the few studies in this literature with a convincing identification strategy is Ahlfeldt and Maennig (2015), who consider the announcement of the closing of one of Germany's airports as a plausible source of exogenous variation in aircraft noise pollution.[7] Other convincing noise studies include the work by Boes and Nüesch (2011), who find a Zürich rental apartment noise discount of around 0.5% per decibel of noise pollution, or more recently Affuso et al. (2019), who use a spatial econometric model to determine the noise discount arising from the Memphis International Airport and find that noise pollution is valued at around $4,800 on average.[8]

In the absence of exogenous changes in flight paths or airport closures, we develop a new identification strategy that allows us to not only estimate the aircraft noise discount on the average property, but also disentangle the effect of this negative externality across soundproofing eligible and ineligible homes. Leveraging information on time-varying abatement eligibility criteria based on two soundproofing initiatives surrounding the MSP International airport from 1990 to 2014, we are able to estimate the causal effect of noise on home values and quantify the effectiveness of these abatement initiatives. To this end, we combine an unbalanced panel dataset on Minneapolis repeat sales from 1990 to 2014 with annual aircraft noise pollution exposure by mapping each property against annually reported MSP contour curves. Furthermore, we exploit the information on abatement eligibility for the 1992 Sound Insulation and 2008 Consent Decree programs.[9] We find that a one decibel increase in noise exposure reduces the rate of home value appreciation by two percentage points (or 6.6% of the average sample appreciation between repeated sales) for abatement ineligible houses. Based on our sample, this effect translates into a noise discount of

1.6%, akin to previous studies.[10]

In addition, our analyses also produce new evidence that the noise effect on abatement eligible properties is statistically significantly different from ineligible ones and in fact, fully muted. We hold these findings plausible given the fact that soundproofing is expensive, and the typical homeowner is usually cash constrained. Therefore, despite the potential high return, without some forms of subsidies it is likely that the typical homeowner may have a difficult time financing noise insulation. In fact, over 90% of the homeowners in each tier of the 2008 consent decree program ended up taking advantage of the abatement initiative, indicating few if any homeowners likely chose to sound proof on their own prior to the program.[11] Given this adoption rate, it is reasonable to expect that the abatement "treatment" mitigated the noise discount and led to higher sale prices than would be otherwise realized, for those properties that sold after the soundproofing.[12] Our results show that the inability to differentiate the noise pollution effects across homes that receive soundproofing and those that do not can lead to biased coefficient estimates that attenuate the estimated noise discounts towards zero.

To the best of our knowledge, our findings are the first known results that depend on using soundproofing eligibility to identify the causal impacts of noise on house prices and suggest that owners of ineligible sample properties, experiencing increases in noise, suffer significant economic losses that average around $25,000 per sale and could reach as high as $100,000 in our sample. Equally important, however, is the fact that our estimates point to the efficiency of the soundproofing initiatives, with an approximate return on investment (ROI) for abatement as high as 40% in Minneapolis.

Collectively, these results hold up to a broad range of robustness checks and have important policy implications. First, our estimates underline the effectiveness of noise abatement as a defense mechanism to mitigate the negative noise pollution externality arising from local air traffic. Secondly, our estimates not only show that the noise abatement strategy reduces the experienced noise pollution, but also produce consistent evidence that soundproofing is a cost effective solution to this global issue. Thirdly, the differentiation across two soundproofing initiatives with distinctly different eligibility criteria suggests that this policy instrument is effective at multiple levels of aircraft noise pollution that reach beyond the federally set threshold of 65 decibel. Lastly, our dynamic estimates produce evidence of persistent noise pollution effects that stand at odds with current abatement policy practices, which delay the abatement response to aircraft noise pollution by several years.

The validity of these findings hinges on the ability of our identification strategy to address three critical concerns of endogeneity that plague the literature on noise pollution and house prices. First, researchers are concerned with the potential for omitted variables bias stemming from unobserved housing characteristics that are correlated with home values and noise pollution and systematically vary across homes that are affected by noise and those that are not. If, for example, noise-affected homes are built with superior windows and doors relative to unaffected homes, cross-sectional studies unaware of these differences would underestimate the correlation between noise pollution and sale price discounts. Multiple observations on the same property, such as the repeat sales sample we employ in our study, circumvent this issue by differencing out all observable and unobservable time-invariant home characteristics that may influence the previous cross-sectional estimates (see, for example, Püschel and Evangelinos 2012; Mense and Kholodilin 2014).

Secondly, a related concern, which arises even with the application of repeat sales data, is the potential presence of unobservable, time-varying neighborhood and/or home characteristics. Examples of these unobservables may include the construction of a new house or renovation of an existing home in the neighborhood that may cause a change in the rate of appreciation of surrounding repeatedly sold properties. Similarly, the observed homes in our sample may undergo renovation that may increase the value or raise the rate of appreciation prior to the repeat sale. The presence of these and other types of unobservable, time-varying neighborhood and/or home characteristics, however, only becomes problematic for our estimation if they are correlated with the observed aircraft noise pollution. The exact bias would depend on the sign of the unobservable-characteristic-to-noise correlation. Sound proofing of noise-affected homes under the airport commission's noise abatement programs, for example, is positively correlated with aircraft noise pollution and would introduce an attenuating bias of our noise discount estimate. Consequently, we control for each property's changing eligibility status during our sample period. To address the possibility of temporal changes in noise-correlated neighborhood characteristics we directly control for Census block-group population and other socioeconomic characteristics.[13]

Lastly, the literature has raised the issue of reverse causality (see, for example, Cohen and Coughlin 2012). While it is economically intuitive that noise pollution creates a disamenity that results in house price discounts and lower rates of appreciation, issues of endogeneity are plausible. Cohen et al. (2019), for example, study traffic noise in the state of Georgia for all transportation modes. They find correlation between traffic in lower-valued neighborhoods, suggesting ambiguity in the causality direction between home prices and traffic noise. While estimations based on repeat sales samples can document the expected inverse correlation, traditional hedonic models using cross-sectional or panel data cannot establish causation without further information.[14]

To address this concern, we leverage the time-varying information on two abatement policies that render plausibly exogenous variation in noise exposure across abatement eligible and ineligible homes. If, in fact, residents experience no disamenity effect from noise pollution and the causality runs from smaller home value appreciation rates to greater noise pollution, soundproofing a house should have no effect on the estimated noise-to-home-value-appreciation relationship. That is, buyers and sellers of affected homes should not respond to soundproofing in their valuation of a given property. If, however, noise pollution is indeed a costly disamenity reflected in lower house sale prices, soundproofing a home against aircraft noise pollution should have the desired mitigation effect and reduce the sale price discount. Differentiating the aircraft noise effect across abatement eligible and ineligible properties before and after the soundproofing initiatives allows us to test these competing hypotheses and examine whether there exists a statistically significant difference in the estimated noise-to-home-value-appreciation relationships. Consistent evidence of this difference establishes the causal effect of noise pollution on house prices.

The critical assumption underlying our identification strategy requires that the eligibility criteria of any abatement policy are uncorrelated with house prices and their rate of appreciation, which is akin to the parallel trends assumption underlying the difference-in-differences methodology used in the program evaluation literature. In the case of the Minneapolis-Saint Paul International airport (MSP), we believe this to be satisfied. Over the past 25 years, the local airport authority, known as the Metropolitan Airports Commission (MAC), has launched two separate soundproofing initiatives to mitigate exposure to aircraft noise pollution. Under the first program, abatement eligibility was strictly a function of a property's location with respect to the 65 decibel threshold based on the projected 1996 noise contour plot, which was calculated and approved in accordance with federal regulation set forth by the FAA. Similarly, the second initiative, launched in 2008, determined soundproofing eligibility based on a property's location in relation to the 60 and 65 decibel threshold based on the 2007 noise contour plot. By design, neither policy correlated abatement eligibility with home values or the rate of home value appreciation. The data support this assertion (see, for example, Figures 3.1 and 3.2) making the differentiation between abatement eligible and ineligible homes a powerful identification strategy.[15]

The remainder of this paper proceeds as follows. We first summarize the related literature, provide historical and institutional background knowledge on the MSP International airport and detail the aforementioned noise abatement initiatives. Next, we describe the data specific to this particular airport and the empirical estimation approach. Lastly, we present the empirical results and findings from various robustness checks, before offering concluding remarks and suggestions for future research.

2 Literature and Background

2.1 Literature Review

Many studies have examined airport noise effects on housing prices over the past 40 years, including for airports in North America (U.S. and Canada) and Europe; and for single family residential properties and rental apartments. Nelson (1980, 2004) provide an excellent overview of the early research on this subject and conduct two meta-analyses of previous airport noise studies. Across this body of research, the author finds relatively modest house price discounts ranging from 0.4 to 1.1 percent per decibel of aircraft noise pollution. Differentiating these discounts across the North American countries, Nelson (2004) estimates indicate a noise discount of 0.8 to 0.9 percent per decibel in Canada, which are higher than those evidenced in the United States. In contrast, Schipper et al. (1998) document much more variation in the estimated noise pollution effects.

In some of the more well-cited studies, Cohen and Coughlin (2008, 2009) find a noise discount in Atlanta of approximately 20% for properties exposed to noise levels of 65 decibel (dB) or more, opposed to those in a "buffer zone" of less than 60 dB. They also find this discount to be increasing over time. McMillen (2004) produces a more conservative estimate of the noise discount suggesting that properties exposed to more than 65 dB of noise near Chicago's OHare airport experience reductions in value of around 9%. However, due to the fact that aircraft were being built quieter in the late-1990s, McMillen (2004) projected that the noise contours would actually shrink with an airport expansion, which would lead to higher home values. Pope (2008) provides evidence of a significantly smaller home value discount for single-family residential properties near the Raleigh-Durham airport, where the sale prices are estimated to decrease by approximately 2.9% when noise is disclosed to potential buyers.

More recently, and in international contexts, Mense and Kholodilin (2014) estimate a 9.6% decrease in sales prices for properties near the new Berlin airport in Germany, with a higher discount for properties in areas with lower flight altitudes. Püschel and Evangelinos (2012) find that for apartment rents in Düsseldorf, Germany there is a rent discount of approximately 1.04% for an additional decibel of noise. In contrast, Salvi (2008) evaluated the response of single-family home values near the Zürich airport, and finds a noise discount of approximately 2% to 8%. Almer et al. (2017) claim to be the first quasi-experimental airport noise study with time-varying treatment effects. They examine Zürich apartment rents, and find that it takes approximately 2 years for rents to return to their previous levels following a noise shock.

For the case of the MSP International airport, however, no such estimates on home value noise discounts are available. To the best of our knowledge, the existing literature investigating the impacts of MSP concerns the aircraft noise effects on physical and mental health (Meister and Donatelle 2000), annoyance rates (Fidell et al. 2002), as well as the airport's role as a global gateway (Paul 2005; Cidell 2006) and driver of regional economic development (Cidell 2014), among other topics.

2.2 Institutional Background

The Minneapolis-St. Paul International Airport has a rich and complex history, particularly with respect to its noise mitigation and abatement efforts. Established in the midst of the Snelling Speedway racetrack, the airport was founded in 1920 and became known as the Wold-Chamberlain Field. While originally used as a single-strip airport to accommodate airmail services provided by Northwest Airlines, it soon outgrew its infrastructure with the arrival of domestic passenger traffic in 1929 and international service by 1948.[16] By the 1960s, MSP had undergone significant expansions including the construction of the Lindbergh Terminal and had become the world headquarters of Northwest Airlines, now Delta Airlines. (Metropolitan Airports Commission 2018a).

Designed to serve four million passengers a year by 1975, MSP quickly outpaced passenger growth projections serving 4.1 million travelers by 1967 (Metropolitan Airports Commission 2018a). MSPs rapid growth trajectory continued throughout the 1970s and 1980s and led to the Metropolitan Airport Planning Act in 1989. Under this act, the Metropolitan Airports Commission and the Metropolitan Council were charged to develop two competing proposals considering the expansion of the existing infrastructure versus the relocation of the entire airport. In 1996, the Minnesota state legislature favored the expansion proposal and the MAC was charged with the implementation of its strategic plan. Supported by $3.1 billion in funding, the original Lindbergh terminal was overhauled and expanded, a second terminal, Terminal 2-Humphrey, was constructed, roadway access and parking were improved, and a light rail line, connecting the MSP International Airport and the downtowns of Minneapolis and St. Paul, was developed (Metropolitan Airports Commission 2018a). Due to these expansions, MSP has been able to serve over 38 million passengers annually and accommodated over 400,000 landings and takeoffs per year over the last decade (Metropolitan Airports Commission 2018b). Today, the airport supports over 80,000 jobs and earns close to $16 billion in yearly business revenue (InterVistas Consulting Inc. 2017).

