Traffic Noise and Housing Values: Evidence from an Airport Concession Renewal*

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Abstract

Credible estimates of the cost of traffic noise are crucial to the assessment of the merits of noise control policies. This study estimates the cost of aircraft noise by measuring its capitalization into housing prices following an unexpected renewal of the operating contract for a local airport. The results show that a one decibel increase in aircraft noise leads to a reduction in housing values of 0.3 percent, or $1,200, on average. The effect is larger the higher is the property's value, size and standard which suggest that owners of these houses benefit relatively more from noise abatement measures.

JEL Codes: Q51, Q53, R23, R31, R41

Keywords: Noise Pollution, Value of environmental goods

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1 Introduction

Traffic noise is seen to be an important environmental problem in many urban areas and significant efforts are devoted to reduce noise exposure levels.[1] The measures are primarily motivated by the annoyance and adverse health impacts caused by noise but are themselves seldom costless. For instance, residential soundproofing generates construction costs while regulation of operational procedures imposes compliance costs. Credible evidence of the cost of traffic noise is therefore crucial to determine whether the benefits of noise abatement measures outweigh the costs. Such evidence is also informative about the benefit distribution of the measures and their merits compared to those targeting other environmental problems.

Since noise is not traded in a market, a popular method to estimate its cost is to use housing values to infer the implicit price of noise exposure. This hedonic approach exploits homebuyers' trade-off between local amenities and house price to value the former. However, the hedonic analysis is made difficult by the non-random assignment of noise exposure for local populations. House prices may be determined by unobserved factors that covary with noise pollution which leads to omitted variable bias in a regression analysis. Households may sort based on preferences for peace and quiet so that the estimate is based on non-random sub-populations. While a growing literature attempts to address these issues by applying quasi-experimental methods to obtain housing price impacts of environmental amenities, noise pollution has received little attention.[2]

The objective of this study is to estimate the cost of aircraft noise by measuring its capitalization into housing prices. I address the identification issues by exploiting the unexpected announcement of the renewal of a concession agreement for a local airport. I match housing transactions to geodata on aircraft noise in the area surrounding the airport and implement a difference-in-differences (DD) estimator that compares the change in prices between the pre- and the post-announcement periods for houses with different levels of aircraft noise exposure.

The results show that noise exposure is on average capitalized into housing prices at a rate of 0.3 percent, or $1,200, per decibel in the post-announcement period. The rate is larger the higher is the assessed market value, size and standard of the house. I also find that houses exposed to higher noise levels are more likely to sell after the announcement, consistent with a story of residential sorting following updated expectations about future noise levels. Compared to the results in the literature, these findings suggest that house values respond less to reductions in aircraft noise than to air quality improvements. A rough cost-benefit analysis illustrates that the implied appreciation of housing values falls short of the cost of sound insulating residential homes.

[1] The World Health Organization estimates that noise pollution is one of the largest environmental problems affecting health in the European Union, second only after air pollution (WHO 2011).

[2] Notable exceptions are Pope (2008), Boes and Nüesch (2011) and Almer, Boes and Nüesch (2017).

These results are relevant to the large body of work estimating the discount rate in house prices due to aircraft noise. Wadud's (2013) review of these studies finds capitalization rates from 0 to 2.3 percent and concluded after a meta-regression that a one decibel increase in aircraft noise leads to a fall in house prices by 0.5 percent on average. This is broadly consistent with previous literature reviews by Nelson (1980, 2004) although lower than the average value of 0.9-1.3 percent in the meta-review by Schipper et al. (1998). However, most of the examined studies are based on cross-sectional comparisons of house prices and noise levels and do not explicitly account for the potential endogeneity of noise exposure. Instead they rely on having included in the regression all factors that covary with noise levels and house prices.

In contrast, the research design employed in this study relies on the assumption that in the absence of the announcement, house prices would not have developed differently depending on noise exposure. The results are robust to several checks to assess this assumption, including placebo tests using dates prior to the announcement and allowing area-specific time trends. Thus, the study adds to the growing set of papers in environmental economics that combine hedonic methods and quasi-experimental research designs to measure capitalization effects.[3] The DD specification produces a capitalization rate that is below most of the other estimates in the literature.

The findings are also relevant to the literature on distributional implications of environmental policies. The larger capitalization rates for houses of higher value, standard and size implies that owners of these properties will benefit relatively more from noise abatement measures, at least in terms of this metric. The implied benefit of noise abatement for households in the highest quartile of the distribution of housing values is more than twice as large as for those in the lowest quartile. The result is in line with other work on distributional effects of environmental policy in general. These studies typically find that such policies are regressive, with higher-income groups receiving proportionally more of the benefits (Banzhaf, 2011; Fullerton 2011; Bento 2013).

Whether noise capitalization rates differ by property value also matters for policy analysists who seek to transfer valuations from one setting to other locations or time periods. The benefits of noise abatement measures could be very different if capitalization rates vary with property values in different regions of the world. Earlier summary studies have made contradictory findings on this topic. Nelson (2004) concluded that differences in house prices between studies did not impact the capitalization estimates, while Wadud (2013) found that capitalization rates increase with house prices. The results of this study support the latter finding and show that the responsiveness of the capitalization rate is relatively large, with an implied elasticity with respect to the property value of 2.

The rest of this study proceeds as follows. The next section gives a brief background on the

[3] Applications include air quality (Chay and Greenstone, 2005; Bui and Mayer, 2003), hazardous waste (Greenstone and Gallagher 2008), brownfield redevelopment (Haninger et al 2012), shale gas development (Muehlenbachs, Spiller and Timmins 2015) and power plants (Currie et al. 2015).

airport and the concession renewal. Section 3 details the data and summary statistics, section 4 discuss the identification strategy and section 5 presents the results. Section 6 offers interpretations of the estimates while section 7 concludes.

2 Background

Bromma Airport is located less than 10 kilometres from the city centre of Stockholm, Sweden. The airport covers some 135,000 square meters, began to operate in the 1930s and was the main airport in Stockholm until the opening of Arlanda Airport in the 1960s. In 2007, Bromma was the third-largest airport in Sweden with 32,000 take-offs and landings. As an artefact of the airport's early operation and the subsequent expansion of the city, there are residential areas located in close vicinity to the airport. Some 30,000 residents are exposed to aircraft noise above the EU-mandated threshold level of 55 decibels (Swedish Transport Agency 2007, 2014).

The airport is situated on land that belongs to the City of Stockholm and has since 1946 been operated by the central government (currently via a state-owned company) through a concession agreement with the city. The concession stipulates the conditions for operating the airport, including a cap on the number of annual take-offs and flight restrictions depending on aircraft weight, time of the day and day of the week.[4]

The existence of the airport has been subject to public debate for decades. Opponents of the airport voice concerns about having an airport operating close to residential areas and argue for alternative uses of the land. Proponents point to its contribution to accessibility and warns about a lack of flight capacity in the region should the airport close. There have been several attempts by political parties to stop the operation of the airport. In 1984, the City of Stockholm and the Swedish Government agreed to move the flight traffic from the airport at the end of 1991, but the plans were never realized due to political opposition. A 1996 report described the conditions for closing down the airport and proposed a shut-down by the year 2001 (Kommunikationsdepartementet 1996). This conclusion was supported by the ruling majority of the Stockholm City Council, the supreme decision-making body of the City of Stockholm. The development was prevented by the election of a new local government in 1998 who instead renewed the concession agreement up until 2011. In 2002, there was yet again a shift of power in the local government and the new ruling majority considered building a new airport in the south of Stockholm that would replace Bromma Airport.

