Aircraft Noise Pollution, Soundproofing, and Lagging House Price Adjustments:

Evidence from the Minneapolis-St. Paul International Airport*

Felix L. Friedt†
Macalester College

Jeffrey P. Cohen‡
University of Connecticut

Abstract

Soundproofing of homes is one approach to mitigating the impacts of airport noise. A lack of available information on soundproofing, however, has limited the ability of researchers to utilize this as an identification strategy for estimating the causal impacts of noise on house prices. In this paper, we focus on Minneapolis-St. Paul International Airport (MSP), and examine the airport noise impacts on housing prices by using two soundproofing initiatives for MSP as an identification strategy. We use information on properties that were eligible for soundproofing, after the soundproofing initiatives, to identify the causal impact of noise on house prices. We find that the magnitudes of the noise impacts on housing prices are approximately 2% per decibel, and are statistically significant. These findings hold up to a broad range of specifications and robustness checks. Our findings are the first known results that depend on using soundproofing eligibility to identify the causal impacts of noise on house prices. We also calculate an estimated return on investment (ROI) for residential soundproofing, and find that this ROI could reach as high as 40% in the areas around MSP.

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

---

*We gratefully acknowledge the financial support from the Macalester College Faculty Research fund. Thanks to Clemens Pilgram and Sarah West for generously sharing the home price and Census data and Andra Boca for excellent research assistance in preparing the airport noise data used in this study.

†Department of Economics, Macalester College, 1600 Grand Avenue, Saint Paul, MN 55105; ffriedt@macalester.edu.

‡Jeffrey P. Cohen, Department of Finance, University of Connecticut, 2100 Hillside Rd, Storrs, CT 06268; jeffrey.cohen@business.uconn.edu

Airport-related noise can have detrimental impacts on the health and well-being of residents nearby. Aircraft noise can interrupt sleep patterns and lead to difficulty in hearing and engaging in verbal conversations, which has been described as significant noise levels by the Federal Aviation Association (FAA) at 65 dB or greater (Federal Aviation Administration 2018). This noise can impact the desirability, and in turn the value of residential property, especially if there are changes in the noise exposure levels of a property between the date of purchase and some later point in time (such as a repeat sale of the same property).

Such impacts are classic examples of "externalities" (as described in detail by Baumol et al. (1988)). This classic literature on externalities - uncompensated costs that are imposed on some people as a result of others' activities - suggests several possible options for dealing with this type of market failure. One is for property-owners and airport authorities and/or airlines to negotiate with each other on how to reduce the residential noise exposure. This option depends on there being low costs of negotiation, which in practice often is not the case, due to attorneys fees, protracted negotiation periods, etc. A second option would be for the airport to purchase the properties from the homeowners. This option is not practical on a comprehensive level because typically there are thousands of houses that are exposed to excessive noise levels. A third possibility is for the airport to compensate homeowners for the damages; however, this would be extremely costly and also would necessitate ongoing compensation if the noise levels were increasing over time. Finally, Baumol et al. (1988) suggest that the homeowners can take defensive actions to avert the externality. In the case of airport noise, this option could entail soundproofing of individual homes.

There are several examples of airport noise mitigation programs with soundproofing across various locations in the U.S., including Atlanta, Boston, Minneapolis, and others. But there has been a lack of attention to this issue in the airport noise impacts on house prices literature, mainly due to a lack of availability of data on the precise properties that have been soundproofed.

Much of the previous literature 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. This can lead to imprecise estimates of the impacts of noise on house values, which, when used for policy purposes, may be undesirable. In this paper, we examine the airport noise impacts on housing prices by using two soundproofing initiatives in Minneapolis as an identification strategy. We use information on properties that were eligible for soundproofing, after the initiation of the noise abatement programs, to identify the causal impact of noise on house prices. We find that the magnitudes of the noise impacts on housing prices are approximately 2% per decibel of aircraft noise pollution, and are statistically significant. Moreover, our investigation into the dynamic responses of housing prices to past changes in aircraft noise indicate rather immediate adjustments within the last three years prior to a property's sale. These findings hold up to a broad range of robustness checks. Our findings are the first known results that depend on using soundproofing eligibility to identify the causal impacts of noise on house prices. We also calculate an estimated return on investment (ROI) for soundproofing, and find that this ROI could reach as high as 40% in Minneapolis.

The remainder of this paper proceeds as follows. We first summarize the literature on airport noise impacts upon house prices and provide some background on the Minneapolis-St. Paul (MSP) International Airport. Next, we describe the data specific to this particular airport and the empirical estimation approach, followed by the empirical results and the findings from the robustness checks. Then we provide concluding remarks and suggestions for future research.