Located in an urban setting, however, the airport's unanticipated exponential growth has also placed significant strains on residential life in its vicinity. Ranking among the busiest U.S. airports, operations have caused several disamenities for the residents of Minneapolis, St. Paul, and the surrounding municipalities, the most paramount of which is aircraft noise pollution. In response to the adverse noise impact, the MAC has developed and implemented several noise abatement programs since the late 1980s. Historically, noise abatement programs are often employed by local airport authorities to mitigate residential exposure and generally supported through federal funds from the FAA (Alexander-Adams 2015). In the case of Minneapolis, the first of these initiatives is known as the 'Sound Insulation Program' and commenced in 1992. Completed in 2006, "the MAC spent a total of approximately $229.5 million on the single-family home [noise] mitigation program during its 14-year lifespan" (Metropolitan Airports Commission 2017, p.9).

The eligibility criteria for this program followed federal regulations established by the FAA requiring airports to provide noise abatement to homes exposed to aircraft noise pollution in excess of 65 dB Day-Night Average Sound Levels (DNL), which is a metric used to determine the average daily noise exposure per year (Federal Aviation Administration 2018). For MSP, this 65 dB DNL noise pollution threshold was determined via a federally approved contour plot projecting the anticipated 1996 aircraft noise levels and is visualized in Figure 1.1.[17] Under this program, any property located within the 65 dB DNL contour was eligible for abatement, including window and door treatments, wall and attic insulation, air conditioning, and air vent baffling, from 1992 until 2006. The black dots in Figure 1.1 represent all eligible sample properties sold after 1992, while the faded, beige dots illustrate sales of ineligible homes outside the noise threshold. The abatement program aimed to reduce exposure to aircraft noise pollution by five dB DNL and average annual abatement costs for the 7,846 treated single-family homes ranged from $17,000 in 1994 to $45,000 per home in 2001 (Metropolitan Airports Commission 2017).[18] In our sample, 5,012 reported sales meet these eligibility criteria under this initial abatement program.

In 1999, MAC negotiated an agreement with airlines operating out of MSP to fund noise abatement for homes in the 60 to 64 dB DNL range. While this ambitious agreement included a commitment to fund $150 million in abatement costs, the specifics of this program were not laid out at that time. Although some of these important details were later added in 2001[19], the MAC decided to scale back on their original commitment and instead agreed to fund only $48 million in abatement efforts in 2004 (City of Minneapolis 2016).[20] In response, the municipalities of Minneapolis, Richfield, and Eagan sued the MAC for violating environmental quality standards and the Minnesota Environmental Rights Act, as well as breaching an enforceable promise to insulate all eligible homes in the 60 to 64 dB DNL range. The prolonged legal dispute stalled further abatement efforts until 2007 when all parties reached a settlement, wherein the MAC agreed to a two-tiered abatement program that offered full insulation (tier one) to properties located within the 63 to 64 dB DNL contour projected for 2007 and partial abatement (tier two) to homes within the 60 to 62 dB DNL region of the forecasted contour, depicted in Figure 1.2.[21]

The program, now known as the Consent Decree abatement program, commenced in 2008. Upon its completion in 2014, 404 out of 457 eligible homes had participated in the tier one program and 5,055 out of 5,428 eligible properties received tier two abatement funding. In our sample, we can identify 694 repeat sales of newly abatement eligible properties under the Consent Decree program that were previously ineligible. In Figure 1.2, we differentiate these newly eligible properties represented by the black dots from homes that were previously eligible under the Sound Insulation Program (grey dots) and those properties ineligible based either on their location or time of sale prior to 2008 (beige dots). To be clear, the assigned eligibility of a sold home depends on two criteria: 1) location and 2) time of sale. That is, many observed home sales are located outside the the 60 DNL contour for 2007 and thus ineligible based on the location criterion (beige dots outside 60 DNL 2007). Likewise, some homes are marked ineligible despite their location inside the 60 DNL for 2007. These homes were sold prior to 2008 and thus ineligible for abatement under the Consent Decree program (beige dots inside 60 DNL 2007). Only if both criteria are met, do we assign abatement eligibility to an observed home sale. The total abatement costs for this second initiative are estimated at around $95 million (Metropolitan Airports Commission 2017).

3 Data

We investigate the effects of changing MSP International airport noise pollution on Minneapolis home values and break new ground by quantifying the effectiveness of the aforementioned noise abatement programs. For the empirical analysis, we draw on three primary datasets including home sales data, spatial airport noise data, and Census data surrounding the MSP International Airport. The home sales and Census data were generously provided by Professor Sarah West and Clemens Pilgram, who study the housing price premiums of the Minneapolis Blue Line light rail (Pilgram and West 2018). Neighborhood characteristics are drawn from the 1990 and 2000 U.S. Census and complemented by the estimates of the Environmental Systems Research Institute (ESRI) available through the proprietary ESRI 2011/2016 Updated Demographic Data dataset. The information provided is disaggregated at the Census block-group level[22] and includes multiple demographic and socioeconomic statistics, including, for example, the percentage of the population that is Caucasian, African American, Hispanic, American Indian, Asian, or Pacific Islander. Other neighborhood characteristics include the percentage of the population under the age of 20 or over the age of 65, as well as the median income. Given a sample period from 1990 through 2014, missing values are linearly interpolated.[23] For further details on the exact matching between block characteristics and parcel data, we refer the reader to Pilgram and West (2018).

The home sale data were originally obtained from the City of Minneapolis' Tax Assessment Office and include all arm's length transactions of single-family home sales in Minneapolis between 1983 and June 2014.[24] Given the availability of the Census data, however, we restrict the sample to market transactions after 1989. The information contained in this dataset include an identification number unique to each parcel, the corresponding property address, the date of sale, and the nominal sale price. We adjust the nominal sale prices for inflation via the Consumer Price Index for all Urban Consumers, sourced from the Bureau of Labor Statistics (BLS), and express real property values in 2014 U.S. dollars. To geocode each home and establish its exposure to aircraft noise, we rely on the MetroGIS parcel data published by the Twin Cities Metropolitan Council in April of 2014. Addressing the common concern of omitted variables that systematically influence individual home values, we focus our analysis on the preferred subsample of repeated sales transactions recorded for unique properties. This panel dataset of 27,541 unique parcels and 46,477 reported sales allows us to control for all time-invariant property and/or neighborhood characteristics.

Annual information on the spatial distribution of aircraft noise pollution has been obtained from the MAC, who owns and operates MSP, and oversees the resulting residential noise pollution.

Noise exposure is commonly measured via aircraft noise contours that represent approximated areas, for which the average noise levels associated with airport-specific aircraft activity exceed the given threshold. In the United States, the principle metric for these thresholds was established by the FAA and is expressed in the aforementioned DNL format, which is measured in decibels. As such, the contours provide a discrete measure of annual average noise exposure over a 24-hour period and do not illustrate airplane flight tracks or the actual noise experienced from a single aircraft noise event. According to the MAC, the calculations of these contours are, in fact, based on the most appropriate version of the FAA's Integrated Noise Model, which relies on aircraft operation counts and times, aircraft types, and flight tracks, rather than actual noise measurements.

Changes in residential aircraft noise exposure can be linked to any number of these factors. Historically, the most significant reductions in noise exposure have resulted from the FAA's regulation of aircraft engines. According to the FAA, the technological improvements of aircraft engines has led to a 90% reduction in significant noise level pollution, measured by the number of people residing in areas experiencing 65 dB DNL or above (Federal Aviation Administration 2018). Rapid growth of air traffic and greater urbanization, however, have counteracted these technological advances and continue to raise the issues of aircraft noise pollution and related policies. Other factors that contribute to changes in noise exposure include, for example, alterations in flight patterns (Boes and Nüesch 2011; Almer et al. 2017) or airport expansions (Mense and Kholodilin 2014). In the case of MSP, variation in noise exposure is rooted in a number of noise mitigating initiatives as well as the nearly tenfold increase in air passenger traffic since 1970.[25]

Figures 2.1 through 2.3 illustrate the resulting changes in noise exposure at the major thresholds (60, 65, and 70 dB DNL) over a twenty year period from 1996 to 2016. Moreover, the maps depict each of the unique Minneapolis parcels repeatedly sold during this sample period. Importantly for our identification strategy, a large share of these homes is affected by aircraft noise pollution of 60 dB DNL or above and experiences significant variation over the 20-year timespan. While the 65 and 70 dB DNL contours, given in Figures 2.2 and 2.3, illustrate a fairly consistent reduction in aircraft noise exposure from 1996 to 2016, we observe significant expansions and shifts in the 60 dB DNL contours, depicted in Figure 2.1, over the sample period. As a result, many of the South Minneapolis sample homes neighboring Richfield fall below the 60 dB DNL noise pollution threshold in 1996, but are subject to this disamenity by 2006. By 2016, however, this noise exposure significantly drops and falls within the 1996 contour. In contrast, many of the properties located in neighborhoods around Lake Harriet and Lake Calhoun, such as East Harriet, King Field, and Tangletown, experience significant reductions in aircraft noise exposure between 1996 and 2006, but are again subject to noise pollution above the 60 dB DNL threshold by 2016. This variation in noise, along with the varying abatement eligibility status, provide a unique opportunity to estimate the aircraft noise pollution effect on Minneapolis homes and quantify the abatement impact.

We have obtained annual data on MSP noise contours, including the ones depicted in Figures 2.1 through 2.3, for 10 years including contours for 1996, and 2006 through 2014. The level of detail of the available information, however, varies across years. For 1996 and 2007 through 2009, for example, the noise contours are only available for the commonly referred to thresholds of 60, 65, 70, and 75 dB DNL. For the years of 2006 and 2010 through 2014, data on residential noise exposure in Minneapolis are available at a more disaggregated level ranging between 60 to 80 dB DNL at one-level increments. Given the temporal and spatial distribution of these noise levels, we use GIS to match each unique and repeatedly sold parcel to the corresponding annual noise level allowing us to observe current and past average annual noise exposure at the times of sale.[26]

For home sales during the years for which no annual contour plot is available, namely between 1990 to 1995 and 1997 to 2005, there are several options to deal with the missing noise information. One option is to restrict the sample to consecutive years for which noise data are available. While this eliminates any uncertainty about approximations, it also severely limits the number of observations and fails to leverage the noise data from 1996. Another option is to interpolate the missing noise values based on the 1996 and 2006 noise data. While this enriches the dataset in terms of the number of observations and utilizes the noise data provided for 1996, one must chose a specific form of interpolation. Overall, we consider and test four alternative options to accommodate the missing noise information and observe very consistent results. Our preferred interpolation strategy, which underlies our primary estimates, imposes an arbitrary cutoff year between 1996 and 2006 and attributes noise levels prior to this cutoff to those experienced in 1996 and those transactions after the cutoff until 2005 to noise levels experienced in 2006. Actual noise experience, of course, may vary from these approximations and the choice for the cutoff year is arbitrary. This option, however, allows us to test the sensitivity of our results against this arbitrarily chosen cutoff and compare estimates across alternative choices. Reassuringly, the alternative choices of threshold years yield robust results, presented in columns (1) through (10) in Table 3.

Second, we consider a linear interpolation of noise values from 1990 to 2006 based on the noise information provided for 1996 and 2006. Given the nonlinearity of the human noise experience with respect to the decibel scale[27], however, we view this linear approximation based on two data points as a suboptimal strategy that may both over- and underestimate actual noise exposure and grossly misrepresent noise levels prior to 1996. The robust results of this sensitivity analysis are presented in column (11) of Table 3.

Third, we consider the exclusion of all transactions prior to 2006. Instead, we focus on a sample from 2006 through 2014, for which we observe annual contour plots, and estimate the noise effect on home values with this restricted sample. In this case, the majority of repeat transactions are lost and the identification strategy rests largely on the Consent Decree abatement program. The results are qualitatively consistent, but also produce larger coefficient estimates that are reported in column (12) of Table 3.

Lastly, we explore the possibility of interpolating noise pollution via an out-of-sample prediction. To this end, we obtain annual daytime and nighttime operations for MSP from 2001 through 2014. To capture the temporal and spatial variation of noise, we regress property-specific noise exposure on MSP aircraft operations interacted with dummy variables that indicate the Census block groups in which the properties are located. Based on the coefficient estimates, we make an out-of-sample prediction of property noise exposure for 2001 through 2005 and re-estimate our primary model on all repeat sales between 2001 and 2014. Similar to third interpolation strategy, this precludes sales prior to the implementation of the initial Sound Insulation program. The results are consistent with our primary estimates and presented in column (13) of Table 3.

