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Quasi-experimental evidence on the effect of aircraft noise on apartment rents

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ABSTRACT

Inferring the implicit price of an environmental good hinges on *ceteris paribus* conditions that are often hard to justify. This paper uses an unexpected change in flight regulations as source of exogenous variation and identifies aircraft noise effects from price adjustments in the market for rental apartments. Controlling for spatial and apartment heterogeneity, we find that aircraft noise reduces apartment rents by about 0.5% per decibel. Our results indicate (i) that noise discounts are overestimated in cross-sectional studies because aircraft noise tends to be negatively correlated with omitted neighborhood and housing amenities and (ii) that noise effects are unlikely to be constant over the entire noise range.

1. Introduction

Since there is no explicit market for environmental goods, revealed-preference methods have often been used to derive an economic value. Most prominently, the hedonic approach of Rosen (1974) employs transaction data to infer an implicit price based on the idea that utility associated with the consumption of a composite product like housing is determined by the utility associated with its constituent parts. Conventionally, the hedonic method requires the regression of prices on the considered environmental good and all other attributes of the property (including structural and neighborhood characteristics) using a cross-section of housing data (overviews on cross-sectional studies are provided, e.g., by Smith and Huang (1995) and Nelson (2004)).

Recently, there have been increasing concerns about the validity of cross-sectional hedonic studies. Since unobserved neighborhood characteristics tend to be correlated with housing prices and the environmental good of interest, cross-sectional estimates are likely to suffer from omitted variable bias (e.g., Chay and Greenstone, 2005; Parmeter and Pope, 2009). As a result, quasi-experimental tests have become a popular tool in the hedonic literature (Greenstone and Gayer, 2009), and have been successfully employed to measure the capitalization of crime (Linden and Rockoff, 2008), school quality (Figlio and Lucas, 2004), air pollution (Chay and Greenstone, 2005), health risk (Davis, 2004), rail access (Gibbons and Machin, 2005), hazardous waste and toxic releases (Greenstone and Gallagher, 2008), or power plants (Davis, in press). Unlike in randomized field experiments, individuals are usually not randomly exposed to the environmental variable of interest, even in a quasi-experimental setup. In order to reduce potential selection bias, it is therefore important to control for time-varying observable confounders and for unobserved spatial and apartment heterogeneity (Greenstone and Gayer, 2009).

This paper is the first to combine a quasi-experiment with a repeat-rent model to study the effect of aircraft noise on rental rates. Repeat-sales or repeat-rent approaches have the advantage that they remove bias from unobserved apartment and neighborhood characteristics that remain unchanged over time (e.g., Case and Shiller, 1989; McMillen, 2003). In order to identify aircraft noise

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effects we use a change in flight regulations at Zurich airport that created variation in noise we argue to be exogenous conditional on apartment fixed effects and time-varying controls.

In April 2003, the German government issued a binding decree that prohibited landings from the north in the early morning and the late evening to protect German communities located close to the Swiss border from "Swiss" aircraft noise. In May 2003, the Swiss *Federal Office of Civil Aviation* allowed landings from the south, which had previously been prohibited. The new flight regime, enforced on October 30, 2003, stated that all aircraft landing in the early morning should approach from the south instead of from the north. The new flight regime serves as a quasi-experiment because (i) it considerably changed the levels of noise pollution around Zurich airport at a discrete point in time and (ii) it was largely unexpected.

A text analysis of articles published in several quality newspapers and weekly magazines, as well as reports from press agencies in Switzerland reveals no reference to the new flight regime before March 2003 (Fig. 1), and thus it is very unlikely that landlords or tenants could have anticipated it. Although one might argue that the existing runways would have allowed landings from the south, the airport's operating regulations (dated May 31, 2001 and still legally valid in April 2003) did not permit any such landings. We therefore deem it reasonable to interpret the change in flight regulations as a quasi-experiment. This allows us to extract causal information from differences in apartment rents before and after the intervention (see also Parmeter and Pope, 2009).