1 Literature and Background

1.1 Literature Review

There have been many studies of airport noise impacts 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 for rental apartments. Nelson (1980, 2004) conducted two meta-studies of other airport noise studies, and found a range of 0.4 to 1.1 percent discount in house price per decibel. Nelson (2004) estimates indicate a noise discount of 0.8 to 0.9 percent per decibel in Canada, which are higher than those in the United States. In contrast, Schipper et al. (1998)

found much more variation in the noise discounts. In some of the more well-cited studies, Cohen and Coughlin (2008, 2009) found a noise discount in Atlanta of approximately 20% for properties exposed to noise levels of 65 dB or more, opposed to those in a "buffer zone" of less than 60 dB. They also found this discount to be increasing over time. McMillen (2004) found a noise discount of 9% for properties exposed to more than 65 dB of noise near Chicago's OHare airport. 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 et al. (2008) finds that for single-family residential properties where noise near Raleigh-Durham airport is disclosed to potential buyers, the sale price is reduced by approximately 2.9%.

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) found that for apartment rents in Düsseldorf, Germany there was a rent discount of approximately 1.04% for an additional decibel of noise. Salvi (2008) studied single-family homes near the Zürich airport, and found 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), or 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.

We contribute to these literatures in several ways; first, we provide new estimates of the home value discount arising due the aircraft noise pollution from the MSP International Airport. Second, exploiting the time-varying aircraft noise exposure on repeatedly sold Minneapolis homes and changing noise abatement policy regimes, we develop a novel identification strategy to determine the causal nature of this noise pollution effect. Third, we break new ground by quantifying the effectiveness of noise abatement initiatives in mitigating these adverse noise effects. Lastly, we investigate the dynamics of home value appreciation in response to changing aircraft noise pollution. Our findings suggest that home market prices adjust within the first three years to changes in aircraft noise pollution - a finding that is at odds with current abatement policy practices.

1.2 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.[1] By the 1960s, MSP had undergone significant expansions including the construction of the primary Lindbergh Terminal and had become the world headquarters of Northwest Airlines, now known as Delta Airlines (MAC 2018a).

Designed to serve four million passengers a year by 1975, MSP quickly outpaced passenger growth projections serving 4.1 million travelers by 1967 (MAC 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 (MAC) 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, 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

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

terminal, Terminal 2-Humphrey, was constructed, roadway access and parking were improved, and the light rail system, connecting the MSP International Airport and the downtowns of Minneapolis and St. Paul, were developed (MAC 2018a). The last component of the expansion proposal consisted of the construction of a fourth runway, which was completed in 2005. 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 (MAC 2018b). Today, the airport has established itself as one of the primary regional economic drivers supporting over 80,000 jobs and earning 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 dis-amenities for the residents of Minneapolis, St. Paul, and the surrounding municipalities, the most paramount of which is the aircraft noise pollution. In response to the adverse noise impact, the MAC has been developing and implementing several noise abatement programs since the late 1980s. Historically, noise abatement programs are often employed by local port 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 programs 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 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 64 decibel (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 the MSP International airport, this 65 dB DNL noise pollution threshold was determined via a federally approved contour plot projecting the anticipated 1996 aircraft noise levels. 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. While the abatement program aimed to reduce exposure to aircraft noise pollution by five dB DNL, average abatement costs for the 7,846 single-family treated homes ranged from $17,000 in 1994 to $45,000 per home in 2001. Properties outside the projected 65 dB DNL aircraft noise range received no abatement support under this program (Metropolitan Airports Commission 2017).

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 and unprecedented 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 specifics were later added in 2001[2], 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).[3] 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.[4] 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. The total abatement costs for the second abatement seven year abatement program are estimated at around $95 million (Metropolitan Airports Commission 2017).

[2]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).

[3]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.

[4]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.

2 Data

Contributing to this evolving literature, we investigate the effects of changing MSP International airport noise pollution on the appreciation of Minneapolis home values and break new ground by producing novel estimates of the impact of the aforementioned noise abatement programs. The highlighted policy changes, including the varying timing and eligibility criteria of the MSP abatement programs, offer a unique identification strategy to establish the causal effect of aircraft noise pollution on home price premia. 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 block group level[5] 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. 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 the universe of single-family home sales in Minneapolis between 1983 and 2014. 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,

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

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 74,018 reported sales allows us to control for all time-invariant property and/or neighborhood characteristics that may be omitted in cross-sectional studies.

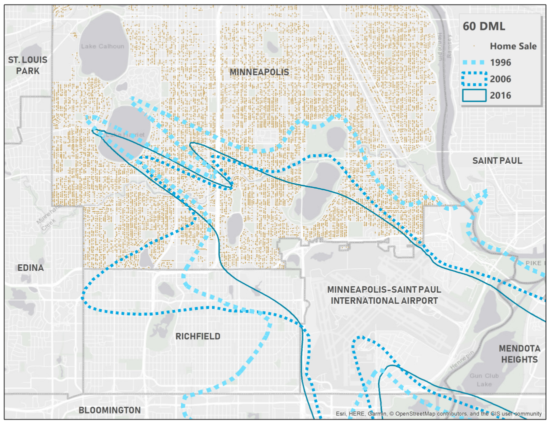
Annual information on the spatial distribution of aircraft noise pollution has been obtained from the MAC, who owns and operates the MSP International airport, and oversees the residential noise pollution resulting from this as well as six other, smaller airports surrounding the Minneapolis-St. Paul area. Noise pollution 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 (INM), which relies on aircraft operation counts, aircraft types, operation times, flight tracks, and ground movements, 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 classified into four stages, the loudest of which (stages 1 and 2) have been prohibited to fly within the contiguous U.S. since December 31st, 2015. 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). 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 rapid growth of the airport.[6]