Table A1 in the Appendix offers insights into the time-varying sample distribution of aircraft noise pollution for repeatedly sold homes in Minneapolis. As expected, most of the homes sold during the sample period lie outside the aircraft noise polluted region. Within the noise area, the majority of homes are exposed to noise pollution between 60 and 64 dB DNL or 65 to 69 dB DNL. Only a few properties experience noise levels in excess of 69 dB DNL and none of these homes are sold after 2008. In comparison to the frequency of transactions above 60 dB DNL, a half-mile buffer region drawn around this contour curve generates a similar volume of sales.

Complementing these noise-specific transaction frequency counts, Figures 3.1 and 3.2 illustrate the annual average home sale prices for Minneapolis. We differentiate average annual sale prices across Minneapolis homes that are abatement eligible and those that are not under the initial soundproofing initiative (Figure 3.1) and the Consent Decree program (Figure 3.2) over two overlapping 14-year periods from 1990 to 2004 and 2000 to 2014, respectively. Combining all observations, the full sample of repeat sales includes 46,477 unique transactions, of which 7,985 fall inside the MSP contour curves at the time of initial sale or resale. Given the eligibility criteria of the two MAC abatement programs, not all of these 7,985 noise-affected transactions are subject to potential soundproofing. In our data, a subsample of 5,012 repeat sales of 1,964 homes are eligible under the first program and 694 repeat sales of 630 properties are newly eligible under the second Consent Decree program. The vertical lines in Figures 3.1 and 3.2 indicate the years of 1992 and 2008, which mark the respective commencements of these abatement initiatives.

Over the course of the 25 sample years, Figures 3.1 and 3.2 show that eligible and ineligible homes are on similar price trajectories experiencing stagnation from 1990 to 1994, rapid appreciation from 1995 until roughly 2006, and significant depreciation during the great recession. There are, however, a few noteworthy sample-specific deviations between eligible and ineligible homes from these trends. First, Figure 3.1 shows that sale prices of eligible and ineligible properties are on similar trajectories until 1993, but experience some deviations thereafter. While ineligible homes experience a sizable drop in average value by 1994, the average sale price of eligible homes holds steady and rises above the average price of ineligible ones. Moreover, Figure 3.1 depicts an average price premium for eligible homes towards the end of the initial soundproofing program from 2000 to 2004. Second, Figure 3.2 illustrates that eligible houses exhibit significantly higher annual sale prices than the ineligible sample average. This level difference for the eligible properties is suggestive of the rising premia for the desirable Southwest Minneapolis neighborhoods, particularly around Lake Harriet and Lake Bde Maka Ska (formerly known as Lake Calhoun). Third, Figure 3.2 shows that eligible homes under the Consent Decree program experience a significant reduction in the rate of appreciation starting in 2006, which coincides with the opening of the fourth runway of MSP and the aforementioned legal dispute over further noise abatement funding. In contrast to these noise-affected homes, all other Minneapolis properties start to experience the reduction in sale prices by 2007. Lastly, starting in 2008, the rate of depreciation of annual sale prices slows down considerably for homes that become eligible under the settled Consent Decree program, while all other, ineligible homes continue to lose in value. The timing of this visible resilience coincides with the commencement of the second MAC abatement program agreed upon through the settlement of the aforementioned legal dispute towards the end of 2007. Overall, these differences in sale prices across eligible and ineligible Minneapolis homes are indicative of the abatement impact and inverse correlation between noise pollution exposure and sale price premia.

In light of the fact that our aforementioned identification strategy hinges on the volatility in noise exposure between sales, Figure A1 in the Appendix presents the frequency distribution of changes in noise pollution across noise affected Minneapolis homes between initial and repeat sales. Over the sample period from 1990 to 2014, the data suggest that some homes within the contour sample experienced as much as a 10 dB DNL reduction and 8 dB DNL increase in their respective noise exposure. The histogram, however, also illustrates that these extreme noise fluctuations are rare among repeatedly sold homes and that the majority of properties experience smaller or no changes in noise pollution. Interestingly, among the repeat sales transactions in our sample, more homes experienced a reduction in noise perhaps indicative of the timing to market a house for sale under favorable noise conditions.[28]

4 Model

We begin with the typical hedonic model, similar to that used in other airport noise housing price studies, such as Cohen and Coughlin (2008). In such models, the purpose is to determine how various characteristics of the property, neighborhood demographics, and airport noise effect property sale prices. By controlling for the demographics and characteristics with regression analysis, it is possible to estimate how additional noise influences property sale prices. Therefore, the hedonic model may take the following form:

$$ln(P_{it}) = \beta_0 + \beta_1 N_{it} + \beta_2 \delta_{it} + \beta_3 N_{it} * \delta_{it} + \beta_4 H_i + \gamma Z_{bt} + \alpha_t + \epsilon_{it}, \tag{1}$$

where P_{it} represents the sale price of property i at time t, β_0 is an intercept term, N_{it} is a vector of aircraft noise exposure, Z_{bt}, is a matrix of demographic variables, such as census block group population share of African Americans, Hispanics, and/or young adults, and median income in the census block group; and H_i represents a matrix of house characteristics, which we assume are time invariant for house i. A time-varying parcel characteristic is given by δ_{it}, which represents a property-specific indicator variable that captures a home's abatement eligibility status at time t. Finally, α_t represents a vector of year-month fixed effects to capture citywide differences during the time of sale, and ϵ_{it} is an error term that is iid with mean zero and constant variance, along with zero covariance across observations i, where $i = 1, 2, .., N$ and N is the number of houses in the sample. The interaction term between a home's noise exposure and its eligibility status captures the differential noise impact across homes that are eligible $(\delta_{it} = 1)$ and those that are ineligible $(\delta_{it} = 0)$ for one of the MAC's abatement programs at time t.

Taking the first difference of (1) for two separate sale dates for property i, which is sold at both time $t + \tau$ and time t (where t represents the first sale and $t + \tau$ represents the second sale), yields:

$$\Delta ln(P_{i,t+\tau}) = \beta_1 \Delta N_{i,t+\tau} + \beta_2 \Delta \delta_{i,t+\tau} + \beta_3 \Delta N_{i,t+\tau} * \delta_{i,t+\tau} + \gamma \Delta Z_{b,t+\tau} + \alpha_{t+\tau} - \alpha_t + \epsilon_{i,t+\tau} - \epsilon_{i,t}. \tag{1'}$$

Since the characteristics of house i, H_i, are assumed to be time-invariant,[29] they drop out when taking the first difference of (1). Furthermore, time-of-home-sale and repeat-sale fixed effects $(\alpha_t,\ \alpha_{t+\tau})$ control not only for the specific timing of each sale of a given house, but also the difference in the time elapsed between the two sales. That is, we would expect there to be a noiseunrelated difference in home value appreciation between a house sold 10 years ago and one sold 1 year ago. Similarly, we expect there to be a difference in home value appreciation rates for a home that was sold in 2004 and 2006 versus a home that was sold in 2009 and 2011. Our fixed effects capture the timing of repeat sales as well as the number of years that has passed between repeat sales and therefore control for both of these potentially confounding factors.[30]

The coefficients of interest are given by β_1 and β_3. While the former indicates the discount on home value appreciation correlated with aircraft noise pollution, the latter captures whether this noise effect is statistically different for abatement eligible properties.

A priori, we expect aircraft noise pollution to be negatively correlated with home values and home value appreciation ($\beta_1 < 0$). Moreover, we are testing the directionality of this relationship via the interaction between noise pollution exposure and abatement eligibility. If aircraft noise pollution does not cause discounted home values, abatement eligibility should have no impact on the estimated correlation coefficient ($\beta_3 = 0$). If, however, aircraft noise pollution causes the discount in home values and the abatement initiatives successfully reduce noise exposure, one would expect a significantly muted noise effect for these potentially insulated homes ($\beta_3 > 0$).[31]

In spirit, our empirical strategy mimics that of a difference-in-differences (DiD) or triple differences design, where the treatment intensity is given by the change in noise pollution and the treatment effect is identified via the comparison of changes in sale prices of non-eligible properties unaffected by noise to those of noise-affected homes. The triple difference comes into play when we differentiate the noise pollution (treatment) effect across noise-affected homes that are abatement eligibility and those that are not. The critical consideration underlying the proper identification in a DiD or triple differences setup is the well-known parallel trends assumption between treatment and control groups that must hold pre-treatment. A violation of this DiD assumption biases traditional treatment effect estimates and would also implicate our findings. If, for example, prior to becoming eligible, abatement eligible properties experience greater rates of home value appreciation than ineligible properties, our estimate of β_3 would be biased upward and we would falsely attribute the positive price changes to the mitigation of noise pollution resulting from the sound proofing initiatives. Similarly, if properties unaffected by noise are on different price trajectories than homes exposed to aircraft noise pollution, this would constitute a violation of the parallel paths assumption and bias our noise discount estimate.

While the parallel trends assumption cannot be tested directly, it is common practice to investigate its validity by plotting the outcome variable across the distinct property types. Reassuringly, Figures 3.1 and 3.2 display remarkably parallel trends in sale prices for abatement eligible and ineligible homes under the initial program prior to 1992 and parallel pre-treatment trends for abatement eligible and ineligible homes under the Consent Decree program prior to 2008.

Another technique to evaluate the parallel paths assumption is to estimate placebo treatment effects prior to the actual treatment. If the treatment and control groups are truly on parallel trends and there are no anticipatory changes in behavior, these leading placebo effects should be statistically insignificant. In our context, we can apply this logic to the pre-treatment comparison between abatement eligible and ineligible properties under the consent decree program. Rather than estimate the average noise effect after becoming abatement eligible, we can estimate time-varying treatment effects similar to an event study and differentiate the noise effect on eligible homes before, during and after the implementation of the Consent Decree program. Reassuringly, the coefficient estimates on the time-varying noise-abatement-eligibility interaction terms presented in Figure 4.1 are statistically indistinguishable from zero prior to treatment and economically as well as statistically significant thereafter for the years of 2008, 2009, 2011, 2012, and 2013. Figure 4.2 displays the resulting noise discounts and shows that these are negative pre-treatment and turn positive after becoming eligible for soundproofing. We interpret these findings as further evidence in support of the parallel paths assumption and our identification strategy.

5 Results

The summary of the data produces preliminary evidence in support of the negative correlation between aircraft related noise pollution and home value premia and indicate home value adjustments in response the MAC's noise abatement programs. To quantify these abatement effects and shed light on the causal impact of changing noise exposure on sale price adjustments, we conduct several empirical analyses based on the Minneapolis repeat-sales data. In general, we find statistically and economically significant evidence that aircraft noise reduces sale prices and that increases in noise exposure slow home value appreciation. Moreover, we find that the noise-related sale price discounts are significantly smaller for abatement eligible homes, which experience a fading noise pollution effect over time. In terms of the dynamic pricing adjustments, our results produce robust evidence suggesting that the noise-related differences in home value appreciation are, in fact, persistent. We find that past increases in noise pollution more than three years prior to the resale of an abatement ineligible property have persistent adverse effects on its appreciation.

For all of the estimations, statistical significance is based on heteroscedasticity robust standard errors clustered at the 2010 Census block-group level. For the full sample estimations covering 46,477 repeat sale observations, this results in adjustments across 350 clusters, whereas the geographically most narrowly defined sample of 7,985 noise-affected repeat sales includes 64 block-group clusters. Statistical significance based on robust standard errors clustered at the more aggregated census-tract level renders consistent inference and conclusions. We scrutinize our findings against parsimonious to full model specifications that include time-of-sale and time-of-repeat-sale fixed effects as well as demographic and socioeconomic block-group characteristics. The discussion of various robustness analyses follow our primary analysis.

5.1 Aircraft Noise Pollution and Abatement Effects

In Table 1, we present our main empirical results obtained from the estimation of Equation (1'). Columns (1), (3), (5), and (7) reflect the parsimonious model results, whereas the full model findings are given in columns (2), (4), (6), and (8). The coefficient estimates of interest are presented in row one of Table 1 and capture the change in home value appreciation in response to a one decibel DNL increase in aircraft noise pollution. Based on the naive specification (columns (1) and (2)) that fails to differentiate between abatement eligible and ineligible homes ($\delta_{it} = 0,\ \forall\ i = 1, .., N;\ t = 1990, .., 2014$), we find the expected negative correlation between aircraft noise pollution and sale price appreciation of the average Minneapolis home. The parsimonious and full-model coefficient estimates, however, are statistically indistinguishable from zero - a finding that comes as no surprise given the airport authority's complex history of noise abatement policy. Many of the noise-polluted homes reported in our sample are eligible for one of the MAC's noise abatement programs. Unless soundproofing against noise pollution is an unvalued home attribute, participation in either of the aforementioned programs would violate the assumption of unchanging home characteristics between repeat sales and undoubtedly confound our noise effect estimates. According to the MAC, the actual investment amounts per house participating in the first abatement program ranged between a low of $17,300 in 1994 to a high of $45,000 in 2001 (Metropolitan Airports Commission 2017) and applied to about half of all the noise affected repeat sales recorded in our sample.[32] For homes experiencing increases in noise exposure, the noise-canceling abatement investment (if valued) would bias our estimates of the true noise discount towards zero.