After the Swedish local elections in September 2006, a centre-right coalition regained the majority of seats in the Stockholm City Council. One year later, on 21 September 2007, they suddenly an-

[4]During the period of study, the opening hours was 7 a.m. to 10 p.m. on weekdays, 9 a.m. to 5 p.m. on Saturdays and 10 a.m. to 8 p.m. on Sundays. The maximum number of take-offs was set to 65,000, of which scheduled flights could not exceed 35,000.

nounced that the city was renewing the concession agreement with the operator through year 2038.[5] The announcement of the renewal of the concession spurred strong reactions since negotiations between representatives from the ruling coalition and the airport operator had been conducted in great secrecy. The opposition even called it a "coup-like decision" (City of Stockholm 2008). None of the main Swedish daily newspapers reported on news related to the concession agreement until after 21 September.[6] The announcement was also accompanied by large price changes in the housing market. Figure 1 shows the average transaction price of houses within and outside the aircraft noise zone surrounding the airport. During the two quarters following the announcement, average prices fell drastically for houses within the noise zone.

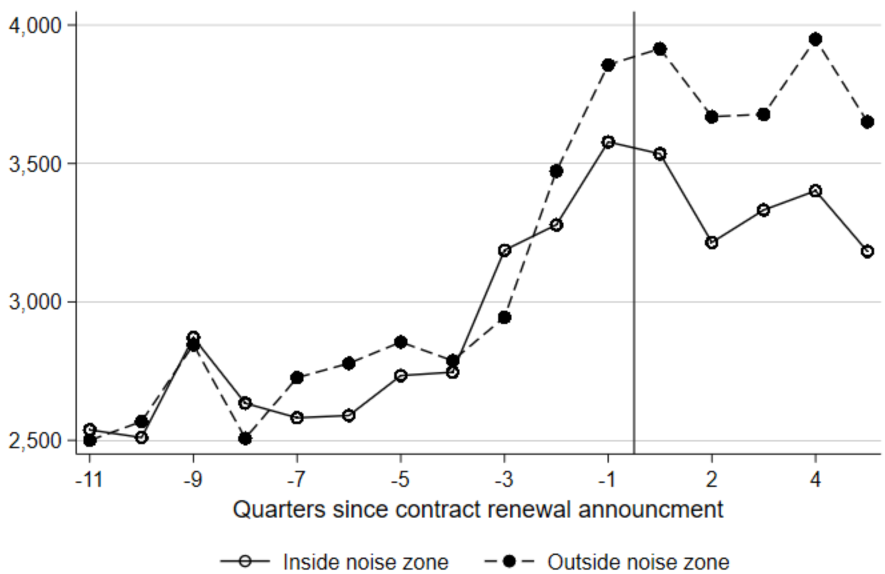

Figure 1: Mean quarterly house price (1000s SEK)

Notes: The figure shows the mean price in 1000s of SEK for houses located within and outside the noise zone. The vertical line indicates the time of the announcement of the contract renewal.

[5]The agreement entered into force when it was approved by the Stockholm City Council in March 2008. It raised the cap on annual take-offs to 40,000 and banned aircrafts with a noise emission exceeding 89 EPN dB (Effective Perceived Noise in decibels). Sunday opening hours were adjusted from between 10 a.m. and 8 p.m. to between 12 a.m and 10 p.m.

[6]Based on the search term "Bromma Airport" ("Bromma flygplats") in year 2007 in the newspaper archives of the National Library of Sweden.

3 Data Sources and Summary Statistics

3.1 Aircraft Noise

The information about local aircraft noise exposure comes from model-based noise data provided by a subsidiary of the state-owned airport operator in Sweden. The model produces georeferenced lines connecting points exposed the same level of aircraft noise omitted from Bromma Airport. The lines are combined to form noise contour segments, which are geographic areas with the same level of aircraft noise exposure. The model calculations follow the standard method set by the European Civil Aviation Conference and account for the level of flight traffic, flight routes, aircraft types and environmental factors such as typology and weather. It captures aircraft noise due to landings, take-offs and overflights at the airport but excludes ground level noise and other noise sources. The model measures outdoor noise levels four meters above ground and is based on flight traffic in 2005. Since traffic did not change substantially year-to-year, the noise levels in 2005 should be an adequate approximation to the conditions in the subsequent year.

The noise measure in the dataset is given in terms of the day-evening-night level, L_{den}, an indicator that aggregates aircraft noise events that occur during a 24-hour period into a single statistic.[7] It gives the steady sound level over the period that would give the same energy as the actual time-varying sound level. The indicator is constructed to add relatively more weight on noise events occurring in the evening and night compared to the day. Its unit is A-weighted decibel (dB), measured on a logarithmic scale. This means that a doubling of sound intensity roughly corresponds to an increase by 3 decibels. On the other hand, the nature of the human perception of sound means that a doubling of the perception of noise, or loudness, corresponds to an increase of 8-10 decibels. The aircraft noise data range between 50 and 70 decibels in increments of one.

3.2 Area Characteristics

The data on area characteristics are provided by the Swedish Tax Authority. The unit of these data are geographic segments delineated by the Swedish Tax Authority to capture how the location of a property affects its price. These areas follow a different segmentation than zip code areas and are predominantly based on geographical boundaries such as parks and roads or other natural boundaries.

The Swedish Tax Authority calculates a range of area-level variables that are used as a basis for property taxation. These include the size, assessed value and water/sewage quality of a standardized plot in each area and monetary adjustments for plots with attributes that deviates from the standard. The adjustments vary across areas to reflect differences in the monetary valuation of the attributes.

[7]Representative levels of noise events are a quiet suburb (50 dB), conversational speech at one meter (60 dB), freeway traffic at 15 meters (70 dB) and a Boeing 737 at two kilometers (97 dB).

Included are also the value of a house with standardized characteristics and adjustment factors showing how age and proximity to water changes the market value of the house. All variables are calculated based on housing transactions in 2004 and 2005, and all apart from the correction factor for water characteristics and water/sewer standard are given for three types of housing units (terraced, detached and linked house).

3.3 Housing Values

The housing transaction data come from a private data provider who collect the information from the Swedish Tax Authority and the National Land Survey of Sweden. In addition to the sales date and price (adjusted by the CPI to 2007 prices), the dataset contains information about the address, size of dwelling and lot area, type of housing unit (terraced, detached and linked house), age, proximity to water, type of grant agreement (registered ownership and site lease) and assessed value of the property [8] and a housing standard index based on the exterior, energy efficiency, kitchen, sanity and other interior characteristics.