Since there is no *a priori* reason why the effect of aircraft noise on apartment rents should be constant, we specify a flexible generalized additive model where the unknown noise function is estimated semi-parametrically using splines. Our results indicate that a linearization of noise effects is justified only for medium noise levels, with significant deviations from linearity for high and low noise values. Based on these results, we conduct a difference-in-differences (DID) analysis which suggests that rents of apartments affected by additional aircraft noise decreased by about 3.5% due to the new flight regulation. Taking advantage of our detailed continuous noise data, we find a corresponding noise discount of about 0.5% per decibel, controlling for spatial and apartment heterogeneity. When estimating pooled cross-sectional models, we find considerably higher noise discounts (about twice as large).

Previous research on quasi-experimental aircraft noise effects has focused on American airports, where noise measures are only available in noise contour bands above 65 and/or above 70 decibels. Most notably, Pope (2008) uses the introduction of a mandatory airport noise disclosure, whereas McMillen (2004) and Cohen and Coughlin (2009) use changes in noise contour bands due to airport expansions and the technological progress of aircraft. This paper, however, deploys continuous and longitudinal noise data on a 100 m-by-100 m square lattice, which enables us to estimate detailed noise discounts *per decibel*.

The paper proceeds as follows. In the next section, we describe the institutional framework and provide a chronological order of events related to the introduction of the new flight regime. In Section 3, we describe the housing and noise data, and how we matched both data sources. Section 4 explains the identification strategy and presents the results. Section 5 concludes.

2. Changes in flight pattern around Zurich airport

Zurich airport is the largest international flight gateway in Switzerland. It operates about 260,000 take-offs and landings per year on three different runways. Fig. 2 provides an overview of the airport. The relative frequencies indicate the distribution of incoming and outgoing aircraft by flight direction in 2007.

Until 2002, over 90% of all aircraft were approaching from the north, more precisely from the northwest on runway 14. Since Zurich airport is located close to the German border (dark dashed line in Fig. 2), incoming aircraft fly at an altitude of less than 4000 feet over German communities. In April 2003, the German government issued a binding decree that prohibited landings from the north in the early morning and the late evening. The flight ban over German territory covers the times 6–7 am and 9 pm to 12 am on weekdays, and 6–9 am and 8 pm to 12 am on weekends. As a result, landings in these time periods had to be redirected to runway 28 (east) as the flight regulations at that time did not allow any other direction.

On May 21, 2003 the *Federal Office of Civil Aviation* changed the regulations such that after October 30, 2003 landings were also permitted from the south on runway 34. The new landing policy at Zurich airport stated that aircraft landing between 6 am and 7 am on weekdays (6 am and 9 am on weekends) should generally approach from the south, and aircraft landing between 9 pm and 12 am on weekdays (8 pm and 12 am on weekends) should

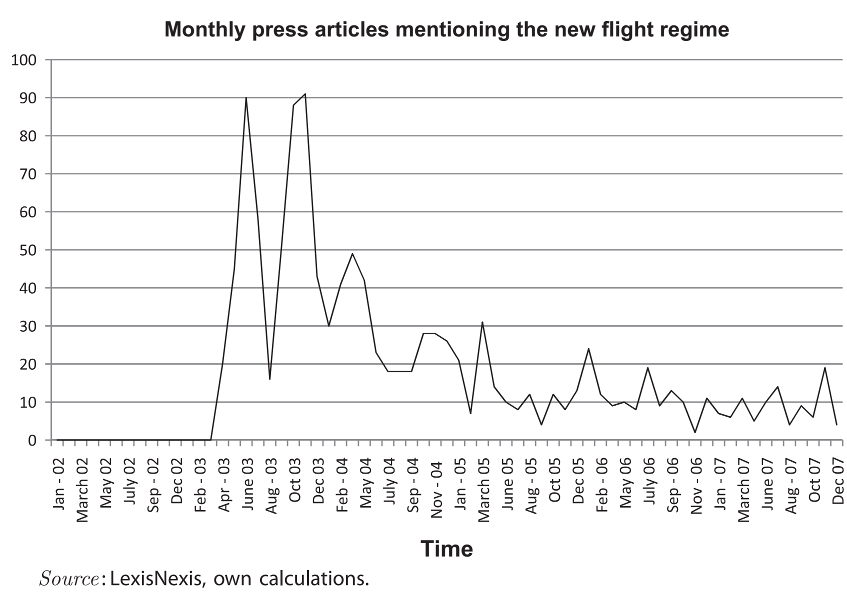
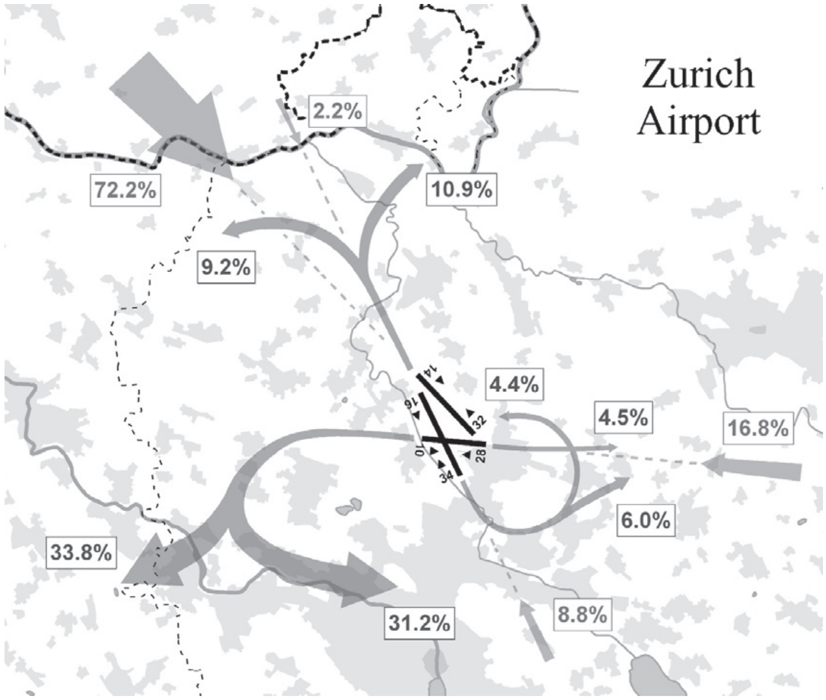