To address this issue, we re-estimate the model (Equation (1')) distinguishing between homes that are noise abatement eligible and those that are not. We find this differentiation by eligibility (columns (3) through (8)) yields economically meaningful and consistent noise pollution effects that are statistically significant at the 1% level. In columns (3) and (4), for example, we restrict the sample to home sales prior to 2007 and isolate the noise effect on ineligible properties from the impact on eligible ones under the first MAC abatement program ($\delta_{it}^{1992} = 1$ if dB DNL $>$ 64 under 1996 contour plot; $t = 1992, .., 2006$; 0 otherwise). The preferred, full-model coefficient estimate of interest (column (4)) suggests that a one-decibel DNL rise in aircraft noise pollution slows the appreciation rate for an exposed, but ineligible home by 1.6 percentage points. In contrast, this depreciating noise effect is fully muted for abatement eligible properties. The coefficient estimate is statistically significantly different at the 1% level and positive ($0.021 - 0.016 > 0$).[33]

Moreover, we find little evidence to suggest that these eligible homes experienced a significant shift concerning their rates of appreciation upon becoming eligible under the first abatement program. The coefficient estimates on $\Delta\delta_{i,t+\tau}^{1992}$ are, in fact, statistically insignificant at the 5% or 1% levels across specifications (columns (3)-(4) and (7)-(8)). Potential explanations for this finding may be that eligibility itself is not a valued amenity in the early 1990's and that we observe only a limited set of homes sold prior to 1992.

Considering the noise effects under the second MAC abatement program, we find consistent coefficient estimates, presented in columns (5) and (6) of Table 1. Excluding all properties eligible under the first abatement program, we instead differentiate the aircraft noise pollution effects across ineligible homes and those eligible under the second abatement initiative ($\delta_{it}^{2008} = 1$ if dB DNL $\in [60, 64]$ under 2007 contour plot; $t = 2008, .., 2014$; 0 otherwise). Based on these sample restrictions, we find economically and statistically significant evidence in support of the expected disamenity and abatement effects mirroring those documented under the first soundproofing initiative. Full-model estimates (column (6)) suggest that a one decibel DNL increase in noise pollution slows the rate of home value appreciation by 1.9 percentage points for abatement ineligible homes, whereas we estimate eligible ones to be unaffected by changes in aircraft noise.

For these eligible homes, however, we also find that the settlement of the prolonged legal dispute and resulting eligibility significantly raise their respective rates of appreciation, relative to the average Minneapolis property. Based on the summary of the data and some anecdotal evidence, this finding comes at no surprise. As indicated by Figure 3.2, newly eligible properties under the Consent Decree program command a significant price premium and greater rates of appreciation. The reason for this premium, reflected in our coefficient estimate for $\Delta\delta_{i,t+\tau}^{2008}$, can be traced back to the desirability of the Southwest Minneapolis neighborhoods, particularly around Lake Harriet, Lake Nokomis, and Lake Bde Maka Ska (formerly known as Lake Calhoun), where aircraft noise is perhaps the only real tangible disamenity prior to the soundproofing initiative.[34,35]

Lastly, we estimate the aircraft noise pollution impacts for the full sample and differentiate the effects across three types of properties: 1. Abatement ineligible homes, 2. abatement eligible homes under the 1992 Sound Insulation program, 3. abatement eligible homes under the 2008 Consent Decree program. The resulting empirical model slightly modifies the previous specification given by Equation (1') and can be expressed as follows:

$$\Delta ln(P_{i,t+\tau}) = \beta_1 \Delta N_{i,t+\tau} + \beta_2 \Delta\delta_{i,t+\tau}^{1992} + \beta_3 \Delta N_{i,t+\tau} * \delta_{i,t+\tau}^{1992} + \beta_4 \Delta\delta_{i,t+\tau}^{2008} + \beta_5 \Delta N_{i,t+\tau} * \delta_{i,t+\tau}^{2008} + \gamma \Delta Z_{b,t+\tau} + \alpha_{t+\tau} - \alpha_t + \epsilon_{i,t+\tau} - \epsilon_{i,t}, \quad (2)$$

where $\delta_{i,t+\tau}^{1992}$ refers to the indicator variable for eligibility under the 1992 abatement program and $\delta_{i,t+\tau}^{2008}$ characterizes homes eligible under the 2008 Consent Decree initiative. All other variables correspond to the previous specification (1').

Again, the point estimates are consistent and provide compelling evidence in support of the expected disamenity effect. Ineligible properties experience a reduction in the rate of home value appreciation in response to an increase in noise exposure, while these disamenity effects are statistically significantly different and fully offset for abatement eligible parcels, irrespective of the specific abatement program. Given that we estimate the noise effect on the change in logged sale prices, the technically correct interpretation of the preferred coefficient estimate presented in column (8) of Table 1 suggests that a one decibel DNL increase in aircraft noise pollution experienced by abatement ineligible homes slows the respective sale price appreciation by 1.9 percentage points over the five-year average time span between sales. Given the fact that the average Minneapolis home value increased by 29% between sales, a one decibel DNL increase in aircraft noise pollution for abatement ineligible homes would slow this growth rate by about 6.6% (=1.9/29 *100%).

Most of the previous literature, however, does not take advantage of a repeat sales sample and instead estimates the noise effect on the log-level of home values, rather than first-differences. The resulting coefficient estimates indicate the percentage change in sale price due to a one dB DNL increase in noise pollution. Akin to these studies and for the ease of comparison, our estimate can be translated into this log-level effect and approximates 1.6%$(= 1.9/[(1+1.29)/2])$. In comparison to previous estimates, this estimated noise discount for the Minneapolis-Saint-Paul International airport of 1.6% is somewhat higher than the estimates that Nelson (1980, 2004) found for a variety of U.S. airport settings, similar to the Pope (2008) findings for Raleigh-Durham, consistent with the lower end of the noise discount found by Salvi (2008) for Zürich airport, and significantly lower than the estimates by Cohen and Coughlin (2008, 2009). However, the estimation strategies that we implement are more rigorous than the majority of the studies summarized in the Nelson (1980, 2004) meta analyses and some of the later research, and this may account for the discrepancies. In particular, one might convolute the estimated disamenity effect of noise pollution with the negative home-value-to-noise correlation due to the reverse causality.

Boes and Nüesch (2011) provide compelling evidence based on a convincing identification strategy that suggests a noise discount of around 0.5% on apartment rents in Zürich, significantly smaller than our estimate of 1.6%. In support of our estimate, however, we argue that there are several potential explanations for this discrepancy. First, it is possible that there are significant differences in tastes between Minneapolis home owners and Zürich apartment renters. It is quite plausible that home owners have a stronger distaste for aircraft noise than renters given the size differential of their respective investments. Moreover, the limitations on Swiss home ownership and exorbitant housing prices in Zürich, in particular, may raise the competition among Zürich renters and lowers the rent discount attached to noise pollution. Aside from these locational differences and discrepancies between renters and home owners, our estimates may diverge from that produced by Boes and Nüesch (2011) because we explicitly control for noise abatement. Changes in noise only matter if home owners or renters are affected by these changes. Soundproofing mitigates noise pollution and eradicates the noise discount. As shown by our naive specification, the presence of sound proofing attenuates noise discount estimates towards zero when we fail to distinguish between abatement eligible and ineligible properties. The naive point estimate of -0.003 translates into a noise discount of around 0.3% per dB DNL that is much closer to the estimate of Boes and Nüesch (2011), who also do not control for apartment differences in noise insulation.

In addition, one of the most recent studies by Affuso et al. (2019) provides convincing evidence that the noise discount in Memphis, TN approaches $4,800 per dB of noise pollution. Using the spatial econometric techniques the authors show that this noise discount approximates 2.3% for the average Memphis home located at an average distance from the airport. Reassuringly, this estimate is quite comparable to ours and lends further support to our findings.

Combining these estimates for eligible and ineligible homes exposed to aircraft noise pollution allows for the approximation of the average and cumulative losses suffered by abatement ineligible properties, as well as the five-year return on abatement investments per one-decibel DNL increase in aircraft noise pollution. Based on our sample, the average aircraft noise affected home sold for roughly $190,000 (measured in 2014 dollars) and appreciated by an average of 29% over a five-year period between initial and repeat sale. Taking these facts and our findings into account, a back-of-the-envelope calculation suggests that the MAC's insulation investments raised the average property value by about $12,500 (=(1.9/29)*$190,000) per one db DNL increase in noise pollution between transactions relative to noise-affected, but abatement ineligible homes.[36] Based on this estimate, the 683 recorded repeat sales of abatement ineligible homes that experienced an increase in aircraft noise pollution of around two dB DNL suffered an average loss of around $25,000 per sale and cumulative losses of around $17 to $18 million over our sample period.

Taking into account that the MAC's abatement program aimed to reduce noise exposure by as much as five dB DNL and cost an average of around $45,000 when adjusted for inflation, we estimate the return on investment close to 40% $\left(= \frac{5*\$12{,}500-\$45{,}000}{\$45{,}000} * 100\%\right)$. We consider this, however, an upper bound on ROI for two reasons. First, the average noise-polluted Minneapolis home experienced a 0.6 dB DNL reduction in aircraft noise exposure over the sample period. Naturally, this reduction in average noise pollution mitigates some of the benefits to noise abatement. Second, not all of the eligible homes were treated with the full five dB DNL noise reduction package, but received partial mitigation funding instead. The partial treatment, of course, lowers the estimated abatement benefits as well as the costs and changes the ROI calculations.

All of these results are robust to the inclusion of changes in block-level socioeconomic and demographic characteristics. When we include all of these characteristics, our analyses produce several statistically significant coefficient estimates that tend to be of the expected sign (see Table 1, columns (2), (4), (6), (8)). With the exception of the first abatement regression analysis, which restricts the sample to observations prior to 2007 (column (4)), these socioeconomic and demographic home value effects are generally consistent across all model specifications. For the preferred full sample analysis presented in column (8) of Table 1, we find that home value appreciation tends to rise with block-level median household income as well as larger population shares of people over 65 and under 20 years of age. In contrast, increases in the neighborhood population shares of African American and American Indian residents, relative to the excluded Caucasian reference group, tend to be correlated with lower rates of home value appreciation.[37] Testing the strict exogeneity of these characteristics, we conduct several robustness checks (see section 5.3.2).

5.2 Dynamic Aircraft Noise and Abatement Effects

While MAC has met its Consent Decree obligations as of 2014 and both of the initial soundproofing initiatives have concluded, the airport authority continues its effort to provide noise mitigation to affected residents. Current policy, however, is based on several amendments to the original 2007 settlement and sets out more restrictive eligibility criteria that require a property to experience aircraft noise pollution in excess of 60 dB DNL for more then three consecutive years.[38] A homeowner can only apply for soundproofing under the current abatement initiative, if the property has been subjected to this prolonged noise pollution. Given this dynamic dimension of the current policy, a key issue of interest relates to the timing and persistence of sale price adjustments in response to past aircraft noise pollution exposure. Whether the estimated noise effects on home value appreciation are immediate or persistent in nature has implications for this current policy practice. If increases in past aircraft noise pollution have adverse effects on home price premia, the lagged policy response may be suboptimal from the residents' and social welfare perspective.

To break new ground on these policy considerations and shed light on the dynamics of home value adjustments in response to alterations in noise pollution, we leverage the unique time variation of our 25 year sample and estimate a modified version of the original specification given by Equation (1'). Considering the noise effect through a dynamic lens, we integrate lagged changes in noise in our empirical model. In particular, we differentiate between the most recent changes in noise pollution over the first three years prior to a home's resale and the remaining alterations in noise exposure between the initial sale and the fourth year prior to the repeat transaction. The resulting specification can be expressed as follows:

$$\begin{aligned}\Delta ln(P_{i,t+\tau}) = \beta_1(N_{i,t+\tau} - N_{i,t+\tau-1}) + \beta_2(N_{i,t+\tau-1} - N_{i,t+\tau-2}) + \\ \beta_3(N_{i,t+\tau-2} - N_{i,t+\tau-3}) + \beta_4(N_{i,t+\tau-4} - N_{i,t}) + \\ \beta_5(N_{i,t+\tau} - N_{i,t+\tau-1}) * \delta_{i,t+\tau} + \beta_6(N_{i,t+\tau-1} - N_{i,t+\tau-2}) * \delta_{i,t+\tau} + \\ \beta_7(N_{i,t+\tau-2} - N_{i,t+\tau-3}) * \delta_{i,t+\tau} + \beta_8(N_{i,t+\tau-4} - N_{i,t}) * \delta_{i,t+\tau} + \\ \beta_9 \Delta\delta_{i,t+\tau} + \gamma\Delta Z_{b,t+\tau} + \alpha_{t+\tau} - \alpha_t + \epsilon_{i,t+\tau} - \epsilon_{i,t},\end{aligned} \tag{3}$$

where Δ continues to represent the first difference between the repeated sales at time $t + \tau$ and t. The newly introduced terms, such as $(N_{i,t+\tau} - N_{i,t+\tau-1})$ and $(N_{i,t+\tau} - N_{i,t+\tau-1}) * \delta_{i,t+\tau}$, capture the differentiated lagged responses of abatement ineligible and eligible home value appreciation with respect to changes in the experienced noise pollution between the k^{th} year prior to resale $(t+\tau-k)$ and the $kth-1$ year prior to resale $(t+\tau-(k-1))$[39]. In line with the previous analysis, we continue to differentiate the current and lagged effects across homes with varying eligibility criteria under the MAC's abatement initiatives. The coefficient estimates of interest are given by β_1 - β_4 and β_5 - β_8, which capture changes in the rate of home value appreciation in response to lagged aircraft noise pollution adjustments for abatement ineligible and eligible properties, respectively.