I translate the addresses of the properties into coordinates using geocoding software which allows me to calculate travel distance and travel time between each house and the airport. Travel distance gives the number of kilometres it takes to go between the house and the airport by car while travel time gives the number of minutes it takes to drive the corresponding distance under normal traffic conditions. I also calculate the geographical distance between each house and the airport, i.e. the distance measured along the surface of the earth.

The coordinates are used to match the location of each house to the georeferenced aircraft noise data. All addresses that fall within a noise contour segment (i.e. exposed to decibel levels between 50-70) are coded as being part of the noise zone. Each house is also assigned a continuous measure of noise exposure based on its location. The noise exposure of houses in the noise zone ranges between 50-61 decibels, with the majority exposed to levels on the lower end of the interval. The housing data also contains an identifier for the area of each property which I use to match houses with the area characteristics.

I limit the analysis to non-zero transactions of single-family residential housing units in the municipalities of Stockholm and Jarfalla, which are the only ones that the airport noise zone is located within. I also restrict the analysis to cover the period 2005 to 2008 which leaves me enough time periods to estimate trends in the covariates and outcome of interest while avoiding confounding the estimated effect with housing market shocks due to the financial crisis in 2008-09. The original sample consists

[8] The market values are based on previous years' housing transactions. The market value of properties sold before 2006 is based on transactions in 2001-2002 while those sold after 2006 have a market value based on transactions in 2004-2005.

of 11,110 housing transactions of which I drop 119 where either the seller or the buyer is recorded as a tenant-owner association and 95 observations that lack information on all housing characteristics. This corresponds to 2% of the full sample. The final sample consists of 10,896 observations.

Table 1: Balancing test

	Living area	Index	Lot area	Detached	Linked	Terraced
Noise	0.004	0.016*	0.045	-0.001	-0.001	0.002
	(0.009)	(0.008)	(0.154)	(0.002)	(0.001)	(0.002)
Obs.	7,922	7,922	7,922	7,922	7,922	7,922
Clusters	231	231	231	231	231	231
Adj. R-sq.	.00013	.0034	.0002	.00039	.0017	.0029
Mean dep. var	11.8	28.7	55.6	0.59	0.12	0.29

Note: Dependent variable indicated in the column heading and mean of the dependent variable shown in the bottom row. Only pre-announcement observations are included. Standard errors in parenthesis are clustered at the area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 2: Balancing test

	Value	Travel dist.	Dist.	Travel time	Sthlm	Beach	Reg. own.
Noise	-0.001	-0.127***	-0.098***	-0.131***	0.003**	-0.001**	0.001*
	(0.001)	(0.013)	(0.010)	(0.016)	(0.001)	(0.000)	(0.000)
Obs.	7,922	7,922	7,922	7,922	7,922	7,922	7,922
Clusters	231	231	231	231	231	231	231
Adj. R-sq.	.0019	.069	.067	.088	.013	.0018	.003
Mean dep. var	14.3	13.5	8.55	18.8	0.85	0.032	0.86

Note: Dependent variable indicated in the column heading and mean of the dependent variable shown in the bottom row. Only pre-announcement observations are included. Standard errors in parenthesis are clustered at the area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

3.4 Summary Statistics

Descriptive statistics for the full sample are shown in table 3. The top panel shows the variables given at the house-level and the bottom panel presents the area characteristics. To investigate any pre-announcement differences among houses of different noise exposure I regress each housing characteristic on its noise level using transactions made before the announcement. This allows for a test for balance in levels of each characteristics in the pre-announcement periods. The estimated coefficients are shown in tables 1 and 2. Houses with higher noise exposure are unsurprisingly located closer to the airport but also tend to have registered ownership, lower probability of beach access and higher standard. The difference between houses outside the noise zone (and thus exposed to no aircraft noise) and those with the most noise exposure (61 dB) is approximately one standard point ($61 \times 0.016 = 1$), or about three percent of the mean housing standard in the sample.

Table 3: Summary statistics

	Mean	SD	Min	Max	Obs.
House-level variables					
log(Price)	14.7	0.86	11.3	17.3	10,896
Noise (dB)	5.20	15.7	0	61	10,896
log(Tax value)	14.4	0.36	13.3	16.0	10,896
Dwelling area (m^2)	118.5	36.4	26	545	10,896
Standard points (index)	28.8	4.26	10	48	10,896
Lot area (m^2)	556.2	370.9	0	15672	10,896
Detached house (%)	0.59	0.49	0	1	10,896
Linked house (%)	0.12	0.32	0	1	10,896
Terraced house (%)	0.29	0.46	0	1	10,896
Stockholm (%)	0.85	0.36	0	1	10,896
Travel distance (km)	13.4	7.31	2.13	116.1	10,896
Geodetic distance (km)	8.48	5.64	0.37	93.3	10,896
Travel time (mins)	18.7	6.69	4.80	109.8	10,896
Beach access (%)	0.033	0.18	0	1	10,896
Registered ownership (%)	0.86	0.35	0	1	10,896
Area-level variables					
Land size, detached house (m^2)	720.8	179.9	150	3000	10,896
Land size, linked house (m^2)	411.3	123.6	100	1400	10,896
Land size, terraced house (m^2)	246.4	77.1	100	600	10,896
Land value, detached house (1000s SEK)	1094.3	384.3	450	3000	10,896
Land value, linked house (1000s SEK)	902.4	328.6	400	2800	10,896
Land value, terraced house (1000s SEK)	787.7	313.4	350	2800	10,896
Land adj. value, detached house	459.2	207.0	60	1070	10,896
Land adj. value, linked house	627.8	266.6	130	2800	10,896
Land adj. value, terraced house	946.8	438.5	210	4670	10,896
Location factor	1.20	0.34	1	2.50	10,896
Water/sewer standard	1.00	0.064	1	3	10,896
Adj. value sewage, detached house (1000s SEK)	14.9	1.86	10	30	10,896
Adj. value sewage, linked house (1000s SEK)	13.5	1.41	10	30	10,896
Adj. value sewage, terraced house (1000s SEK)	11.7	0.93	10	26	10,896
House value, detached house	11.0	1.09	9	24	10,896
House value, linked house	10.5	0.85	9	24	10,896
House value, terraced house	10.3	0.78	8.50	24	10,896
Age impact, detached house	95.8	2.04	90	100	10,896
Age impact, linked house	95.2	1.81	90	100	10,896
Age impact, terraced house	95.0	1.75	90	100	10,896

Note: The summary statistics are reported for all houses.

4 Empirical Strategy

The first factor for identifying the capitalization of aircraft noise into housing prices is the spatial variation of noise omitted from the airport. The second is the announcement of the airport concession renewal made in September 2007 which was accompanied by large changes in housing prices in the noise zone.[9] The capitalization rate is estimated as the change in prices between the pre- and the post-announcement periods for houses with different levels of aircraft noise exposure. The estimation is implemented by running versions of the following regression over the period 2005-2008

$$\log P_{i,a,n,t} = \alpha Noise_i \times Post_t + \tau_t + \theta_n + \gamma X_{i,a} + \epsilon_{i,a,n,t} \tag{1}$$

where i indicates house, a is area, t is quarter, and n is noise level. The outcome of interest is the log of the house price, $Post_t$ is an indicator variable equal to one for all transactions in the quarters after the announcement of the concession renewal (i.e. from Q4 2007 and onwards).[10] $Noise_i$ is the decibel level of aircraft noise exposure of the house in transaction i. It is given by its 2005 value and therefore lacks the subscript t. The vector θ_n contains noise-level fixed effects that capture unobserved, time-invariant differences between houses of different noise levels and τ_t is a vector of quarter-by-year fixed effects that controls for overall trends in housing prices. X_{ia} includes the housing and area characteristics shown in table 3. Standard errors are clustered at the area level, i.e. the geographic segment defined by the Swedish Tax Authority.