Fig. 1. Monthly number of press articles mentioning the new flight regime.

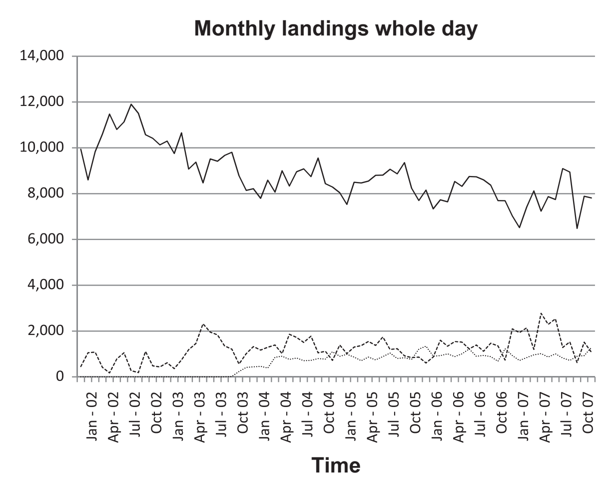


Source: Unique, vector@swisstopo.ch, gg25@swisstopo.ch. Percentages of all flights in 2007.

Fig. 2. Zurich airport: runways, departure/landing schemes.

approach from the east. Exceptions to this general rule are only allowed in special weather conditions, namely strong wind, or fog and mist, or in the case of emergency flights (Unique, 2005, 2007).

The next two figures illustrate the monthly number of landings by flight path and time of the day. Fig. 3 shows the monthly averages on the basis of airport operation time, i.e., from 6 am to 12 am. We observe a downward trend in the number of landings from the north, with the largest drop in 2003, and a significant increase in the number of landings from the east and the south. The monthly landings from the east reached a peak level in summer 2003. Landings from the south started in October 2003, after the new flight regulation took effect.



Source: Unique, own calculations. Monthly number of landings from the north (runways 14 and 16; solid), from the east (runway 28; dashed), and from the south (runway 34; dotted).

Fig. 3. Monthly number of landings over the whole day.

Fig. 4 illustrates the monthly landings for the early morning hours (6–7 am) and for the late evening (9 pm to 12 am). Before 2003, landings in the early morning were operated from the north, in 2003 mainly from the east, and thereafter from the south. Fig. 4 shows a significant decrease in the number of landings from the north in both times, in the early morning and in the late evening. The temporary increase of landings in the early morning observed in October 2005 is due to the test phase of a new flight path from the northwest over Swiss territory. Because this new landing procedure had to be carried out by a visual approach instead of using the otherwise prevailing instrument landing system, the change in flight regulations was denied for safety reasons by the *Federal Office for Civil Aviation* (FOCA, 2008).