The results are presented in Table 2 and offer consistent support of the initial conclusions. More importantly, however, our findings provide novel evidence on the persistent adjustment of home price premia in response to past changes in aircraft noise pollution. Similar to our previous findings, the naive model specification, which fails to differentiate between eligible and ineligible homes, suggests that changes in aircraft noise pollution have statistically insignificant effects on the average home value appreciation. This misleading and inaccurate result, however, is clearly overturned when we differentiate the noise pollution effects across eligible and ineligible homes under the various abatement programs. Irrespective of the specific sample restrictions or abatement initiative under consideration, we find statistically and economically significant adverse noise effects on the rate of home value appreciation for abatement ineligible properties. Overall, these adverse noise effects, given in columns (3) through (8) of Table 2 are consistent across the first through third lag of changes in noise exposure and suggest that a one dB DNL increase in noise pollution one through three years prior to the resale of a given property reduces its rate of appreciation by 1.8 to 2.5 percentage points. Even the estimated impact of cumulative change in noise pollution from the time of initial sale until the fourth year prior to resale has significant adverse effects on house prices, with point estimates ranging from -0.1 to -0.16, and statistical significance at the 5% level for the preferred specification given in column (8) of Table 2.

In general, abatement eligible homes experience statistically significantly different aircraft noise pollution effects that more than offset the adverse noise impact we estimate for ineligible homes. Irrespective of the abatement program, first through third lagged adjustments in noise pollution have a muted effect on home value appreciation that is statistically different from the noise effect on ineligible homes at the 1% or 5% significance levels. Four years or more prior to resale, abatement eligibility only has a marginal offsetting effect against noise adjustments.

Overall, these findings provide convincing evidence in support of the fact that a significant share of the price adjustment due to changing aircraft noise pollution occurs within the first three years prior to a property's sale. Current policy practice, however, requires three years of consecutive exposure to noise pollution above the 60 dB DNL threshold to be eligible for the latest MAC abatement program. As a result, this novel abatement program fails to compensate owners of untreated homes for the depreciation effect occurring during the first two to three consecutive years of exposure to aircraft noise pollution in excess of the eligibility threshold. Even more problematic is the fact that annual changes in noise exposure may lead to abatement ineligible temporary noise pollution that has lasting adverse effects on the affected, yet untreated, home values.

In a related dynamic analysis, we also dissect the overall abatement effect of the Consent Decree program in the spirit of an event study and estimate the abatement effect pre- and post treatment. Specifically, we separate the mitigating effect of abatement eligibility across four pre-treatment years from 2004 through 2007 and six post-treatment years from 2008 until 2013.[40] The dynamic evolution of the mitigating Consent Decree abatement effect is presented in Figure 4.1 and illustrates the gradual implementation and effectiveness of this initiative. While ineligible homes are found to experience the expected reduction in home value appreciation in response to aircraft noise pollution, abatement eligible homes under the Consent Decree program display varying noise effects during the first three years of this initiative and no treatment effect prior to its implementation. In fact, we find that the mitigating abatement effects (depicted in Figure 4.1) are statistically insignificant for the years of 2004 through 2007 prior to treatment as well as 2010, and only marginally significant in 2008, whereas eligible homes sold in 2009 or between 2011 and 2013 experience a fully muted noise pollution effect that is statistically different from that of ineligible homes at the 5% to 1% significance levels. We display the dynamic noise discounts for these eligible homes in Figure 4.2. The underlying coefficient estimates are reported in column

(1) of Table A1 in the appendix. Since our identification rests on eligibility commencing in 2008, rather than actual treatment, these results are very intuitive and reflect the gradual adoption of soundproofing among the eligible homes. Furthermore, the statistically insignificant pre-treatment effects lend further support to the parallel paths assumption underlying our identification strategy.

5.3 Robustness

To provide additional support for our primary findings, we test the sensitivity of our results against a host of robustness checks. In the following subsections, we present the results obtained from various heterogeneity analyses, including model alterations that distinguish noise pollution effects across varying home values (Section 5.3.1), investigations of the strict exogeneity of block-group control variables (Section 5.3.2), and several sample restrictions (Section 5.3.3). The coefficient estimates are reported in Tables A2 and A3 in the Appendix. Moreover, we discuss the sensitivity of our findings against variations in the aforementioned noise interpolations (Section 5.3.4) and present these results in Table 3. In general, these robustness checks yield consistent noise effect estimates that underscore the insights gained from the primary analyses.

5.3.1 Heterogeneity Analyses

Among various potential model alterations that could yield insights into the heterogeneity of the estimated noise pollution effect, we begin by testing whether the noise pollution effect on abatement ineligible homes varies during the years of the great recession and thereafter. Reassuringly, we find that the primary noise impact, presented in column (2) of Table A2, is consistently estimated at -0.019 and statistically significant at the 1% level. Interacting the change in noise pollution with indicator variables for the years of 2008 through 2012 yields largely statistically insignificant coefficient estimates, with the exception of 2010. We interpret these results to suggest that the noise pollution effect on home value appreciation is not overshadowed by the onset of the housing market collapse starting in 2008, but perhaps worsened during its 2010 trough.

In contrast to this temporal heterogeneity analysis, we also test whether the noise effect on ineligible homes varies across low- to high-valued homes (see column (3) of Table A2). Given an average sale price of around $200,000, we arbitrarily define homes sold at a price below $100,000 as lower-valued properties and those sold for more than $500,000 as high-valued assets. Based on this differentiation, we find that the adverse home value appreciation effect of aircraft noise pollution is primarily driven by higher-valued properties, which experience a reduction in the rate of appreciation by 5.5 percentage points; a three- to fourfold increase in the effect.

As part of the final model alteration, we test whether the estimated noise discount diminishes or increases with respect to aircraft noise pollution. To this end, we integrate the square of the change in aircraft noise pollution between sales as an explanatory variable. Based on our estimates, we find no evidence that the noise discount diminishes or rises at greater levels of noise pollution. The coefficient estimates presented in column (4) of Table A2 illustrate a statistically insignificant change in home values in response to the squared change in noise exposure.

5.3.2 Control Variable Exogeneity

A common concern in the literature is the potential endogeneity of neighborhood socioeconomic and demographic characteristics, which may respond to changes in the distribution of house prices and noise pollution. While a contemporaneous feedback effect in these variables to changes in noise pollution and home values are difficult to justify, the intermediate response in neighborhood demographics, for example, is more plausible. That is, initially low levels of noise pollution or property values may attract residents of particular socioeconomic groups that have distinct preferences over noise pollution and changes thereof, which would violate the assumption of strict exogeneity and create a potential bias in our coefficient estimates of interest.

To address this concern, we implement two separate robustness checks that investigate the potential violation of strict exogeneity.[41] The first approach follows the discussion by Anderson and Hsiao (1981, 1982) who suggest the use of lagged level variables to instrument for the potentially endogenous variation in their respective first differences. While Anderson and Hsiao employ this technique in a dynamic panel context, parallels can be drawn for our estimation setting. In particular, we instrument for the potentially endogenous changes in socioeconomic and demographic block-level characteristics between the initial and repeat sales of a particular property with level values of these control variables lagged over several years prior to the initial sale. Based on the Hansen j-statistic for over-identification, lagged values of neighborhood characteristics five to six years prior to the initial sale of a given property provide the most robust set of instruments, where the null hypothesis of valid instruments cannot be rejected at any conventional significance level. The results based on this instrumental variables (IV) approach are presented in column (5) of Table A2 produce robust evidence that addresses the potential violation of the strict exogeneity of our control variables. Moreover, the reported first-stage Kleibergen-Paap statistic strongly rejects the null hypothesis of under-identification and provides further evidence that the model is properly identified. Lastly, the IV results are robust whether we employ the two-stage least squares, limited-information maximum likelihood (LIML), or two-step generalized method of moments (GMM) estimators suggesting that the estimation does not suffer from weak instruments.[42]

The second approach, follows work by Holtz-Eakin and Schwartz (1995) or Duranton and Turner (2012), who argue for the use of 'long differences' to overcome some of the potentially endogenous short-run variation concerning their respective variables of interest.[43] 'Long differences' typically refer to the change in given variable with respect to its original value at the beginning of the sample. Applying this framework in our setting, we calculate the change in neighborhood characteristics at the time of sale of a given property with respect to its block-specific value in 1990. This long-run adjustment in socioeconomic and demographic control variables is plausibly exogenous to the contemporaneous and intermediate changes in noise pollution and property values between sales. The results presented in column (6) of Table A2 provide evidence in support of this argument and are consistent with our primary findings. The coefficient estimates suggest that a one dB increase in noise pollution reduces the rate of home value appreciation by 1.9 to 2.2 percentage points for abatement ineligible properties, whereas eligible homes are unaffected.

5.3.3 Sample Restrictions

In terms of sample restrictions, we begin by testing the sensitivity of our results against the number of repeat sales for a unique property. While 85% of our sample residences are sold less than four times over our 25 year sample period, some properties are sold as many as eight times during this time frame. Since some of these very frequently sold homes may represent investment properties that undergo substantial renovation and/or restoration between sales, the assumption of time-invariant housing characteristics may be violated for these properties. Excluding homes sold more than two to four times during our sample (see columns (1) through (3) of Table A3) yields qualitatively robust noise effect estimates for abatement eligible and ineligible homes that are nearly identical in magnitude to the primary point estimates presented in Table 1.

Along a different dimension, we test the robustness of our findings by geographically restricting the sample around the MSP International airport. To this end, we first limit the sample to noise-affected properties within the contour plots at the time of sale and/or resale and those properties within a half-mile buffer around the outer most annual contour plot. The results presented in column (4) of Table A3 are quantitatively similar, but only marginally significant at the 10% level. Further restricting the sample to exclude buffer observations, yields consistent estimates that are statistically significant at the 5% to 10% levels (see column (5) of Table A3).

Lastly, we test for the sensitivity of our results against the presence of influential outliers that may bias our primary findings. As the arms-length sale prices in our sample range from $7,300 to $4.7 million, we re-estimate Equation (2) excluding observations beyond two or one standard deviations from the sample average. The results are presented in columns (6) and (7), respectively, and indicate very consistent aircraft noise pollution effects on abatement eligible and ineligible homes that continue to be statistically significant at the 1% level. Specifically, the results show that in the absence of these outliers a one dB DNL increase in aircraft noise pollution lowers the rate of home value appreciation of abatement ineligible Minneapolis homes by 1.7 to 1.9 percentage points, while abatement eligible properties are immune to these changes.

5.3.4 Noise Interpolation

The final robustness check tests the consistency of our findings against the competing options for interpolating or restricting the missing noise observations. Specifically, we begin by varying the threshold year for interpolating the missing 1990 to 1995 and 1997 to 2005 noise levels. We set alternative thresholds between 1996 and 2005. The results are presented in columns (1) through (10) of Table 3 and largely consistent with our primary estimates reflected by the coefficients depicted in column (4). Coefficient estimates of the adverse home value appreciation effect of noise pollution on abatement ineligible properties range from -0.10 to -0.19 and are statistically significant at the 5% or 1% levels, with exception of the 2005 cutoff. Similarly, the results for abatement eligible properties are largely consistent across these threshold choices. Only three of the 20 point estimates are statistically insignificant at any of the conventional levels.

Alternatively, we explore the sensitivity of our primary findings against a linear interpolation of missing noise values. Reassuringly, the results of this second interpolation strategy, presented in column (11) of Table 3, offer consistent point estimates, nearly identical in coefficient magnitude and statistically significant at the 5% level for both abatement-eligible and ineligible homes.