The coefficient of interest is α, the estimated impact of aircraft noise on housing prices. It measures the additional change in the average house price growth between the pre- and post-announcement periods for each decibel of noise exposure. A negative coefficient means that prices decreased by more for houses exposed to higher noise levels. The main identifying assumption is that in the absence of the concession renewal announcement, the trend in the average log house price would not have differed depending on the level of noise exposure, conditional on all covariates. This assumption would be violated in the absence of parallel time trends and differences in compositional changes depending on noise exposure. Another concern is that home buyers anticipated the announcement of the continuing operation of the airport, so that the future path of noise levels were already capitalized into housing prices at the time of the announcement.

I run several robustness checks to assess these threats. I augment equation (1) to include area fixed effects which allows for highly localized price-level differences.[11] I report specifications in which

[9] I follow Kessel et al. (2018) who utilize the same house price shock to instrument for wealth in their analysis of consumption responses to wealth changes.

[10] Note that the announcement was made on 21 September 2007, nine days before the start of the fourth quarter. Dropping house transactions recorded between 21-30 September does not change the results.

[11] Twenty out of 236 area fixed effects are not identified due to no within-area variation in noise levels.

time trends are interacted by either area fixed effects or housing characteristics, thus allowing for different price trends along these sets of variables. I perform placebo regressions where I test for pre-announcement deviations in prices depending on noise exposure. I investigate the housing market dynamics by testing whether the announcement affected the sales probability and housing characteristics.

The identification strategy also relies on the assumption that there were no other events affecting the housing market that coincided with the announcement of the contract renewal. One source of concern is the replacement of a state-wide property tax with a property tax levied by the municipalities, which was put forward as a bill on 19 September 2007, two days before the announcement of the contract renewal. However, the policy was an explicit electoral promise of the centre-right coalition that won the 2006 national elections and was proposed in April 2007, why it already should have been capitalized into prices. In addition, differential impacts of the property tax abolishment would be picked up by the control for assessed property value since it determines the absolute value of the property tax for each house.

5 Results

5.1 Main results

I begin by showing visual evidence to motivate the subsequent regression analyses. I estimate equation (1) with noise exposure interacted with each of the quarter-by-year fixed effects (leaving the first quarter of 2005 as the reference). This allows for a judgement of the identifying assumption that in the absence of the concession renewal announcement, the trend in the average log house price would not have differed depending on the level of noise exposure. Figure 2 plots the estimated coefficients on the interaction terms along with their 95 percent confidence interval and table 14 in the appendix shows the full regression results. The post-announcement coefficients are stable around -0.3 to -0.5 percent and individually statistically significant at the 95 percent level in three out of five periods. Reassuringly, there are no statistically significant deviations of log prices depending on noise exposure in the pre-announcement periods.

Table 4 reports regression results based on different versions of equation (1). Column 1 presents the estimate from a regression with control variables excluded. The results show that compared to pre-announcement, the post-announcement reduction in prices was larger for houses with higher levels of noise exposure. The point estimate is statistically significant and imply that an additional decibel aircraft noise exposure reduces the house price by 0.32 percent on average. One concern with this estimate is that the differential price change between houses exposed to different noise levels also is

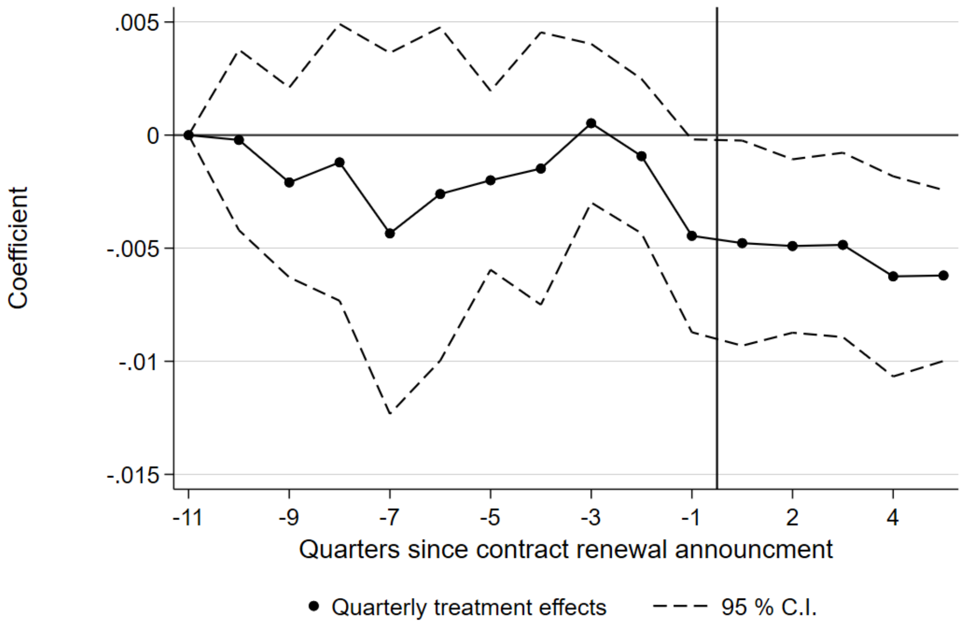

Figure 2: Quarterly effects

Notes: The figure presents coefficients and their 95% confidence interval from a regression of log house prices on quarterly dummies interacted with the level of noise exposure as well as controls for house- and area characteristics and noise-level fixed effects. The first quarter of 2005 is omitted and serve as reference. The vertical line marks the timing of the concession renewal announcement. The regression results are shown in table-form in table 14 in the appendix.

due to differences in other costs and benefits associated with a local airport. For instance, it might be that noise exposure is correlated with visual disamenities or air pollution from the airport and that the estimated capitalization rate also reflects these effects. To assess such concern, column 2 presents the result from a regression with the full set of controls for housing and area characteristics. These include the geographic distance to the airport, which proxies for factors like visual disamenities, and travel time and travel distance to the airport, which capture any accessibility effects. The inclusion of controls barely changes the estimate which supports the interpretation that it solely reflects the discount rate in house prices due to noise.