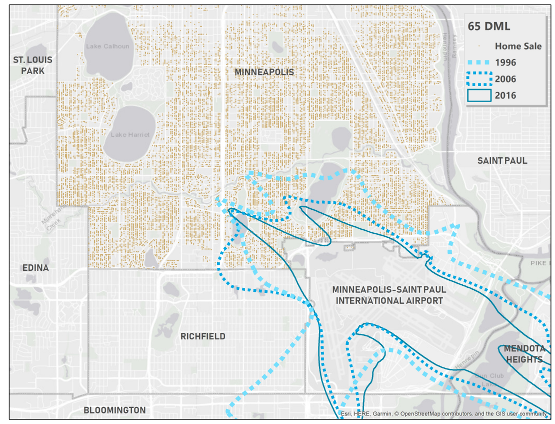
Figures 1.1 through 1.3 illustrate the resulting changes in noise exposure at the major thresholds (60, 65, and 70 dB DNL) over a twenty year period from 1996 to 2016. Moreover, the maps depict each of the unique Minneapolis parcels repeatedly sold during this sample period. Importantly for our identification 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 1.2 and 1.3, illustrate a fairly consistent reduction in aircraft noise exposure from 1996 to 2016, we observe considerable expansions and shifts in the 60 dB DNL contours, depicted in Figure 1.1, 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 dis-amenity 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 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.

MSP noise contours, including the ones depicted in Figures 1.1 through 1.3, are available for 1996, 2006, and every year thereafter. The richness of information available, however, varies across years. For 1996 and 2007 through 2009, for example, the noise contours are only available

[6] 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. More importantly perhaps, the airport has grown tenfold since the 1970.



1.1: DNL 60



1.2: DNL 65

Figure 1: Variation in Residential Noise Exposure from MSP Air Traffic (1996-2016)

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 noise exposure at the time of sale and resale.[7] For home sales during the years for which no annual contour plot is available, namely between 1990 to 1995 and 1997 to 2005, we interpolate the corresponding noise values. Transactions prior to 2000 are matched with the contour curves available for 1996, whereas sales occurring during the years of 2000 to 2006 are matched with the contour plots for 2006. Reassuringly the empirical results are robust against variations in the cutoff year of 2000 and available upon request.

Table 1 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 this 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

[7]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.

2008. In comparison to the number of aircraft noise polluted transactions, a half-mile buffer region drawn around the 60 dB DNL contour generates a similar volume of sales.

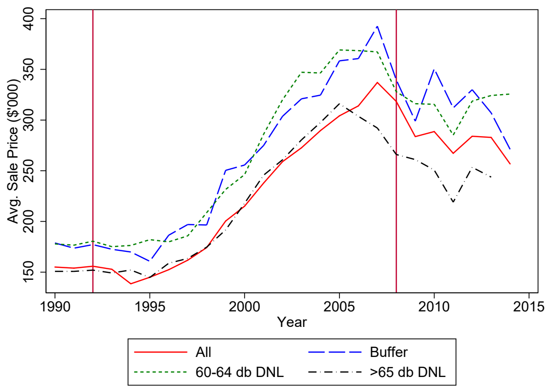
Complementing these noise-specific frequency counts, Figure 2.1 illustrates the annual average home sale prices for Minneapolis. We differentiate average annual sale prices across the full Minneapolis sample and three subsamples of repeated sale transactions, including a set of abatement eligible homes sold while experiencing 65 dB DNL or above, a sample of properties with changing abatement eligibility status subject to 60 to 64 dB DNL noise pollution at the time of sale, and an abatement ineligible buffer sample made up of sold properties located within a half-mile radius from the 60 dB DNL contours. Based on the eligibility criteria of the two MAC abatement programs, our sample includes 5,012 repeat sales of 1,964 eligible homes under the first program and 694 repeat sales of 630 newly eligible properties under the second Consent Decree program. The two vertical lines indicate the years of 1992 and 2008, which mark the respective commencements of these abatement initiatives.