Thirdly, we consider the restriction of our sample to repeatedly sold properties after 2005, for which annual information on aircraft noise pollution is continuously available. The number of observations drops to 2,738 repeat sales[44] and limits the identification to the Consent Decree program. The point estimates for abatement eligible and ineligible properties under this soundproofing initiative remain statistically significant at the 1% to 5% level and increase in absolute magnitude relative to the alternative interpolation strategies.

The final interpolation strategy relies on an out-of-sample prediction of noise pollution. To capture the temporal and spatial variation of noise pollution, we model annual property-specific aircraft noise exposure as a function of the annual frequency of daytime and nighttime operations at MSP and interact these variables with Census block-group indicators. The regression analysis is restricted to 2006 through 2014, years for which we observe both MSP noise contours and operations. Based on the coefficient estimates, we make an out-of-sample prediction of property-specific noise exposure from 2001 through 2005, years for which we only observe MSP aircraft operations. We use the predicted noise levels from 2001 through 2005 and actual noise measurements from 2006 to 2014 to re-estimate the sale price discount and abatement eligibility effects. The results are presented in column (13) of Table 3 and yield qualitatively and quantitatively similar coefficients.

Overall, these robustness analyses provide compelling evidence of the consistency of our primary findings and support our initial conclusions. In summary, we find that aircraft noise pollution has adverse causal effects on home value appreciation that can be fully mitigated via the investigated abatement programs. Moreover, this adverse appreciation effect of noise pollution is immediate and persistent over more than three years prior to a property's sale putting the effectiveness of current policy practice into question.

6 Conclusion

In the analysis above, we utilize information on relatedly sold and noise-polluted Minneapolis properties and differentiate between homes that are eligible for noise abatement near MSP and those that are not to identify airport noise impacts on house prices. Moreover, we exploit the time variation in aircraft noise pollution and switching abatement policy regimes to explore the dynamic evolution of this noise effect leading up to a property's sale. Our findings hold up to a broad range of specifications and robustness checks.

More specifically, MSP experienced two separate soundproofing initiatives, one in the early 1990s and another, called the Consent Degree program, began in 2008 and ended in 2014. The treatment group consists of repeatedly sold Minneapolis homes exposed to MSP's aircraft noise pollution of 60 dB DNL or above from 1990 until 2014. Among these properties, however, we differentiate the noise impact across those houses that are eligible for soundproofing through these initiatives and those that are not, after the commencement of the programs. We examine how houses in the treatment groups are impacted by airport noise, and find that the magnitudes of the noise effects on housing prices are approximately 2% per decibel DNL for abatement ineligible homes, and are statistically significant. In contrast, we find that the noise effect for soundproofing eligible homes is significantly different and fully muted.

These results are robust to estimating separate regressions for each of the two initiatives, including treatment effects for both soundproofing programs in the same regression, and a number of heterogeneity and sensitivity analyses. We also find that the model holds up to including lagged changes in noise pollution. In fact, our estimates suggest that home values respond to past changes in aircraft noise pollution for more than three years prior to a property's sale. This evidence of the long-run impacts of noise on house prices marks another contribution of our work, in addition to the short-run effects that are more commonly considered in the literature.

There are several potential policy implications of our findings. First, our estimates suggest that owners of abatement ineligible properties suffer losses of around $12,500 per dB DNL increase in aircraft noise pollution. Across the 683 sample transactions involving abatement ineligible homes that experience an average increase of about two dB DNL between sales, this estimate suggests cumulative losses of around $17 to $18 million, with individual losses as high as $100,000.

Second, based on our estimates, we are able to calculate an upper bound on the Return on Investment (ROI) of noise abatement of approximately 40%. As such, soundproofing is clearly an attractive alternative to other potential solutions to airport noise, such as the direct purchase of noise-affected properties. Another potential solution to the noise problem, financial compensation to homeowners who experience more noise than there was when they purchased the property, would not be expected to yield the same ROI as soundproofing. This is because of the fact that flow of funds would not necessarily become capitalized into the property value in the same manner as soundproofing. Alternatively, the airport authority might impose flight restrictions on aircraft to mitigate noise pollution. While this policy would be expected to enhance the value of some properties due to the resulting lower noise exposure, it is not clear a priori whether this would be desirable because of the financial impacts on the airlines from restricting their operations. Clearly, soundproofing seems to be a potentially attractive solution to mitigating airport noise because of the potential to dampen house price declines from additional aircraft noise pollution in the future.

Third, our dynamic estimates suggest that aircraft noise pollution has a prolonged adverse effect on house prices. Current policy practice requires homes to be exposed to significant aircraft noise pollution for three consecutive years before becoming noise abatement eligible. Our evidence, however, suggests that noise pollution has significant impacts on a property's rate of appreciation for more than three years prior to its sale putting the effectiveness of this current policy regime into question. As such, our findings point to significant and sustained losses to noise affected homeowners up to three years prior to meeting the latest soundproofing eligibility criteria.

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Table 1: Housing price appreciation, parsimonious and full model specification across varying abatement samples

Dependent Variable:	**Naive Specification**		**1992 Abatement**		**2008 Abatement**		**1992 & 2008 Abatement**	
$\Delta ln(P_{i,t+\tau})$	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
$\Delta N_{i,t+\tau}$ (Δ dB DNL)	-0.003	-0.003	-0.018***	-0.016***	-0.019***	-0.019***	-0.019***	-0.019***
	(0.003)	(0.003)	(0.006)	(0.005)	(0.006)	(0.007)	(0.006)	(0.007)
$\Delta N_{i,t+\tau}\ X\ \delta^{1992}_{i,t+\tau}$			0.023**	0.021***			0.021***	0.022***
			(0.009)	(0.008)			(0.007)	(0.007)
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$					0.026***	0.025***	0.026***	0.025***
					(0.006)	(0.006)	(0.006)	(0.006)
$\Delta\delta^{1992}_{i,t+\tau}$ (Eligible Homes, 1992)			0.021	0.030*			0.020	0.022
			(0.014)	(0.016)			(0.014)	(0.016)
$\Delta\delta^{2008}_{i,t+\tau}$ (Eligible Homes, 2008)					0.059***	0.048***	0.058***	0.046***
					(0.014)	(0.013)	(0.014)	(0.013)
$\%\Delta$ African American		-0.536***		-0.173**		-0.541***		-0.531***
		(0.087)		(0.079)		(0.089)		(0.087)
$\%\Delta$ Hispanic		0.188*		0.872***		0.210**		0.203**
		(0.101)		(0.127)		(0.104)		(0.101)
$\%\Delta$ Asian or Pacific Islander		-0.207		0.421**		-0.269		-0.204
		(0.171)		(0.184)		(0.173)		(0.172)
$\%\Delta$ American Indian		-1.006***		-0.426		-0.970***		-0.991***
		(0.229)		(0.299)		(0.230)		(0.229)
$\%\Delta$ Other Race		0.367		-0.459		0.291		0.367
		(0.334)		(0.436)		(0.353)		(0.336)
$\%\Delta$ Under 20		0.546***		-0.668***		0.579***		0.539***
		(0.138)		(0.157)		(0.140)		(0.138)
$\%\Delta$ Over 65		0.562***		0.254**		0.516***		0.545***
		(0.112)		(0.111)		(0.112)		(0.112)
$\%\Delta$ ln(Median Income)		0.109***		0.071***		0.108***		0.111***
		(0.027)		(0.026)		(0.027)		(0.026)
Observations	46477	46477	34273	34273	43034	43034	46477	46477
Adjusted R^2	0.677	0.681	0.705	0.709	0.672	0.676	0.678	0.682
Time-of-Sale FE	Y	Y	Y	Y	Y	Y	Y	Y

Notes: Standard errors, reported in the parenthesis, are clustered at the block-group level. The results presented in columns (1)-(2) are based on the naive model specification treating all homes identically, whereas the results given in columns (3) through (8) differentiate between abatement eligible and ineligible homes. Coefficients presented in columns (3) and (4) consider the noise effect under the first abatement program prior to 2007, whereas the results given in columns (5) and (6) isolate the noise effect under the second abatement program excluding homes that were abatement eligible under the first abatement program. Lastly, the results given in columns (7) and (8) illustrate the full sample noise effects simultaneously differentiating across abatement ineligible and eligible homes under both policy regimes. Statistical significance at the conventional levels is indicated by *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

Table 2: Housing price appreciation, lagged noise effects across varying abatement samples

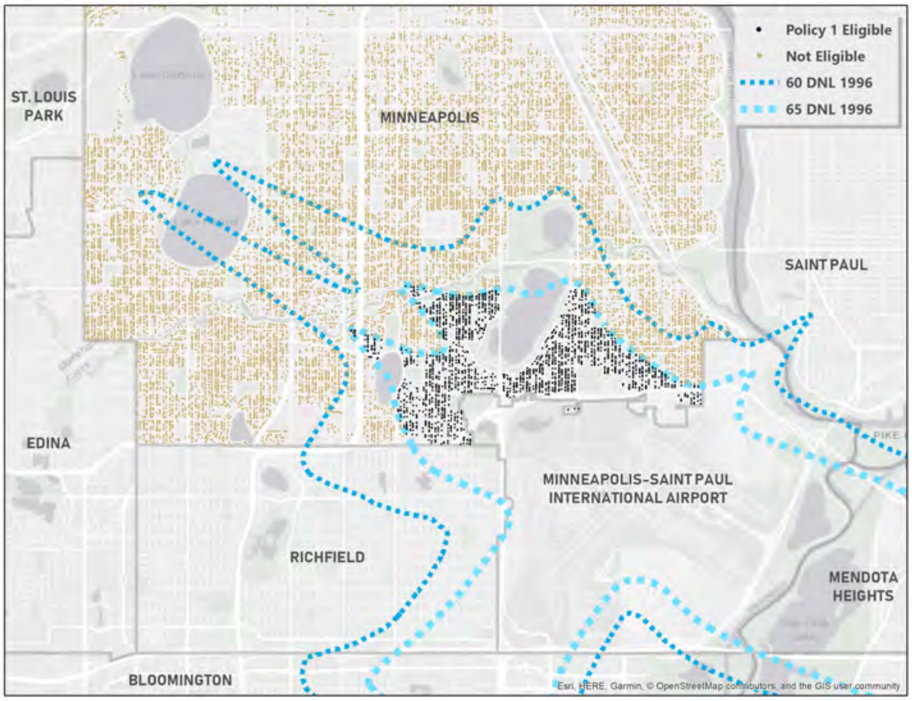
Dependent Variable: $\Delta ln(P_{i,t+\tau})$	Naive Specification (1)	(2)	1992 Abatement (3)	(4)	2008 Abatement (5)	(6)	1992 & 2008 Abatement (7)	(8)
$(N_{i,t+\tau} - N_{i,t+\tau-1})$ (Δ dB DNL)	0.002	0.003	-0.025***	-0.022***	-0.022***	-0.021***	-0.022***	-0.021***
	(0.003)	(0.003)	(0.006)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)
$(N_{i,t+\tau-1} - N_{i,t+\tau-2})$ (Δ dB DNL)	0.002	0.002	-0.020***	-0.018***	-0.020***	-0.020***	-0.020***	-0.020***
	(0.004)	(0.004)	(0.006)	(0.006)	(0.006)	(0.007)	(0.006)	(0.007)
$(N_{i,t+\tau-2} - N_{i,t+\tau-3})$ (Δ dB DNL)	-0.002	-0.002	-0.023**	-0.022**	-0.024**	-0.024**	-0.023**	-0.024**
	(0.004)	(0.004)	(0.011)	(0.010)	(0.011)	(0.011)	(0.011)	(0.011)
$(N_{i,t+\tau-3} - N_{i,t+\tau})$ (Δ dB DNL)	-0.007*	-0.007*	-0.012*	-0.010*	-0.016**	-0.016**	-0.016**	-0.016**
	(0.004)	(0.004)	(0.006)	(0.006)	(0.007)	(0.007)	(0.007)	(0.007)
$(N_{i,t+\tau} - N_{i,t+\tau-1})$ X $\delta^{1992}_{i,t+\tau}$			0.033***	0.030***			0.032***	0.031***
			(0.012)	(0.011)			(0.008)	(0.008)
$(N_{i,t+\tau-1} - N_{i,t+\tau-2})$ X $\delta^{1992}_{i,t+\tau}$			0.024**	0.023**			0.028***	0.029***
			(0.011)	(0.010)			(0.008)	(0.008)
$(N_{i,t+\tau-2} - N_{i,t+\tau-3})$ X $\delta^{1992}_{i,t+\tau}$			0.031**	0.030**			0.028**	0.028**
			(0.014)	(0.013)			(0.012)	(0.012)
$(N_{i,t+\tau-3} - N_{i,t+\tau})$ X $\delta^{1992}_{i,t+\tau}$			0.015*	0.014*			0.012	0.012
			(0.008)	(0.007)			(0.008)	(0.008)
$(N_{i,t+\tau} - N_{i,t+\tau-1})$ X $\delta^{2008}_{i,t+\tau}$					0.051***	0.049***	0.050***	0.048***
					(0.014)	(0.014)	(0.013)	(0.014)
$(N_{i,t+\tau-1} - N_{i,t+\tau-2})$ X $\delta^{2008}_{i,t+\tau}$					0.041***	0.039***	0.040***	0.038***
					(0.010)	(0.011)	(0.010)	(0.010)
$(N_{i,t+\tau-2} - N_{i,t+\tau-3})$ X $\delta^{2008}_{i,t+\tau}$					0.042***	0.041***	0.042***	0.041***
					(0.013)	(0.012)	(0.012)	(0.012)
$(N_{i,t+\tau-3} - N_{i,t+\tau})$ X $\delta^{2008}_{i,t+\tau}$					0.014*	0.014*	0.015*	0.015*
					(0.008)	(0.008)	(0.008)	(0.008)
Observations	46477	46477	34273	34273	43034	43034	46477	46477
Adjusted R^2	0.677	0.681	0.705	0.709	0.672	0.676	0.678	0.682
Time-of-Sale FE	Y	Y	Y	Y	Y	Y	Y	Y
Socioeconomic controls	-	Y	-	Y	-	Y	-	Y