Columns 3 to 5 present results from alternative specifications that assess the underlying assumptions of the research design. Column 3 provides the results from a regression in which area fixed effects are added to equation (1), thus allowing for highly localized differences in log-prices. The identifying variation now comes from differential price changes for houses located within the same area but exposed to different levels of noise. The point estimate is largely unaffected and remains statistically significant. Column 4 reports the result from a regression where housing covariates are interacted with a linear time trend. The estimate of -0.35 percent is statistically significant which

Table 4: Difference-in-difference estimates of the effect of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.0033*	-0.0036**	-0.0029*	-0.0035*	-0.0018
	(0.0013)	(0.0012)	(0.0012)	(0.0014)	(0.0013)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Controls × trend				✓	
Area FE × trend					✓
Observations	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.41	0.42	0.42

Note: The table presents coefficient estimates from different versions of equation (1). See the descriptive statistics for the full list of covariates. All regressions include noise-level fixed effects and quarter-by-year fixed effects. Post is a dummy switched on after the third quarter in 2007. Standard errors in parenthesis are clustered at area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

mitigate concerns that the results are driven by differential price trends due to housing attributes. In column 5 the time trend in house prices is allowed to develop differently between areas by interacting a linear time trend with the area fixed effects. The estimate is closer to zero compare to the others but not statistically significant at conventional levels and its confidence interval overlaps the other estimates.[12]

Taken together, these results show that a one-decibel increase in aircraft noise levels leads to a reduction in house prices by 0.3 percent on average (this is the mean of the estimates in table 4 weighted by the inverse of their standard errors). The estimate is on the lower end of the range of 0-2.3 percent and below the mean of 0.5 percent in the hedonic literature on aircraft noise pollution (Wadud 2013). Given the pre-announcement average house price in the noise zone, this translates into a nominal decrease of $1,200 per decibel.

5.2 Heterogeneous Effects

To explore any heterogeneity in capitalization rates I include an additional interaction term between $Noise_i \times Post_t$ and the demeaned value of a particular housing characteristics (assessed market value, dwelling area, lot area or standard). The results from the regressions are presented in table 5. The first row shows the average capitalization rate evaluated at the (noise zone) mean of each housing

[12]Table 15 in the appendix reproduces the result in table 4 but uses standard errors clustered at areas that have been aggregated into 39 neighbourhoods. The pattern of statistical significance between the specifications remains virtually the same.

characteristic. The other coefficients show the additional rate for each unit of the corresponding characteristic. All but one estimate are statistically significant from zero.

Table 5: Heterogeneous effects of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)
Noise × Post	-0.0025*	-0.0030**	-0.0030*	-0.0029*
	(0.0012)	(0.0011)	(0.0012)	(0.0012)
Noise × Post				
× Demeaned tax value (100'000s SEK)	-0.0003**			
	(0.0001)			
Noise × Post				
× Demeaned dwelling area (10m^2)		-0.0005*		
		(0.0002)		
Noise × Post				
× Demeaned lot area (10 m^2)			-0.0000	
			(0.0000)	
Noise × Post				
× Demeaned standard index				-0.0002*
				(0.0001)
Controls	✓	✓	✓	✓
Area FE	✓	✓	✓	✓
Obs.	10,896	10,896	10,896	10,896
Clusters	236	236	236	236
Adj. R^2	0.41	0.40	0.40	0.40
Mean dep. var	17.2	12	57.4	29.6

Note: The table presents coefficient estimates from four separate regressions where the variable of interest, Noise × Post, has been interacted with the demeaned value of the housing characteristic indicated in column one. The dependent variable in all regressions is the log of house price. All regressions include controls for house characteristics, except for the characteristic indicated in the column heading. Standard errors in parenthesis are clustered at the area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The heterogeneous effect in terms of assessed market value is shown in column 1. The estimate in the top row suggest that the noise discount is 0.25 percent at the mean level of assessed value in the noise zone (1.7 million SEK) and is increasing by 0.03 percentage points for each additional 100,000 SEK in market value. This translates into an elasticity of noise discount with respect to property prices of 2.[13]As another illustration of this magnitude, the interquartile range for market value of houses in the noise zone is 660,000 SEK, which means that the noise discount for houses in the top quartile is more than twice the size of that in the bottom quartile (0.15 and 0.32 percent respectively).

[13]Increasing property prices by one percent (17,000 SEK) raises the capitalization rate by $0.17 * 0.0003 = 0.00051$, which is two percent of the sample mean ($0.00051/0.0025 = 0.02$).

The estimates in column 2 and 4 show that the capitalization rate increases by 0.05 percentage points for every ten square meter increase in dwelling area and by 0.02 for each unit increase in the housing standard index. The rate for houses in the top quartile is almost twice the size of those in the bottom quartile in the dwelling area distribution (0.2 and 0.37 percent) and some 30 percent larger in the distribution of housing standard (0.25 and 0.34 percent). Appendix tables 8 to 11 present the regression results using various specification. The point estimates are largely the same in these regressions although the degree of precision varies.

The findings imply that noise reduction measures are capitalized at a higher rate into houses of higher market value, size and standard. Owners of these houses benefit relatively more by these measures, at least in terms of this metric, which highlights the distributional consequences of noise abatement measures. The differences are non-negligible, in particular across assessed values and size.

5.3 Housing Market Dynamics

To better understand the estimated capitalization rates, I investigate the dynamics in the housing market. I first test whether noise exposure affects the post-announcement probability of being sold by creating a quarterly panel for each house in the sample and estimate the sales-probability model

$$Sold_{it} = \gamma Noise_i \times Post_t + \tau_t + \delta_i + \epsilon_{it} \tag{2}$$

where the probability of house i being sold in quarter t is given by house and quarterly fixed effects and the interaction $Noise_i \times Post_t$. The results are reported in appendix table 16 and shows that the probability of a houses being sold after the announcement increased by 0.00027 (standard error 0.00009) percentage points for each decibel of noise exposure. Evaluated at the sample mean, this effect corresponds to a 3.7 percent change in the sales probability for each decibel noise exposure.

To further explore the housing market dynamics, I investigate whether houses sold in the post-announcement period differed systematically from those sold before depending on the level of noise exposure. If this is the case, the differential price change for houses with different noise levels might also reflect quality differences. I implement the test by estimate equation (1) with housing characteristics as dependent variables. The coefficient on the interaction $Noise_i \times Post_t$ now tests for post-announcement differences in the corresponding characteristic depending on the level of noise exposure. The results are shown in table 6 and 7. Reassuringly, all point estimates are statistically insignificant and small in magnitude relative to the mean of the dependent variables (shown in the bottom row of each column).

These two exercises together suggest that the announcement affected the timing of sales and that the composition of sales in the post-announcement period shifted to houses of higher noise exposure.

But there were no substantial changes in the characteristics of the housing units being sold, apart from their noise levels.