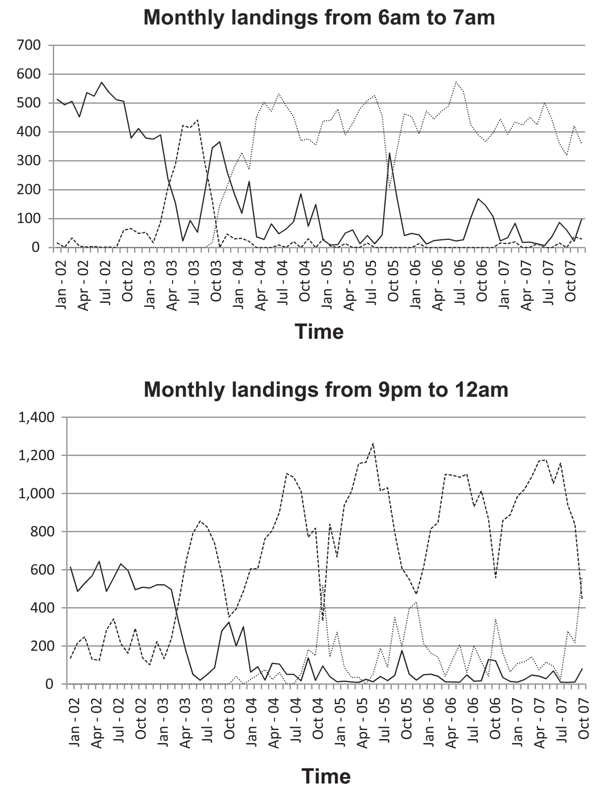
Another observation in Fig. 4 relates to seasonal effects and associated weather conditions. According to the new flight regime and the corresponding safety regulations, incoming aircraft in the late evening are directed to approach from the south when visibility is less than 4300 m but more than 750 m. In the case of visibility of less than 750 m, aircraft approach from the north. This explains the temporary drop of late landings from the east during the wintertime, when the weather in the Zurich region is often very foggy.

Due to the increased number of aircraft landings from the east and south in the early morning and late evening, the new flight regime also required a moderate redistribution of outgoing flights (Unique, 2008). The number of departures from runway 16 (towards the south) dropped, whereas the number of outgoing flights in the northward direction increased. Since aircraft taking off ascend very steeply, they do not fall under the flight ban over Germany in the early morning and late evening.

3. Data

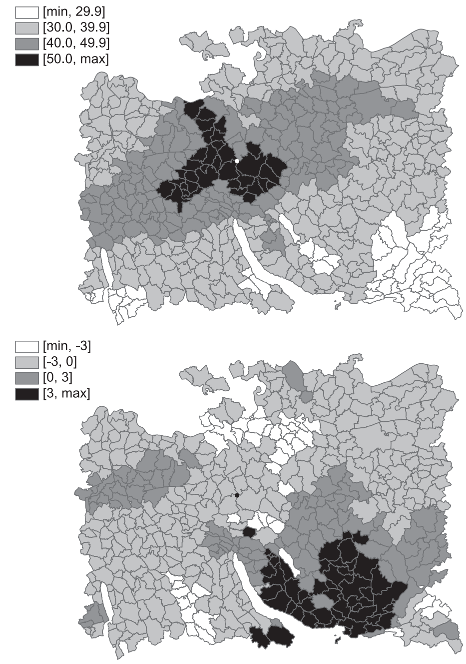
3.1. Aircraft noise data and affected regions

We evaluate location-specific exposure to aircraft noise using model-based noise data provided by the *Swiss Federal Laboratories*



Source: Unique, own calculations. Monthly number of landings from the north (runways 14 and 16; solid), from the east (runway 28; dashed), and from the south (runway 34; dotted).

Fig. 4. Monthly landings in the morning and evening.



Source: EMPA, own calculations. Upper map: average noise exposure in dB(A) from 6:00 to 22:00 in 2004. Lower map: changes from 2002 to 2004. Zurich airport indicated by the white/black dot.