Over the course of the 25 sample years, Figure 2.1 shows that homes in all four samples 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 from these trends. First, properties within the buffer and 60 to 64 decibel DNL samples exhibit significantly higher annual sale prices than the full sample average. This level difference for the buffer and 60-64 dB DNL samples is suggestive of the rising premia for the desirable Southwest Minneapolis neighborhoods, particularly around Lakes Harriet and Bde Maka Ska, formerly known as Lake Calhoun. Secondly, homes above the 60 dB DNL threshold experience a significant reduction in the rate of appreciation starting in 2005, which coincides with the phase-out period of the first insulation program, opening of the fourth runway of MSP, and the beginning of the aforementioned legal dispute over further noise abatement funding. In contrast to these noise affected homes, the average Minneapolis property and those located in the buffer region continue to experience a rapid rate of home value appreciation until 2007. Lastly, starting in 2008, the rate of depreciation of annual sale prices experienced by the average property

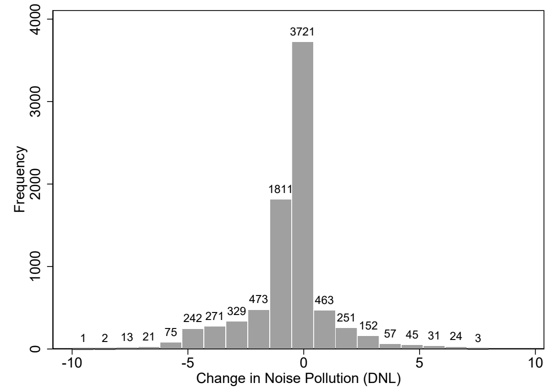
Table 1: Number of annual home sales by noise level

Year	DNL $\in [60, 64]$	DNL $\in [65, 69]$	DNL ≥ 70	Buffer $DNL < 60$	Other $DNL < 60$	Total
1990	355	170	36	470	2019	3050
1991	330	169	40	479	1789	2807
1992	342	189	44	538	1827	2940
1993	427	195	55	589	2019	3285
1994	360	202	57	546	2260	3425
1995	381	163	48	546	2114	3252
1996	378	203	51	576	2372	3580
1997	392	197	44	582	2296	3511
1998	439	220	69	669	2502	3899
1999	410	222	73	597	2441	3743
2000	321	163	17	501	2804	3806
2001	313	165	24	499	3114	4115
2002	333	141	16	509	3026	4025
2003	345	171	20	521	3308	4365
2004	322	161	13	544	3315	4355
2005	293	136	7	473	3082	3991
2006	255	101	21	417	2410	3204
2007	257	92	8	300	1570	2227
2008	158	51	2	227	1064	1502
2009	127	56	0	209	1380	1772
2010	110	18	0	182	1173	1483
2011	95	15	0	161	967	1238
2012	113	16	0	257	1366	1752
2013	140	17	0	282	1605	2044
2014	29	0	0	63	555	647
Total	7025	3233	645	10737	52378	74018

Notes: The matching of homes and aircraft noise pollution at the key thresholds is based on a GIS mapping of properties against the corresponding annual contour plots published by the MAC. While home sales between 1990 and 1999 are associated with the 1996 contour plot, transactions between 2000 and 2006 are associated with the 2006 contour plot. Sales during all other years are matched with the corresponding annual contour plots. Properties within the buffer sample are located within a half-mile radius around the outer most contour curve representing a minimum noise exposure of 60 dB DNL for the given year. All other properties located outside of this buffer or any of the contour curves are counted under the column labeled as ‘Other’.



2.1: Avg. annual sale prices ($’000)



2.2: Changes in noise exposure

Figure 2: Home Prices and Noise Pollution

slows down considerably for homes within the noise sample and particularly those within the 60 to 64 dB DNL range. The timing of this visible resilience coincides with 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 aircraft noise polluted properties and the average Minneapolis’ home are indicative of the abatement impact and inverse correlation between noise pollution exposure and sale price premia.

Suggestive of the expected inverse relationship, these observations, however, offer little insight into the directionality of causation. While greater exposure to aircraft noise pollution may cause lower home values, it is also conceivable that lower home values attract greater air traffic and intensified noise exposure. To shed light on the nature of the causal relationship, we utilize the spatial and temporal variation in noise pollution and home values provided by the Minneapolis repeat sales sample and differentiate the noise effect across homes that are abatement eligible and those ineligible for the insulation treatment before and after the policy changes in 1992 and 2008.

In light of the fact that this identification strategy hinges on the volatility in noise exposure between sales, Figure 2.2 presents the frequency distribution of changes in noise pollution across 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.[8] 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.[9]

3 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:

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

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 year-month fixed effects to capture citywide differences during the time

[8]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).

[9]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.

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:

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

Since the characteristics of house i, H_i, are assumed to be time-invariant, they drop out when taking the first difference of (1). 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, but instead results from intentionally chosen flight tracks over low-value neighborhoods, 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 reduced noise exposure, one would expect a significantly muted noise effect for these potentially insulated homes $(\beta_3 > 0)$.[10]

[10] One important caveat to mention, is the fact 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 homes, the identified interaction effect is biased towards zero and should be interpreted as a conservative estimate of the abatement impact.

4 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 causes discounted sales 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, we find that the noise-related differences in home value appreciation are largely driven by the most recent changes in noise pollution, particularly those one to three years prior to the resale of a given property.