Table 6: Test for compositional changes

	Living area	Index	Lot area	Detached	Linked	Terraced
Noise × Post	-0.006	-0.001	-0.022	-0.000	0.000	-0.000
	(0.004)	(0.007)	(0.026)	(0.000)	(0.000)	(0.000)
Controls	✓	✓	✓	✓	✓	✓
Obs.	10,896	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236	236
Mean dep. var	12.0	29.4	57.4	0.55	0.075	0.38

Note: The table presents results from regressions based on equation (1) with the dependent variable indicated in the column heading. The regressors are the noise level, noise-level fixed effects and controls for area and housing characteristics, except for the one used as dependent variable. Standard errors in parenthesis are clustered at area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 7: Test for compositional changes

	Value	Travel dist.	Dist.	Travel time	Sthlm	Beach	Reg. own.
Noise × Post	0.000	0.001	-0.001	0.001	-0.000	-0.000	-0.000
	(0.000)	(0.001)	(0.001)	(0.002)	(0.000)	(0.000)	(0.000)
Controls	✓	✓	✓	✓	✓		✓
Obs.	10,896	10,896	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236	236	236
Mean dep. var	14.3	7.45	3.90	12.6	0.98	0.0081	0.92

Note: The table presents results from regressions based on equation (1) with the dependent variable indicated in the column heading. The regressors are the noise level, noise-level fixed effects and controls for area and housing characteristics, except for the one used as dependent variable. Standard errors in parenthesis are clustered at area level. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The finding that aircraft noise exposure led to reduced residential tenure in houses of higher noise exposure is consistent with previous findings documenting a relationship between residential turnover and local amenities, e.g., in the context of lead-remediation (Billings and Schnepel 2017) and air quality (Lang 2015). The results of this study show that residential turnover also respond to new information about future levels of local amenities. It is also noticeable that the estimated housing price differential due to aircraft noise coincided with increased turnover frequency of houses exposed to more aircraft noise. Alternatively put, existing residents are less likely to stay in a home if it is subject to higher levels of noise exposure. One explanation for this observation is residential sorting based on preferences for noise in response to updated expectations of future noise levels. This interpretation is supported by a number of studies finding empirical support for preference-based sorting, including applications to air quality (Banzaf and Walsh 2008) and school quality (Cellini et al. 2010). Unfortunately, direct test of preference-based sorting along homebuyer characteristics is not possible with the data set at hand.

5.4 Additional Robustness Tests

This section contains additional test to assess the robustness of the results. To further investigate the parallel trends assumption, I run regressions on equation (1) using only transactions in the pre-announcement period. I divide these transactions into segments of consecutive quarters of various length. For each segment, the indicator $Post_t$ equals one for the transactions in the second half. The coefficient on the interaction between noise exposure and $Post_t$ now tests if there were any changes in trends in the log house price depending on noise exposure at a certain quarter in the pre-announcement period. Varying the number of quarters in each segment and the starting quarter for each segment produces several of these tests. Table 12 and 13 in the appendix shows the results for segments consisting of six, eight and ten quarters. None of the coefficients are statistically significant at conventional levels and the point estimates are low. These results all support the hypothesis that the trend in housing prices did not differ depending on noise exposure in the pre-announcement period.

One additional issue is that the estimated effect can pick up general equilibrium mechanisms where changes in house values in one area alters the demand and supply of those properties and effectively the prices in the whole local housing market (Anenberg and Kung 2014). To address this, I estimate the regression models in table 4 using only two of the post-announcement quarters. The results are shown in table 17 in the appendix. The estimated effect is relatively unaffected and range between -0.3 and -0.2 percent, but the degree of precision varies, perhaps due to the reduction in sample size.

6 Interpretation

The results show that noise is on average capitalized into housing prices at a rate of 0.3 percent per decibel. Given the pre-announcement average house price in the noise zone, this translates into a nominal decrease of $1,200 per decibel. One way to interpret the estimated effect is to compare it to the cost of reducing noise exposure levels of houses. Previous large-scale investments in sound insulation of houses in Scandinavian countries amounted to $35,000 per insulated house and is estimated to have achieved a seven-decibel reduction of indoor noise levels on average (Admundsen 2006). This translates into a project cost of $5,000 per decibel and household, well above the estimate capitalization rate of $1,200. Granted, there is uncertainty in the estimated figures from such projects and cost-effectiveness will differ between settings. But considering that the capitalization rate covers the disutility of both indoor and outdoor noise, while sound insulation only reduces indoor levels, noise reductions would have to be sizeable for such projects to lead to house price appreciations at par with the costs.

It is also meaningful to contrast the responsiveness of house prices to noise with that to other environmental externalities. Particularly suitable for comparison is air pollution, as it has been subject to a great deal of research and is deemed just a pervasive health problem in urban areas as noise (WHO 2011). Since a ten-decibel increase roughly corresponds to a doubling of perceived noise levels, the implied elasticity of housing values with respect to aircraft noise is -0.03 (increasing perceived noise levels by 100 percent reduces housing values by 3 percent).[14]The elasticity of housing values with respect to particulate concentration range between -0.04 to -0.07 in the meta-analysis of Smith and Huang (1995) and reach magnitudes of -0.2 to -0.6 in more recent studies (Chay and Greenstone 2005; Bayer, Keohane and Timmins 2009; Bento, Freedman and Lang 2015). This comparison suggest that house prices respond less to noise reductions than to proportionate improvements in air quality.

The impact of aircraft noise on housing prices thus appears to be small relative to the costs of sound proofing houses and to the impact of air quality. This is perhaps surprising given that noise can be considered a readily perceptible disamenity. One reason for this finding is that home buyers may not be fully aware of noise exposure levels. Although the airport had been a widely debated topic for decades and noise contour maps were published regularly, house buyers might not have paid attention or collect sufficient information about noise exposure before their purchase.[15] Another possible explanation is that the announcement led to updated expectations about the future noise levels in the noise zone and that people with low valuation of noise located to houses with higher noise levels in the post-announcement period. The higher rate of residential turnover in houses of higher noise exposure after the announcement is suggestive of this. [16]

Finally, it is important to underline that the housing price impact is an incomplete measure of the welfare consequences of noise reductions. It reflects the household's disutility of noise, stemming from present and future annoyance for household members, but is not capturing the full welfare effects. For instance, unless households are fully informed about the health impacts of noise, the measure is unlikely to capture the cost due to e.g. health services and lost productivity that long-term noise exposure can lead to (WHO 2011). The measure also excludes the cost of any defensive investments against noise exposure that households make, such as soundproofing windows and walls.

[14]An alternative calculation would be to use the three-decibel increase that corresponds to doubling the *sound intensity*, in which case the elasticity is -0.01 (increasing sound intensity by 100 percent leads to a fall in housing values by $0.3 \times 3 = 1$ percent). The main point of the analysis is unaffected by such change.

[15]Pope (2008) shows that airport noise disclosures reduced the values of the surrounding properties, suggesting that buyers initially were less than fully informed.

[16]Evidence of residential relocation due to environmental changes is studied in e.g., Banzhaf and Walsh (2005) and Cameron and McConnaha (2005).

7 Conclusion

This study has estimated the cost of aircraft noise by measuring its capitalization into housing prices. The identification strategy has utilized spatial variation in noise exposure and temporal variation in housing prices induced by the announcement of a renewal of a concession agreement for a local airport. The results show that a one decibel increase in aircraft noise exposure leads to a decrease in housing values of 0.3 percent or $1,200 on average. The capitalization rate is larger for houses of higher value, standard and size. I also find that after the announcement, houses exposed to higher noise levels are more likely to sell which is consistent with residential sorting following updated expectations about future noise levels. Compared to the results in the literature, these findings suggest that house values respond less to reductions in aircraft noise than to air quality improvements. A rough cost-benefit analysis illustrates that the implied appreciation of housing values falls short of the cost of sound insulating residential homes.