Fig. 5. Daytime noise exposure 06:00–22:00.

for Materials Science and Technology (EMPA). The EMPA model employs effective radar flight track information together with aircraft noise profiles, as well as environmental characteristics such as terrain or prevalent winds, to predict high-resolution noise intensities around Zurich airport. Unlike many other studies that only have access to specific noise contours (e.g., McMillen, 2004), EMPA offers annual data on noise exposure on a 100 m-by-100 m square lattice.

Traditionally, aircraft noise nuisance of European airports was measured by the *noise and number index* (*NNI*) that aggregates the number of noisy events and their maximum noise levels over a day into a single statistic. Since the *NNI* fails to account for the *duration* of noisy events, it has been replaced by L_{eq} as the standard metric (Tomkins et al., 2004). L_{eq} is an equivalence metric corresponding to a steady sound level for a given time interval that would produce the same energy as the actual time-varying sound level. In our analysis, we use $L_{eq}^{d}(16)$ as noise measure. $L_{eq}^{d}(16)$ is the average daytime noise exposure for the 16 h interval from 6 am to 10 pm. The units of measurement are A-weighted decibels, abbreviated by dB(A). For additional details about the EMPA model, we refer to Pietrzko and Buetikofer (2002).

The change in landing regulations significantly altered the exposure to aircraft noise around the airport. Fig. 5 provides a graphical illustration of local noise exposure as well as the changes in aircraft noise due to the new flight regime. Both graphs in Fig. 5 show annual noise data aggregated on the zipcode level (determined by the noise information of the population-weighted center of gravity).

The upper graph shows the daytime 16-h equivalent steady noise level from 6 am to 10 pm, $L_{eq}^{d}(16)$, for the year 2004, i.e., for the year immediately following the introduction of the new flight regime. Zurich airport is indicated by the white dot in the center of the map. The dark regions correspond to the highest levels of exposure to aircraft noise, the white regions to the lowest. As expected, we observe the most intense noise pollution in the areas directly surrounding the airport and in the direction of the three runways – consistent with the flight paths shown in Fig. 2.

The lower graph shows the changes in $L_{eq}^{d}(16)$ from 2002 to 2004. The dark shaded regions experienced an increase of more than 3 dB(A), the (light) gray shaded zipcodes experienced changes between −3 and +3 dB(A), and the white shaded zipcodes experienced an average decrease of 3 dB(A) or more. We observe that the regions to the southeast of the airport experienced the largest noise increases from 2002 to 2004, which is attributable to the permission of landings from this direction after October 30, 2003. Note again that landings from the east were already permitted before the new flight regulation took effect.

3.2. Housing data

We use housing data provided by *Homegate Corporation*, the largest real estate internet portal in Switzerland. The *Homegate* website (http://www.homegate.ch) is accessed by all major real estate agencies and by private people to advertise their properties. Records include housing type (rental apartment or property housing), rental rate (with and without utilities) or sales price, the exact advertisement start and end dates, the year of construction, the number of rooms, and the area in square meters for apartments and houses in Canton Zurich that were advertised from October 2001 to December 2006. The *Homegate* data are representative of the housing market in Canton Zurich: The distribution of the number of rooms and average prices, or rents, are virtually the same as in the official housing census in 2000. The *Homegate* data cover around 10% of all transactions in the rental market in Canton Zurich.

The data contain additional details about individual room size, kitchen, bathrooms, storage, heating, quality information, and the like, but these are mainly summarized in an open text field from which it is difficult to extract consistent information. Therefore, we exclude it from our analysis. We have information on address details. But unfortunately, street information was entered with substantial error so that addresses could not be used for geocoding. The next higher level of spatial resolution, the zipcodes, are accurately measured and documented. Using geographical information system (GIS) software provided by *MicroGIS* we calculated the coordinates of the population-weighted center of gravity for each zipcode. The coordinates were then employed to match the high-resolution noise data to the housing data.