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 47,677 repeat sale observations, this results in adjustments across 350 clusters, whereas the most narrowly defined sample of 7,985 noise affected repeat sales includes 64 block-group clusters. Statistical significance based on clusters at the more aggregated census-tract level renders consistent inference and conclusions. We scrutinize our findings against parsimonious to full model specifications and test their sensitivity across multiple heterogeneity analyses and sample restrictions. While the parsimonious model specification quantifies the noise pollution effect only controlling for time-of-sale and time-of-repeat-sale fixed effects, we obtain robust results based on richer models that further control for the aforementioned demographic and socioeconomic block-group characteristics.

4.1 Aircraft Noise Pollution and Abatement Effects

In Table 2, 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 2 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 ($\delta_{it} = 0,\ \forall\, i = 1, .., I;\ t = 1990, .., 2014$), 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 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. 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.[11] The expected bias is quite clear. For homes experiencing increases in noise exposure, the noise-canceling abatement investment would bias our estimates of the true impact of aircraft noise pollution on home values 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

[11] 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.

Table 2: 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)
$\Delta\delta^{1992}_{i,t+\tau}$ (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)
$\Delta N_{i,t+\tau}\ X\ \delta^{1992}_{i,t+\tau}$			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)
%Δ African American		-0.536***		-0.173**		-0.541***		-0.531***
		(0.087)		(0.079)		(0.089)		(0.087)
%Δ Hispanic		0.188*		0.872***		0.210**		0.203**
		(0.101)		(0.127)		(0.104)		(0.101)
%Δ Asian or Pacific Islander		-0.207		0.421**		-0.269		-0.204
		(0.171)		(0.184)		(0.173)		(0.172)
%Δ American Indian		-1.006***		-0.426		-0.970***		-0.991***
		(0.229)		(0.299)		(0.230)		(0.229)
%Δ Other Race		0.367		-0.459		0.291		0.367
		(0.334)		(0.436)		(0.353)		(0.336)
%Δ Under 20		0.546***		-0.668***		0.579***		0.539***
		(0.138)		(0.157)		(0.140)		(0.138)
%Δ Over 65		0.562***		0.254**		0.516***		0.545***
		(0.112)		(0.111)		(0.112)		(0.112)
%Δ 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
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 *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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, for which the coefficient estimate is statistically significantly different at the 1% level and of a positive sign overall ($0.023 - 0.016 > 0$). Moreover, we find little evidence to suggest that these eligible homes experienced a significant shift concerning their rates of appreciation upon becoming eligible.

Considering the noise effects under the second MAC abatement program, we find highly consistent coefficient estimates, presented in columns (5) and (6) of Table 2. 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 dis-amenity effect created by noise exposure. 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.

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 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:

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

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

Again, the point estimates are highly consistent and provide strong evidence in support of the expected dis-amenity effect. Ineligible properties experience a reduction in the rate of home value appreciation in response to an increase in noise exposure, while these dis-amenity effects are statistically significantly different and fully offset for abatement eligible parcels, irrespective of the specific abatement program. The interpretation of the preferred coefficient estimate presented in column (8) of Table 2 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 average rate of appreciation by about 6.6% (=1.9/29 *100%).

Combining these estimates for eligible and ineligible homes exposed to aircraft noise pollution allows for the approximation of 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.

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 and resulting ROI.

Concerning the socioeconomic and demographic control variables, our analyses produce several statistically significant coefficient estimates that tend to be of the expected sign. With the exception of the first abatement regression analysis, which restricts the sample to observations prior to 2007, 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 2, 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.[12]

Overall, our estimates of the noise discount for the Minneapolis-Saint-Paul International airport are approximately 2%, which is reasonably robust across specifications. This is consistent with the lower end of the noise discount found by Salvi (2008) for Zürich airport, similar to the Pope et al. (2008) findings for Raleigh-Durham, and somewhat higher than the estimates that Nelson (1980, 2004) found for a variety of U.S. airport settings. However, the estimation strategies that we implement are more sophisticated than the majority of the studies summarized in the Nelson

[12]While 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.

(1980, 2004) meta analyses, and this may account for the discrepancies.

4.2 Dynamic Aircraft Noise and Abatement Effects

Another important question that can be addressed with the rich information provided by our repeat sales sample of Minneapolis homes relates to the timing of sale price adjustments in response to aircraft noise pollution exposure. Whether the estimated noise effects on home value appreciation are immediate or lagging in nature has considerable policy implications. For the MSP International airport, for example, the MAC has met its Consent Decree obligations as of 2014 and has since implemented several amendments to the original settlement. One of the key policy changes is the newly defined eligibility criteria, which essentially requires a three year consecutive exposure to aircraft noise pollution above the 60 dB DNL threshold.[13] If, indeed, increases in aircraft noise pollution have an immediate adverse effect on home price premia, the lagged policy response may be suboptimal from the residents' 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 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 alternations in noise exposure between the initial sale and the fourth year

[13]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).

prior to the repeat transaction. The resulting specification can be expressed as follows:

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

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 from the k^{th} year prior to resale $(t + \tau - k)$ to the $kth - 1$ year prior to resale $(t + \tau - (k - 1))$. 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 through β_4 and β_5 through 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 3 and offer consistent support of the initial conclusions. More importantly, however, our findings provide novel evidence on the predominantly short-run adjustment of home price premia in response to recent 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 largely insignificant statistical effects on the average home value appreciation. This misleading and inaccurate result is strongly 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 3 are highly 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. In contrast, the estimated impact of the fourth lag of noise adjustment, which captures the cumulative change in noise pollution from the time of initial sale until the fourth year prior to resale, is noticeably smaller in absolute magnitude, with point estimates ranging from -0.1 to -0.16, and only marginally significant at the 10% or 5% levels.