The findings imply that noise abatement measures provide benefits that are unevenly distributed. Owners of houses of higher value, size and standard will benefit relatively more from these measures. Still, there remain unexplored questions that should be investigated further to fully understand the cost of aircraft noise. The degree to which housing markets capitalize health risks of traffic noise is not yet well-understood (see Davis (2004) and Currie et al. (2015) for hedonic applications related to environmental risk) and neither are differences in capitalization rates due to defensive investments in noise insulation.

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Appendix: Tables

A: Heterogeneous Effects

Table 8: Heterogeneous effects of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.00455**	-0.00324**	-0.00254*	-0.00335*	-0.00140
	(0.00144)	(0.00114)	(0.00117)	(0.00141)	(0.00122)
Noise × Post × Demeaned tax value (100'000s SEK)	0.00078***	-0.00025*	-0.00026**	-0.00012	-0.00018
	(0.00008)	(0.00010)	(0.00009)	(0.00012)	(0.00011)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Area × trend					✓
Controls × trend				✓	
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.41	0.42	0.42
Mean dep. var	17.2	17.2	17.2	17.2	17.2

Note: Standard errors clustered at value area in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 9: Heterogeneous effects of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.00327*	-0.00363**	-0.00298**	-0.00354*	-0.00172
	(0.00138)	(0.00114)	(0.00114)	(0.00140)	(0.00133)
Noise × Post × Demeaned dwelling area (10m^2)	0.00061***	-0.00039**	-0.00052*	-0.00025	-0.00031
	(0.00013)	(0.00014)	(0.00020)	(0.00019)	(0.00016)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Area × trend					✓
Controls × trend				✓	
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.40	0.42	0.42
Mean dep. var	12	12	12	12	12

Note: Standard errors clustered at value area in parentheses.
* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 10: Heterogeneous effects of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.00334*	-0.00361**	-0.00297*	-0.00354*	-0.00168
	(0.00144)	(0.00123)	(0.00122)	(0.00140)	(0.00133)
Noise × Post					
× Demeaned lot area (10 m^2)	0.00008***	-0.00003**	-0.00003	0.00000	-0.00002
	(0.00002)	(0.00001)	(0.00002)	(0.00002)	(0.00001)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Area × trend					✓
Controls × trend				✓	
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.40	0.42	0.42
Mean dep. var	57.4	57.4	57.4	57.4	57.4

Note: Standard errors clustered at value area in parentheses.

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

Table 11: Heterogeneous effects of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.00341**	-0.00358**	-0.00292*	-0.00353*	-0.00175
	(0.00131)	(0.00117)	(0.00118)	(0.00140)	(0.00131)
Noise × Post					
× Demeaned standard index	0.00029**	-0.00011	-0.00016*	-0.00005	-0.00007
	(0.00009)	(0.00007)	(0.00007)	(0.00008)	(0.00007)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Area × trend					✓
Controls × trend				✓	
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.40	0.42	0.42
Mean dep. var	29.6	29.6	29.6	29.6	29.6

Note: Standard errors clustered at value area in parentheses.

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

B: Placebo tests

Table 12: Rolling-window placebo tests

	(1)	(2)	(3)	(4)	(5)	(6)
Noise × Post	-0.0005	-0.0018	-0.0006	0.0007	0.0016	0.0005
	(0.0015)	(0.0013)	(0.0019)	(0.0026)	(0.0027)	(0.0013)
Area FE	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Obs.	4,358	4,520	4,541	4,356	4,327	4,356
Clusters	209	217	220	216	214	214
Adj. R^2	0.44	0.41	0.37	0.37	0.35	0.35
Window	6	6	6	6	6	6

Note: The table present regression result based on equation (1) using only pre-announcement observations. The variable of interest is the interaction between noise exposure and an indicator Post which equals one for the observations in the second half in the sample and equals 0 otherwise. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 13: Rolling-window placebo tests

	(1)	(2)	(3)	(4)	(5)	(6)
Noise × Post	-0.0016	-0.0002	0.0006	0.0002	0.0000	-0.0001
	(0.0011)	(0.0016)	(0.0023)	(0.0021)	(0.0013)	(0.0020)
Area FE	✓	✓	✓	✓	✓	✓
Controls	✓	✓	✓	✓	✓	✓
Obs.	5,975	5,980	5,884	5,715	7,318	7,339
Clusters	223	224	224	225	226	231
Adj. R^2	0.40	0.38	0.37	0.38	0.39	0.38
Window	8	8	8	8	10	10

Note: The table present regression result based on equation (1) using only pre-announcement observations. The variable of interest is the interaction between noise exposure and an indicator Post which equals one for the observations in the second half in the sample and equals 0 otherwise. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Table 14: Placebo test

	(1)	(2)	(3)	(4)	(5)
Treatment-10	-0.0005	-0.0002	0.0003	-0.0001	0.0009
	(0.0023)	(0.0020)	(0.0019)	(0.0018)	(0.0022)
Treatment-9	-0.0021	-0.0021	-0.0010	-0.0014	0.0000
	(0.0023)	(0.0021)	(0.0021)	(0.0021)	(0.0024)
Treatment-8	-0.0004	-0.0012	0.0005	-0.0004	0.0021
	(0.0031)	(0.0031)	(0.0027)	(0.0026)	(0.0029)
Treatment-7	-0.0040	-0.0043	-0.0040	-0.0049	-0.0022
	(0.0043)	(0.0041)	(0.0038)	(0.0038)	(0.0043)
Treatment-6	-0.0035	-0.0026	-0.0016	-0.0026	0.0004
	(0.0036)	(0.0037)	(0.0034)	(0.0034)	(0.0037)
Treatment-5	-0.0031	-0.0020	-0.0009	-0.0020	0.0014
	(0.0024)	(0.0020)	(0.0015)	(0.0017)	(0.0021)
Treatment-4	-0.0018	-0.0015	-0.0011	-0.0024	0.0014
	(0.0035)	(0.0031)	(0.0029)	(0.0030)	(0.0030)
Treatment-3	0.0004	0.0005	0.0023	0.0011	0.0051*
	(0.0023)	(0.0018)	(0.0015)	(0.0018)	(0.0021)
Treatment-2	-0.0021	-0.0009	-0.0001	-0.0014	0.0032
	(0.0023)	(0.0017)	(0.0016)	(0.0017)	(0.0023)
Treatment-1	-0.0038	-0.0045*	-0.0039*	-0.0052*	-0.0003
	(0.0026)	(0.0022)	(0.0019)	(0.0021)	(0.0029)
Treatment	-0.0049	-0.0048*	-0.0035	-0.0049*	0.0001
	(0.0026)	(0.0023)	(0.0020)	(0.0023)	(0.0029)
Treatment+1	-0.0048*	-0.0049*	-0.0028	-0.0043	0.0007
	(0.0023)	(0.0019)	(0.0019)	(0.0022)	(0.0029)
Treatment+2	-0.0050*	-0.0049*	-0.0036	-0.0055*	0.0003
	(0.0024)	(0.0021)	(0.0020)	(0.0022)	(0.0032)
Treatment+3	-0.0058*	-0.0062**	-0.0043*	-0.0052*	-0.0004
	(0.0025)	(0.0022)	(0.0021)	(0.0024)	(0.0035)
Treatment+4	-0.0060*	-0.0062**	-0.0046*	-0.0056*	0.0003
	(0.0026)	(0.0019)	(0.0021)	(0.0024)	(0.0033)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Controls × trend				✓	
Area FE × trend					✓
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	236	236	236	236	236
Adj. R^2	0.08	0.33	0.41	0.42	0.42