Notes: Standard errors, reported in the parenthesis, are clustered at the block-group level. The results presented in columns (1)-(2) are based on the naive model specification treating all homes identically, whereas the results given in columns (3) through (8) differentiate between abatement eligible and ineligible homes. Coefficients presented in columns (3) and (4) consider the noise effect under the first abatement program prior to 2007, whereas the results given in columns (5) and (6) isolate the noise effect under the second abatement program excluding homes that were abatement eligible under the first abatement program. Lastly, the results given in columns (7) and (8) illustrate the full sample noise effects simultaneously differentiating across abatement ineligible and eligible homes under both policy regimes. Statistical significance at the conventional levels is indicated by *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

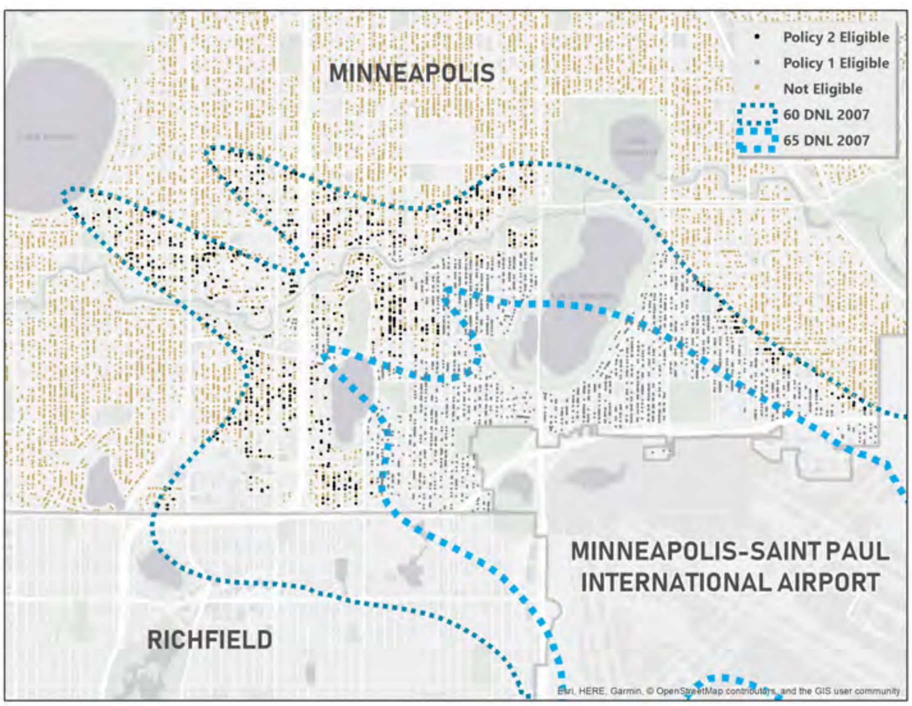
Table 3: Robustness - Noise interpolation options

$\Delta ln(P_{i,t+\tau})$	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)
$\Delta N_{i,t+\tau}$	-0.014**	-0.016**	-0.019***	-0.019***	-0.015***	-0.013**	-0.010**	-0.010**	-0.014***	-0.011	-0.018**	-0.039**	-0.022***
	(0.006)	(0.006)	(0.007)	(0.007)	(0.006)	(0.006)	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)	(0.020)	(0.008)
$\Delta N_{i,t+\tau}$ X $\delta^{1992}_{i,t+\tau}$	0.017***	0.019***	0.021***	0.022***	0.017***	0.015**	0.011**	0.011**	0.015***	0.011	0.020**	0.029	0.013*
	(0.006)	(0.007)	(0.007)	(0.007)	(0.007)	(0.007)	(0.005)	(0.005)	(0.005)	(0.008)	(0.008)	(0.020)	(0.07)
$\Delta N_{i,t+\tau}$ X $\delta^{2008}_{i,t+\tau}$	0.028***	0.028***	0.028***	0.025***	0.021***	0.020***	0.015**	0.012*	0.011	0.010	0.023**	0.064***	0.024***
	(0.007)	(0.007)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.007)	(0.007)	(0.014)	(0.009)	(0.024)	(0.009)
$\Delta\delta^{1992}_{i,t+\tau}$	0.023	0.023	0.022	0.022	0.022	0.022	0.021	0.021	0.021	0.021	0.023	-	-
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.015)	-	-
$\Delta\delta^{2008}_{i,t+\tau}$	0.055***	0.052***	0.050***	0.046***	0.047***	0.047***	0.046***	0.043***	0.040***	0.042***	0.046***	0.070**	0.035**
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.012)	(0.013)	(0.013)	(0.014)	(0.013)	(0.030)	(0.016)
Observations	46,477	46,477	46,477	46,477	46,477	46,477	46,477	46,477	46,477	46,477	46,477	2,738	14,027
Adjusted R^2	0.682	0.682	0.682	0.682	0.682	0.681	0.681	0.681	0.681	0.681	0.682	0.363	0.439
Time-of-Sale FE	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Controls	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
Noise Interpolation	Cutoff 1996	Cutoff 1997	Cutoff 1998	Cutoff 1999	Cutoff 2000	Cutoff 2001	Cutoff 2002	Cutoff 2003	Cutoff 2004	Cutoff 2005	Linear Interpolation	Restricted Sample	Out-of-sample Interpolation

Notes: Standard errors, reported in the parenthesis, are clustered at the block-group level. This table presents the sensitivity analysis against the varying noise interpolation options. Option 1. requires an arbitrarily chosen cutoff year. The results presented in columns (1)-(10) are based on varying cutoff years ranging from 1996 through 2005. Results provided in column (11) are based on interpolation option 2., which assumes a linear interpolation from 1990 to 2006. Coefficient estimates in accordance with interpolation option 3. are presented in column (12) and based on the restricted repeat sales sample from 2006 through 2014, for which annual noise data is continuously available. Coefficient estimates in accordance with interpolation option 4. are presented in column (13) and based on the out-of-sample interpolation of noise based on annual airport operations from 2001 through 2014. Point estimates presented in column (4) repeat the primary estimates presented in column (8) of Table 1. Statistical significance at the conventional levels is indicated by *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.



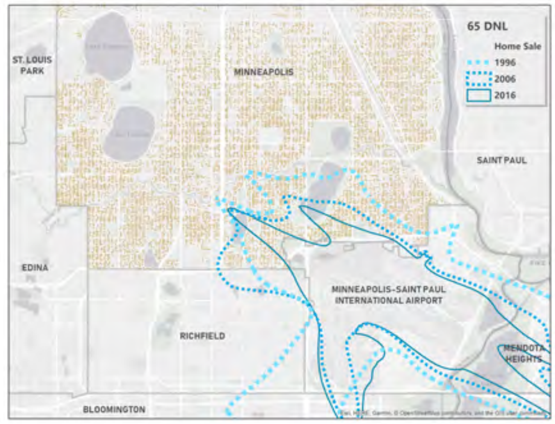
1.1: Sound Insulation Program Eligibility (1992-2006)



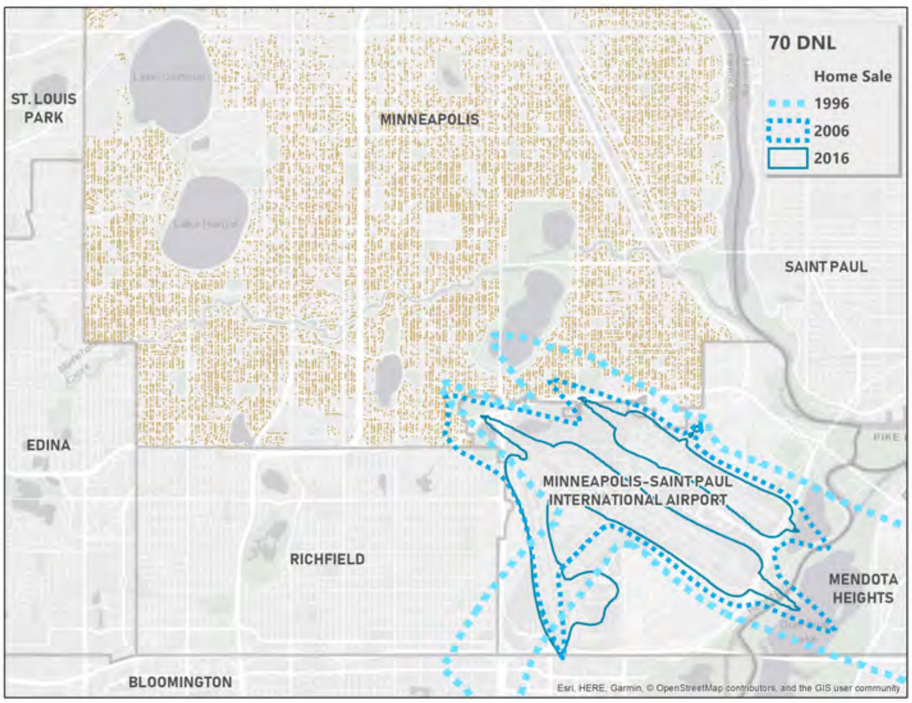
1.2: Consent Decree Program Eligibility (2008-2014)

Figure 1: Abatement Program Eligibilities

2.1: DNL 60

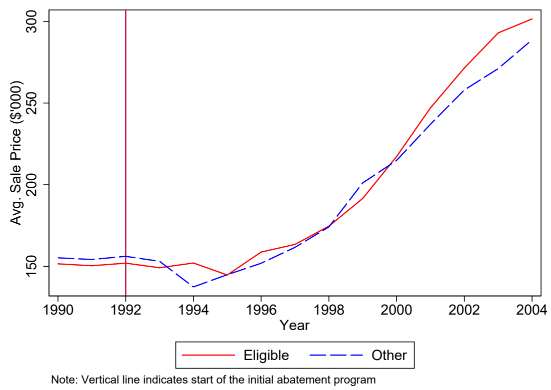


2.2: DNL 65

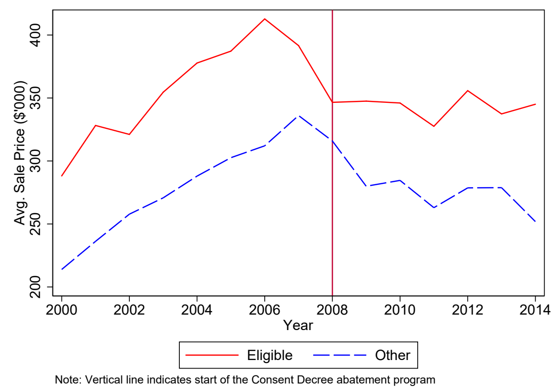


2.3: DNL 70

Figure 2: Variation in Residential Aircraft Noise Pollution (1996-2016)

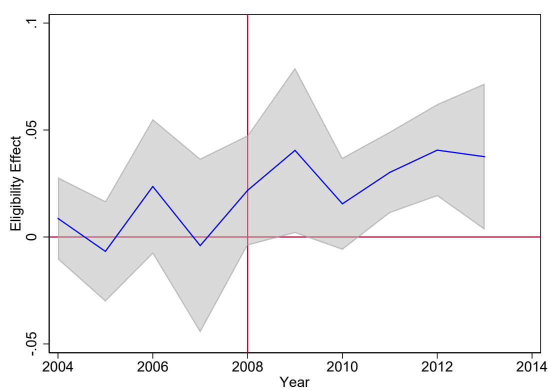


3.1: Sound Insulation Program (1990-2004)

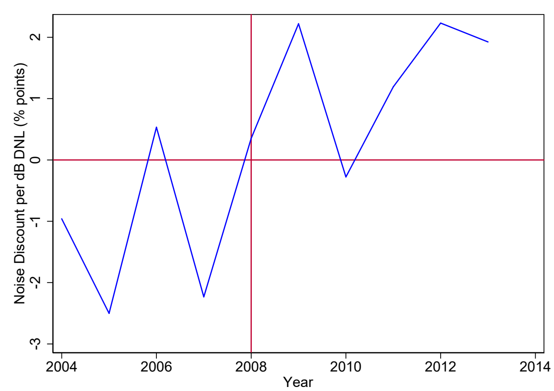


3.2: Consent Decree Program (2000-2014)

Figure 3: Home Prices by Abatement Eligibility Across Both Initiatives



4.1: Eligibility Effect



4.2: Noise Discount per dB DNL

Figure 4: Pre- and Post-Abatement Eligibility Effect and Noise Discount by Year

Notes

[1]Air pollution near airports can also have dramatic impacts on population health and costs of health care. For instance, Schlenker and Walker (2015) find that increases in pollution by one standard deviation result in $540,000 increases in costs of treatment for heart and pulmonary patients near California airports. They use "idiosyncratic variation" in aircraft taxi time at airports, which leads to greater carbon monoxide exposure, to identify how carbon monoxide exposure impacts health costs and outcomes. The Schlenker and Walker (2015) focus is different from ours in that they consider aircraft idling time to instrument for air pollution effects on health outcome and costs. In contrast, we consider changes in soundproofing regulations to examine how aircraft noise impacts house prices.