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. In contrast, we find that abatement eligibility only has a marginal offsetting effect for noise adjustments four years or more prior to the resale of a given property. This latter finding is indicative of the rather imprecise estimation of the long-run noise effect on the rate of home value appreciation and suggestive of a potentially gradual sale price recovery post mitigation treatment.

Overall, these findings suggest 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. Potentially even more problematic is the fact that annually changing geographic noise profiles may lead to abatement ineligible temporary noise pollution that has immediate and adverse effects on the affected home values.

Table 3: Housing price appreciation, lagged noise effects 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)
$(N_{i,t+\tau} - N_{i,t+\tau-1})$ (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
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 *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

4.3 Robustness

We test the sensitivity of our results against a host of model alterations and additional sample restrictions. Throughout these robustness checks we estimate a variation of Equation (2), which simultaneously differentiates the noise impact across abatement ineligible and eligible homes under both abatement initiatives. In general, the sensitivity analysis yields consistent noise effect estimates that underscore the insights gained from this study.

4.3.1 Heterogeneity Analyses

Among the various model alterations, we begin by dissecting the overall abatement effect of the Consent Decree program across its seven year lifespan from 2008 until 2014.[14] The dynamic evolution of the mitigating Consent Decree abatement effect is presented in column (1) of Table 4 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. In fact, we find that the mitigating abatement effects are statistically insignificant for the years of 2008 and 2010, 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.

In addition to this dynamic consideration, we also test whether the noise pollution impact on abatement ineligible homes varies during the years of the great recession. Reassuringly, we find that the primary noise impact, presented in column (2) of Table 4 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 and 2009 yields statistically insignificant coefficient estimates suggesting that the adverse noise pollution effect on home value appreciation is not overshadowed by the housing market collapse starting in 2008.

[14] 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.

Table 4: Robustness: heterogeneity analysis

$\Delta ln(P_{i,t+\tau})$	(1)	(2)	(3)	(4)
$\Delta N_{i,t+\tau}$ (Δ dB DNL)	-0.019***	-0.019***	-0.011**	-0.023***
	(0.007)	(0.007)	(0.005)	(0.008)
$\Delta N_{i,t+\tau}\ X\ \delta^{1992}_{i,t+\tau}$	0.022***	0.021***	0.009*	0.021***
	(0.007)	(0.008)	(0.005)	(0.007)
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$		0.023***	0.018***	0.024***
		(0.007)	(0.005)	(0.007)
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2008)	0.019			
	(0.013)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2009)	0.042**			
	(0.020)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2010)	0.014			
	(0.010)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2011)	0.024***			
	(0.009)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2012)	0.038***			
	(0.010)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2013)	0.034**			
	(0.017)			
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$ (2014)	-0.010			
	(0.018)			
$\Delta N_{i,t+\tau}\ X$ 2008		0.007		
		(0.005)		
$\Delta N_{i,t+\tau}\ X$ 2009		-0.000		
		(0.006)		
$\Delta N_{i,t+\tau}\ X$ Low-valued homes (P<\$100,000)			0.037*	
			(0.020)	
$\Delta N_{i,t+\tau}\ X$ High-valued homes (P>\$500,000)			-0.044**	
			(0.017)	
$(\Delta N_{i,t+\tau})^2$				0.001
				(0.001)
Observations	46477	46477	46477	46477
Adjusted R^2	0.682	0.682	0.694	0.682
Sale FE	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 heterogeneity analyses presented in columns (1)-(4) differentiates the noise effect across different sample years and property groups. Coefficients presented in column (1) consider the dynamic annual evolution of the abatement effect under the Consent Decree program after 2007. In contrast, the results given in column (2) differentiate the noise effect on abatement ineligible homes during the great recession, while the results given in column (3) distinguish this effect across low- and high-valued properties. Lastly, the coefficient estimates presented in column (4) explore the nonlinearity of the noise effect on abatement ineligible homes. For all regression analyses interacting the change in noise pollution with various indicator variables, we include the first-differenced terms, but do not report their respective coefficient estimates for the sake of brevity. Statistical significance at the conventional levels is indicated by *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

In contrast to this temporal heterogeneity analysis, we also test whether the noise effect on ineligible homes varies across the cross-sectional dimension. In column (3) of Table 4, we present our findings concerning the adverse noise pollution effect across low- to high-valued homes. 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 adverse noise effect relative to the average abatement-ineligible home. In contrast, we find that lower-valued homes experience rather limited adverse aircraft noise effects, although we treat this finding with caution given its marginal significance at the 10% level.