Note: The table present coefficient estimate of the interaction of noise exposure and a quarterly time dummy. The first quarter of 2005 is omitted. Standard errors in parenthesis are clustered by value area. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

C: Clustering

Table 15: Difference-in-difference estimates of the effect of aircraft noise on log housing prices

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.0033*	-0.0036*	-0.0029*	-0.0016	-0.0018
	(0.0014)	(0.0013)	(0.0013)	(0.0015)	(0.0013)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Controls × trend				✓	
Area FE × trend					✓
Obs.	10,896	10,896	10,896	10,896	10,896
Clusters	39	39	39	39	39
Adj. R^2	0.08	0.33	0.41	0.42	0.42

Note: The table presents coefficient estimates from different versions of equation (1). See the descriptive statistics for the full list of covariates. Post is a dummy switched on after the third quarter in 2007. Standard errors in parenthesis are clustered at areas aggregated into 39 neighbourhoods. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

D: Sale-probability Model

Table 16: Sale-probability model

	(1)
Noise × Post	0.00027**
	(0.00009)
House FE	✓
Quarter FE	✓
Obs.	158,080
No. houses	9,880
Mean sale pr.	0.0072

Note: The table present regression result based on equation (2). Standard errors in parenthesis are clustered by value area. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

E:Additional robustness tests

Table 17: Restricted time period

	(1)	(2)	(3)	(4)	(5)
Noise × Post	-0.0029*	-0.0032*	-0.0024	-0.0028	-0.0020
	(0.0014)	(0.0013)	(0.0013)	(0.0016)	(0.0013)
Controls		✓	✓	✓	✓
Area FE			✓	✓	✓
Controls × trend				✓	
Area FE × trend					✓
Obs.	9,135	9,135	9,135	9,135	9,135
Clusters	234	234	234	234	234
Adj. R^2	0.06	0.31	0.40	0.41	0.41

Note: The table presents coefficient estimates from different versions of equation (1). See the descriptive statistics for the full list of covariates. Post is a dummy switched on after the third quarter in 2007. Post-announcement period is restricted to two quarters. Standard errors in parenthesis are clustered by value area. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Appendix A2: The Hedonic Method

The association between housing prices and environmental goods has been studied for decades in economics.[17] The hedonic model by Rosen (1974) provides a formal economic interpretation of the relationship and is widely used to infer the implicit price of an amenity for which there exists no market.

The model describes the equilibrium in a market for a differentiated product whose price is a function of its characteristics. In the case of housing, the price may depend on the physical attributes of the property, neighbourhood attributes and environmental (dis)amenities. The partial derivate of the house price with respect to some characteristic gives the marginal price of that characteristic implicit in the price of the house, holding all other attributes constant. This is referred to as the slope of the hedonic price function and has been one of the main parameters of interest in the applied hedonic literature.

The importance of the slope of the price function stems from its interpretation in the hedonic model. The model describes how the price function is defined by the equilibrium interaction between buyers and sellers. Buyers optimize by selecting the house where their marginal willingness to pay (WTP) for each characteristic is equal to the slope of the hedonic price function.[18] Sellers maximize profits by acting so that their marginal cost of supplying each characteristic is equal to its hedonic price. In other words, at each point of the hedonic price function, the marginal cost of a housing characteristic is equal to a consumer's marginal WTP for it. Since the gradient of the hedonic price function equals the marginal WTP for an incremental change in an amenity, it can be used as a

[17] See e.g., Riedker and Henning (1967) and Freeman (1974).

[18] Formally, they set the slope of the price function equal to their marginal rate of substitution between each characteristic and a composite good, which is how WTP is defined in this model.

welfare measure. There is a large body of hedonic price studies that regress house prices on housing attributes and environmental amenities. The coefficient on the amenity of interest is the estimate of the slope of the hedonic price function with respect to that amenity ¬¬and thus the marginal WTP for it.

However, there are several problems to address when applying a hedonic regression model. With cross-sectional data, the marginal WTP implied by the hedonic gradient at the level of the amenity chosen by a house buyer represents only one point on her marginal WTP function (Brown and Rosen 1982; Epple 1987; Bartik 1987). Estimating marginal WTP functions for individuals or taste-types is very difficult as it is impossible to observe more than one house choice made by an individual under a single set of prices (Ekeland et al. 2004; Bajari and Timmins 2012). The applied hedonic literature has rarely estimated heterogeneous MWTP functions but instead made the strong assumption that consumer preferences are homogenous and therefore represented by the price function itself. Under this assumption, the estimated slope of the price function equals the constant marginal WTP in the population.

Another issue is to obtain consistent estimates of the hedonic gradient. This exercise is made difficult by the risk of failing to account for all factors that covary with both housing prices and the amenity of interest and household sorting (Bartik 1987; Epple 1987). Estimates of the housing price-noise level gradient are inconsistent if determinants of housing prices and noise levels are omitted from the regression. Several studies indeed find that conventional regression analysis gives unreliable estimates of the hedonic price schedule gradient (Chay and Greenstone 2005, Bayer, Keohane, Timmins 2009; Deschenes and Greenstone 2007). Household sorting across locations based on preferences poses a problem when estimating population-wide parameters. Ideally, one would randomize households' location and use their relocation to estimate their trade-off between noise and housing price. In absence of such randomization one would expect households to sort across locations based partly on preferences for noise pollution so that those with relatively low valuation of traffic noise locate to areas with higher exposure (Klaiber and Smith 2013). The estimated parameter of interest for this group may therefore be an inadequate representation for the population at large.

A large body of hedonic studies has tried to overcome the endogeneity and sorting issues by using quasi-experimental research designs. This includes applications dealing with aircraft noise (Pope 2008; Boes and Nüesch 2011 and Almer, Boes and Nüesch 2017), air quality (Chay and Greenstone, 2005; Bui and Mayer, 2003), hazardous waste (Greenstone and Gallagher 2008), brownfield redevelopment (Haninger et al 2012), shale gas development (Muehlenbachs, Spiller and Timmins 2015) and power plants (Currie et al. 2015). These studies typically utilize temporal variation to estimate capitalization effects and the implied marginal WTP. However, interpreting the rate at which environmental amenities are capitalized into housing values as a welfare measure therefore requires caution. Kuminoff and Pope (2014) highlight that the capitalization rate is not necessarily the same as the marginal WTP in the hedonic model if the price function adjusts over time. Research designs that use temporal price variation will provide an inaccurate description of the hedonic gradient (and preferences) if changes in amenities, preferences, wealth or technology causes the function to shift.

In other words, while a consistent estimate of the capitalization rate does provide insights into the cost of aircraft noise, interpreting it as households' marginal WTP for noise reductions requires the assumptions of i) homogenous preferences with respect to noise exposure and ii) a constant hedonic price function over the period of study.