Even though the *Homegate* data cover both the rental and the property market, we focus on the former here. There are three reasons for this choice: First, despite being one of the world's wealthiest nations, Switzerland has the lowest homeownership rate in Western Europe: Only 34.6% of Swiss households were homeowners in 2000, while about two thirds of the population rented accommodation built and owned by landlords (FOH, 2004). Second, while Swiss properties for sale change ownership only every 20 years on average, rental contracts endure much shorter periods, namely 6–7 years (Werczberger, 1997). Tenants are less settled than homeowners and have lower relocation and transaction costs. Bayer et al. (2009) show that when moving is costly, the variation in housing prices may only reflect part of the value of differences in local amenities. The benefit people get from moving to a quiet neighborhood must compensate them not only for the higher rents, but also for the out-of-pocket and psychological costs of moving. The downward bias of the estimated noise discount is thus expected to be much smaller in the rental market than in the property market. Third, the analysis of the property market is additionally complicated by the fact that property prices are affected by the homeowner's expectations of the future, whereas rents reflect current conditions. Some empirical tests of the property market around Zurich airport (see Table A1 in the appendix) reveal small and insignificant noise discounts.

In order to identify a causal noise effect, we impose some additional constraints. First, we define a time frame of adjustment in which prices were reacting to the introduction of the new flight regime. The period of adjustment includes the time immediately following the policy change, until a new market equilibrium is reached, but also the few months prior to the policy change, when media coverage increased public awareness and created expectations of the possible consequences of the new flight regime. The first article mentioning a potential change in flight regulations appeared in March 2003 (see Fig. 1). Nevertheless, in order to be on the safe side, we exclude all observations between January 1, 2003 and 1 year after October 30, 2003. In addition, we eliminate 70 outlying observations, namely apartments with a rental rate below 500 and above 8000 Swiss Francs, because they are likely subject to reporting errors.

For a subsample of apartments we have panel information, i.e., we have observations both before and after the introduction of the new flight regime as these apartments were repeatedly advertised (two or more times). For the repeat-rent subsample, we restrict the sample to one observation shortly preceding and following the time of adjustment in order to rule out potential negative selection issues (see also the two last paragraphs in Section 4.2). All in all, this leaves us with 19,721 observations. Panel information is available for a subsample of 687 rental apartments (1374 observations).

4. How does aircraft noise affect rental rates?

The goal of our study is to evaluate the effect of aircraft noise on apartment rents. In order to tackle this problem empirically, we estimate models of the form

$$\ln(rent) = f(noise) + X'\theta + \varepsilon \qquad (1)$$

where *rent* is the rental rate (without utilities) of an apartment in a given zipcode and year. The function f of daytime noise $L^{d}_{eq}(16)$ is treated as flexible here and will accommodate the various model assumptions that we exploit to estimate the noise effects. X denotes the vector of covariates, ε is an idiosyncratic error term.[1]

Our analysis proceeds in three steps. First, we estimate a generalized additive model with an unspecified noise function. We employ a flexible semi-parametric approach because the hedonic theory provides little guidance on the shape of the hedonic price function (Ekeland et al., 2004). Second, we define affected and unaffected apartments based on the semi-parametric results and based on physiological arguments concerning a minimum perceptible noise change. Then, we compare price trends in the treatment group and in the control group over time, regression adjusted for various confounding influences. Third, we estimate a more detailed noise effect than the DID average taking advantage of the continuous noise data.

4.1. Semi-parametric regression results

The noise function $f(noise)$ is estimated semi-parametrically using a cubic B-spline approach with knots chosen equally spaced at noise levels of 30, 40, and 50 dB(A). The spline functions are constructed using piecewise third-order polynomials (see de Boor, 2001). The approach chosen here may reveal any non-linearities in the relationship between apartment rents and aircraft noise while reducing the multicollinearity of higher order polynomials and still allowing for a straightforward account of covariates. We control for a second order polynomial in age, and time and apartment fixed effects that take account of common time trends and time-constant apartment heterogeneity.

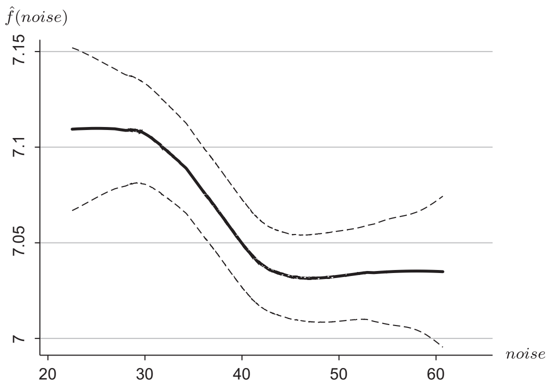
Fig. 6 shows the results. The solid line represents the estimated function $\hat{f}(noise)$, the dashed lines correspond to a 95% confidence interval. The semi-parametric results indicate that the relationship between rents and daytime aircraft noise is non-linear. We find that increases in noise have an almost constant negative effect only for medium noise levels, and almost no effect for noise levels below 30 dB(A) and above 50 dB(A). However, the highest noise level in our data is only about 62 dB(A). Our findings, therefore, do not necessarily contradict other studies (e.g., McMillen, 2004; Cohen and Coughlin, 2009) that show significantly negative effects for noise levels above 65 dB(A).