As part of the final model alteration, we test for the nonlinearity of the estimated noise effect. To this end, we integrate the square of the change in aircraft noise pollution between sales as an explanatory variable of home value appreciation. Based on our estimates, we find no evidence of such nonlinearities. The coefficient estimates presented in column (4) of Table 4 illustrate a statistically significant and consistent adverse level effect of noise pollution on abatement ineligible homes and statistically insignificant change in the rate of appreciation in response to the squared change in noise exposure.

4.3.2 Sample Restrictions

In terms of additional 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 19 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 4) yields robust noise effect estimates that are nearly identical in magnitude to the primary point estimates presented in Table 2 and statistically significant at the 1% or 5% levels.

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 5 are quantitatively similar, but only marginally significant at the 10% level. Further restricting the sample and excluding even the buffer observations, yields consistent estimates that are statistically significant at the 5% to 10% levels.

Lastly, we test for the sensitivity of our results against the presence of influential outliers that may bias our primary findings. As the property values 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 (7) and (8), respectively, and indicate a very consistent aircraft noise pollution effect on abatement ineligible homes that continues to be statistically significant at the 1% level. Specifically, we find that, excluding 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 we find abatement eligible properties under either mitigation initiative to be immune to these changes in noise exposure.

5 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

Table 5: Robustness: sample restrictions

$\Delta ln(P_{i,t+\tau})$	(1)	(2)	(3)	(4)	(5)	(6)	(7)
$\Delta N_{i,t+\tau}$ (Δ dB DNL)	-0.019**	-0.018**	-0.019***	-0.013*	-0.015**	-0.019***	-0.017***
	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)	(0.006)
$\Delta N_{i,t+\tau}\ X\ \delta^{1992}_{i,t+\tau}$	0.025***	0.022***	0.022***	0.011	0.012*	0.020***	0.019**
	(0.009)	(0.008)	(0.008)	(0.007)	(0.007)	(0.007)	(0.007)
$\Delta N_{i,t+\tau}\ X\ \delta^{2008}_{i,t+\tau}$	0.038***	0.027***	0.026***	0.020**	0.019*	0.023***	0.021***
	(0.012)	(0.007)	(0.006)	(0.010)	(0.012)	(0.006)	(0.006)
$\Delta\delta^{1992}_{i,t+\tau}$ (Eligible Homes, 1992)	0.010	0.020	0.023	-0.006	-0.001	0.026*	0.011
	(0.020)	(0.017)	(0.015)	(0.015)	(0.015)	(0.016)	(0.015)
$\Delta\delta^{2008}_{i,t+\tau}$ (Eligible Homes, 2008)	0.016	0.041**	0.046***	0.018	0.029	0.053***	0.052***
	(0.020)	(0.016)	(0.014)	(0.012)	(0.017)	(0.013)	(0.014)
Observations	14839	31093	40966	13070	7985	44583	41700
Adjusted R^2	0.732	0.712	0.694	0.762	0.805	0.687	0.711
Sale FE	Y	Y	Y	Y	Y	Y	Y
Socioeconomic controls	Y	Y	Y	Y	Y	Y	Y
Sample Restrictions	# of Sales< 3	# of Sales< 4	# of Sales< 5	Buffer	Contour	2 Std. Dev.	1 Std. Dev.

Notes: Standard errors, reported in the parenthesis, are clustered at the block-group level. The results presented in columns (1)-(3) restrict the sample in terms of the number of unique property repeat sales. While the results presented in column (1) are based on a sample that excludes homes sold more than twice during the sample period, the analyses given in columns (2) and (3) exclude those properties sold more than three and four times during the sample period, respectively. Coefficients estimates presented in column (4) are based on a sample that only includes homes exposed to aircraft noise pollution or within the half-mile buffer around the outer most annual contour plots, whereas the analysis given in column (5) further restricts the sample and excludes the buffer observations. Lastly, the results presented in columns (6) and (7) are based on samples that exclude sale price outliers that exceed a difference of two or one standard deviations from the average real sale price, respectively. Statistical significance at the conventional levels is indicated by *** $p < 0.01$, ** $p < 0.05$, * $p < 0.1$.

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 all 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 initiative 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 changes in aircraft noise pollution up to three years prior to a property's sale. This evidence of 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. Lastly, we also observe that several years after soundproofing eligibility, the noise discount diminishes, which implies that soundproofing may be effective over longer periods of time.

There are several potential policy implications of our findings. First, 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 airport authorities purchasing the properties from affected homeowners. 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. While imposing flight restrictions on aircraft would be expected to enhance the value of some properties due to the resulting lower noise, 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 airport noise because of the potential to dampen house price declines from additional noise.

Second, 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 that noise pollution up to three years prior to a property's sale, however, has significant impacts on its rate of appreciation puts the effectiveness of this policy regime into question. Our findings point to significant and sustained losses to noise affected homeowners up to three years prior to meeting the latest soundproofing eligibility criteria.