[2]The threshold for significant aircraft noise levels has been set by the Federal Aviation Association (FAA) at 65 decibel or greater (Federal Aviation Administration 2018).

[3]Rosen (1974) popularized the study of Kain and Quigley (1970) on hedonic housing price models. Banzhaf (2018) focuses on including externalities in the hedonic framework as a set of property "characteristics".

[4]While theoretical approaches to reduce residential noise exposure may involve negotiations between airport authorities and residents, airport acquisition of affected homes, or direct compensation of affected home owners, these policy options often face prohibitively high costs in practice.

[5]One might argue that financial (or some other form of) compensation may attract more buyers to an area, leading to price increases. However, when there is a one-time compensation based on the difference between noise at the date of purchase and noise at the date of compensation, this should not attract more buyers if the potential buyers do not expect any additional future changes in noise.

[6]Girvin (2009) summarizes common practices of noise mitigation near airports around the world.

[7]Ahlfeldt and Maennig (2015) differ from our analysis in several ways. First, we use a different source of exogenous variation - changes in soundproofing regulations for an airport that is in continuous operation - whereas Ahlfeldt and Maennig (2015) consider the closing announcement of an airport as a source of variation. Second, while they estimate a hedonic difference-in-differences regression to examine the capitalization of noise, they then use this capitalization estimate as a way to estimate how these price signals may have impacted voting for a new airport concept. In contrast, we utilize our noise effect estimates to quantify the effectiveness of two noise abatement initiatives.

[8]While Boes and Nüesch (2011) consider a change in flight path regulations as a quasi-experiment in identifying the impacts of noise on apartment prices near Zürich airport, Affuso et al. (2019) approximate aircraft noise levels via the interaction of geographically-varying city sound pressure levels and a property's distance to the airport. In contrast, we focus on single family homes in Minneapolis, MN in our analysis, along with a noise abatement regulation change for our quasi-experiment.

[9]Here the "treatment" is receiving "free" or highly discounted soundproofing. The noise-program interaction is capturing the effect of receiving the subsidized soundproofing for noisy properties, opposed to the control group of the pre-abatement noisy and non-noisy properties, and the post-abatement properties that are not noisy and do not receive subsidized soundproofing. Thus, we are essentially modeling the effect of soundproofing on house price appreciation between the first and second sale for this repeat sales sample.

[10]This estimate is approximately three times larger than the estimate by Boes and Nüesch (2011), who investigate the noise discount among Swiss renters, rather than Minneapolis home owners. Additional explanations for this deviation in estimates are discussed further in section 5.1.

[11]Low or no interest loans might be one alternative policy solution leading to a shared burden between residents and the airport authority. This might be an approach to entice cash-constrained homeowners to undertake soundproofing on their own while alleviating the cash constraint with minimal support from the MAC.

[12]Interviews with local Minneapolis real estate agents suggest that sound proofing is, indeed, a valued amenity that is highlighted to potential buyers.

[13]We also scrutinize the sensitivity of our results against the inclusion of time-of-sale and time-of-repeat sale fixed effects that vary by Minneapolis neighborhood. The inclusion of over 5000 neighborhood-specific time-of-initial and repeat-sale fixed effects yields quantitatively and qualitatively similar coefficient estimates that are available upon request.

[14]This is an issue raised by Cohen and Coughlin (2012).

[15]We provide more detailed information on these abatement initiatives in the following sections. Graphical representations of the critical abatement eligibility criteria are given in Figures 1.1 and 1.2.

[16]The arrival of international traffic lead to the final name change of the airport, now known as the Minneapolis-St. Paul International Airport.

[17]We gratefully acknowledge that all of the maps presented in this study were produced by Ashley Nepp.

[18]While the MAC has published information on the number of treated properties, we do not have any data on the number of eligible homes and adoption rates under this initial program.

[19]In August 2001, MAC voted to offer the same insulation package installed in 65+ dB DNL homes on a first come first serve basis until funds run out. In December 2001, this decision was rescinded and replaced by a two tiered approach differentiating between homes experiencing 60 to 62 dB DNL and those exposed to 63 to 64 dB DNL (City of Minneapolis 2016).

[20]This abatement program would no longer fund any sound insulation for homes exposed to 60 to 64 dB DNL aircraft noise pollution and instead offer subsidies for central air conditioning.

[21]Partial abatement included either a new central air conditioning unit and a $4,000 credit on the aforementioned insulation options or a $14,000 credit on these insulation options and no air conditioning replacement. Unfortunately, the 2007 contour plots, made available by the MAC, only indicate the 60, 65, 70, and 75 dB DNL thresholds and prohibit us from further differentiating eligibility across the two tiers of the Consent Decree Program. Given the fact that most properties qualified for the partial, rather than the full, abatement package, our estimates regarding the effectiveness of this soundproofing initiative should more closely reflect the benefits of the lower tier package.

[22]A block group is defined as a geographic unit containing approximately 1000 people.

[23]A natural concern is the strict exogeneity of the block-level characteristics with respect to home values that must hold in order to properly identify the noise pollution effect. To address this concern we conduct several common robustness checks, further explained in section 5.3.2, and test the sensitivity of our results against the inclusion of these neighborhood characteristics. As shown in Tables 1 and 2 as well as Table A2, our findings are robust whether we directly control for changes in these socioeconomic characteristics, exclude them, or instrument for the changes with lagged values of neighborhood characteristics in Anderson-Hsiao fashion (Anderson and Hsiao 1981, 1982).

[24]In addition to Minneapolis, aircraft noise pollution in excess of 60 dB DNL stemming from operations around the MSP International Airport affects the municipalities of Richfield and Eagan, MN. Our current analysis focuses on home sales in the Minneapolis jurisdiction, but future studies may contrast noise effects across these suburban neighborhoods and test whether there are systematic differences in noise discounts among the metropolitan and suburban districts. These investigations, however, go beyond the scope of this study and hinge on the availability of suburban home sale data.

[25]In addition to the previously highlighted abatement programs, the MAC has published a summary of its numerous noise mitigation initiatives. According to the airport authority, the principle contributors to reductions and shifting patterns in average noise exposure include changes to flight routes and operations, such as the establishment and extended use of a noise compatible departure corridor over the suburbs of Eagan and Mendota Heights, a runway use system that prioritizes runways based on minimal residential noise exposure, and voluntary restrictions on aircraft types during nighttime flights.

[26]Based on this matching algorithm, a home that is located within the 60 dB DNL contour, but lies outside the 61 dB DNL contour, for example, is part of a set of sold properties experiencing 60 dB DNL for the given sample year.

[27]In this context, it is important to clarify that human noise experience measured on the decibel scale is nonlinear. Humans roughly equate a ten-decibel increase, from 60 to 70 dB for example, with a doubling of perceived noise (Stevens 1972).

[28]The analysis of this timing to market goes beyond the scope of this study and is an area of future inquiry. To the extent that lower noise exposure increases the supply of homes, the implied reduction in home values would attenuate our results towards zero. We, therefore, view our estimates as conservative lower bounds of the noise effect on home values.

[29]With repeat sales models, characteristics are assumed to be time-invariant, which is not necessarily true in reality when some houses are renovated between the dates of the sales. However this concern likely is relevant for only a fairly small portion of our sample and likely applies to frequently sold properties. To address this concern, we test the sensitivity of our results against the exclusion of frequently sold, and perhaps renovated, homes. The results presented in columns (1)-(3) of Table A3 in the Appendix are quantitatively and qualitatively consistent with our primary findings.

[30]Alternatively, we could normalize home value appreciation rates explicitly by calculating the average annual changes in log home values between repeat sales. As expected, estimations using these annualized home value appreciation rates yield robust coefficient estimates and are available upon request.

[31]One important caveat is the fact that our information is limited to abatement eligibility, rather than actual treatment. That is, we may characterize a home as abatement eligible, while the owners may have actually declined treatment. According to the MAC, however, these cases are rather limited. Information on the Consent Decree abatement program, in fact, suggest participation rates of more than 88% for abatement eligible homes. To the extent that

we falsely attribute abatement to some of the eligible, but untreated homes, the identified interaction effect is biased towards zero and should be interpreted as a conservative estimate of the abatement impact.

[32]Out of 10,903 noise-affected sales reported in our sample, 5,127 observations are eligible for aircraft noise abatement under at least one of the two aforementioned initiatives.

[33]Given the fact that we identify the abatement effect based on eligibility rather than actual implementation, the estimated coefficients can be interpreted as 'intent-to-treat' (ITT) abatement effects. To the extent that not all eligible homes adopt soundproofing, ITT varies from the traditional treatment effect estimates. The more conventional average treatment effect or treatment on the treated (TOT) effect can be approximated from the ITT coefficient estimates dividing by the adoption rate, which exceeds 92% for the consent decree program. Given this high adoption rate, ITT≈TOT and thus we proceed our discussion without the technical differentiation between these treatment effects.

[34]For a geographic reference, see Figure 1.2.

[35]Other potential explanation for the difference in eligibility coefficients between the 1992 and 2008 programs ($\Delta\delta^{1992}_{i,t+\tau}$ vs. $\Delta\delta^{2008}_{i,t+\tau}$) include the limited amount of sales recorded prior to 1992, which make its identification challenging, and/or the possible change in expectations of home owners who start to anticipate the rising home values upon sound proofing by 2008.

[36]Further restricting the sample to repeat sale transactions of abatement ineligible homes that experience an increase in noise pollution during our sample period yields a very comparable estimate of the potential soundproofing investment benefit of $12,680 (=(1.9/(48.8+1.9))*$338,358) per dB DNL.

[37]While all of the following empirical analyses incorporate the socioeconomic and demographic control variables, we limit our discussion to the coefficient estimates of interest: the aircraft noise pollution impact on home values. In general, our findings are very consistent and a full set of results including the socioeconomic and demographic coefficient estimates is available upon request.

[38]More details on these Consent Decree amendments can be found in the MAC's 'Minneapolis-St. Paul International Airport 2017 Annual Noise Contour Report' (Metropolitan Airports Commission 2017).

[39]Some of these lagged differences in noise pollution may be equal to zero if noise did not change from one year to the next. This is particularly true for the interpolated values between 1990 and 1999 and 2000 to 2006. Since we observe annual contour plots for each year from 2006 to 2014, however, there is a large degree of variation of noise for these years that allows us to identify each of the lags presented in Equation 3.

[40]Unfortunately, we are unable to perform this analysis for the initial abatement program, as our sample does not contain enough repeated sales for the initial years to identify the dynamic evolution of the abatement effect.

[41]While the Arellano and Bond (1991) estimator has received attention in the literature on control variable exogeneity, we do not have a balanced panel, which complicates the application of Arellano and Bond (1991) in our context.

[42]The results for LIML and GMM estimations are available upon request.

[43]Duranton and Turner (2012) use these long differences in conjunction with a convincing IV approach based on historical data for motorway development.

[44]This drastic reduction in the number of observations is due to the fact that we focus on repeat sales and need at least two transactions per unique property between 2006 and 2014.