References

Marcia Alexander-Adams. Fact sheet - the faa airport noise program, 03 2015. Accessed on 11/16/2018 from https://www.faa.gov/news/fact_sheets/news_story.cfm?newsId=18114.

Christian Almer, Stefan Boes, and Stephan Nüesch. Adjustments in the housing market after an environmental shock: evidence from a large-scale change in aircraft noise exposure. *Oxford Economic Papers*, 69(4):918–938, 2017.

William J Baumol, William Jack Baumol, Wallace E Oates, Vijay S Bawa, WS Bawa, and David F Bradford. *The theory of environmental policy*. Cambridge university press, 1988.

Stefan Boes and Stephan Nüesch. Quasi-experimental evidence on the effect of aircraft noise on apartment rents. *Journal of Urban Economics*, 69(2):196–204, 2011.

Julie Cidell. Air transportation, airports, and the discourses and practices of globalization. *Urban Geography*, 27(7):651–663, 2006.

Julie Cidell. The role of major infrastructure in subregional economic development: an empirical study of airports and cities. *Journal of Economic Geography*, 15(6):1125–1144, 2014.

City of Minneapolis. Key events in local airport noise history, 10 2016. Accessed on 11/16/2018 from http://www.minneapolismn.gov/airportnoise/airportnoise_noisehistory.

Jeffrey P Cohen and Cletus C Coughlin. Spatial hedonic models of airport noise, proximity, and housing prices. *Journal of Regional Science*, 48(5):859–878, 2008.

Jeffrey P Cohen and Cletus C Coughlin. Changing noise levels and housing prices near the atlanta airport. *Growth and Change*, 40(2):287–313, 2009.

Federal Aviation Administration. Aircraft noise issues, 01 2018. Accessed on 11/07/2018 from `https://www.faa.gov/about/office_org/headquarters_offices/apl/noise_emissions/airport_aircraft_noise_issues/`.

Sanford Fidell, Karl Pearsons, Laura Silvati, and Matthew Sneddon. Relationship between low-frequency aircraft noise and annoyance due to rattle and vibration. *The Journal of the Acoustical Society of America*, 111(4):1743–1750, 2002.

InterVistas Consulting Inc. Minneapolis-st. paul international airport: Economic impact of its operations 2016, 9 2017. Accessed on 12/15/2018 from `http://mspairport.com/sites/default/files/2017-09/MSP%20Economic%20Impact%20Study%202016%20FINAL%20DRAFT%20REPORT%20%2814Sep2017%29.pdf`.

Metropolitan Airports Commision MAC. History, 2018a. Accessed on 12/15/2018 from `https://www.mspairport.com/about-msp/history`.

Metropolitan Airports Commission MAC. About msp, 2018b. Accessed on 12/15/2018 from `https://www.mspairport.com/about-msp`.

Daniel P McMillen. Airport expansions and property values: the case of chicago o'hare airport. *Journal of urban economics*, 55(3):627–640, 2004.

Edward A Meister and Rebecca J Donatelle. The impact of commercial-aircraft noise on human health: A neighborhood study in metropolitan minnesota. *Journal of Environmental Health*, 63 (4), 2000.

Andreas Mense and Konstantin A Kholodilin. Noise expectations and house prices: the reaction of property prices to an airport expansion. *The Annals of Regional Science*, 52(3):763–797, 2014.

Metropolitan Airports Commission. Minneapolis st. paul international airport (msp) 2017 annual noise contour report. Technical report, 2017.

Jon P Nelson. Airports and property values: a survey of recent evidence. *Journal of transport economics and policy*, pages 37–52, 1980.

Jon P Nelson. Meta-analysis of airport noise and hedonic property values. *Journal of Transport Economics and Policy (JTEP)*, 38(1):1–27, 2004.

Darel E Paul. The local politics of'going global': making and unmaking minneapolis-st paul as a world city. *Urban Studies*, 42(12):2103–2122, 2005.

Clemens A Pilgram and Sarah E West. Fading premiums: The effect of light rail on residential property values in minneapolis, minnesota. *Regional Science and Urban Economics*, 69:1–10, 2018.

Jaren C Pope et al. Buyer information and the hedonic: The impact of a seller disclosure on the implicit price for airport noise. *Journal of Urban Economics*, 63(2):498–516, 2008.

Ronny Püschel and Christos Evangelinos. Evaluating noise annoyance cost recovery at düsseldorf international airport. *Transportation Research Part D: Transport and Environment*, 17(8):598–604, 2012.

Marco Salvi. Spatial estimation of the impact of airport noise on residential housing prices. *Swiss journal of economics and statistics*, 144(4):577–606, 2008.

Youdi Schipper, Peter Nijkamp, and Piet Rietveld. Why do aircraft noise value estimates differ? a meta-analysis. *Journal of air transport management*, 4(2):117–124, 1998.

SS Stevens. Perceived level of noise by mark vii and decibels (e). *The Journal of the Acoustical Society of America*, 51(2B):575–601, 1972.