Our semi-parametric results place a strict cautionary note on the use of constant effect hedonic models to evaluate noise impacts. We find that in our context constant noise discounts are only justified for medium noise levels. In the following, we therefore concentrate on apartments in this noise range, between 30 and 50 dB(A) in 2002.

4.2. Difference-in-differences analysis of noise discounts

Next, we employ a difference-in-differences (DID) approach in order to estimate the effect of the new flight regime on apartment rents. We define apartments in zipcodes with an increase of more than 3 dB(A) daytime noise between 2002 and 2004 as affected by the new flight regime. Apartments in zipcodes with noise changes between −3 and 0 dB(A) are defined as unaffected, since a slight

[1] Eq. (1) does not incorporate interactions between noise and other observed attributes. This might be a restrictive assumption. For example, if occupants of modern, well-insulated apartments are less exposed to noise than occupants of older apartments, then the noise effect is moderated by the apartment's age. We tested this possibility and found that the interactions were insignificant in all considered specifications. We are grateful to Stuart Rosenthal for making this suggestion.



Notes: Object fixed effects model of log rental prices on cubic B-splines of daytime noise (knots at 30, 40, 50, 60 dB(A)). Controls include time dummies and a second order polynomial in age. Smoothed noise effects indicated by the solid line, 95%-confidence interval indicated by the dashed line. Vertical axis: average log rental price (w/o utilities). Horizontal axis: average noise exposure in dB(A) from 6:00 to 22:00.

Fig. 6. Non-linear hedonic estimates of noise effects on rental prices.

decrease can be explained by the design of quieter jet engines and the replacement of old aircraft by modern ones. The following reasoning underlies the cut-off values: First, 3 dB(A) is the smallest change in amplitude a human ear can perceive (Reindel, 2001). Second, we used noise data from previous years and obtained changes in noise exposure that were consistent with the above definitions of unaffected regions. Third, sensitivity tests (see Table A2 in the appendix) were performed and the noise impact did not vary much because the classification of zipcodes remained relatively stable.

Table 1 shows some descriptive statistics of the aircraft noise measure, the rental price, the number of rooms, and the age of the apartment *pre* and *post* the flight regime change. We also distinguish between the treatment and the control region, as defined before, and the overall cantonal area, i.e., the unrestricted sample.

In a standard DID setup, we estimate the policy effect by specifying

$$f(noise) = \alpha \; noise\ region + \beta \; after\ policy + \gamma \; noise\ region \times after\ policy \tag{2}$$

where α measures the time-invariant differences between the treatment and the control region, β measures the common time trend, and γ measures the average effect of the new flight regime on apartment rents.

We define *noise region* as an indicator for the treatment region, i.e., a binary variable that takes value one for apartments located in zipcodes that were affected by the new flight regime, and that takes value zero for apartments in the control group. The policy relevant time period is indicated by *after policy* which equals one for apartments advertised after October 2004, and zero before January 2003. The relevant intervention is the introduction of the new flight regime, formally indicated by the interaction *noise region* $\times$ *after policy*.

The coefficient γ can be consistently estimated by least squares if the interaction term does not capture additional unbalanced trends between the treatment and control group. In general, this assumption is hard to justify, in particular when both groups differ in their composition of apartments. For example, valuable housing characteristics such as apartment size, age, or location characteristics other than noise may follow different time trends in the two groups and thus contaminate the noise effect. In order to reduce omitted variable bias, we proceed sequentially. In a *first step*, we remove confounding influences by controlling for the number of rooms, a second order polynomial in age, and the floor as basic observable apartment characteristics.

A potential problem with this "selection on observables" approach is that the listed factors only partly cover the relevant housing characteristics. There may be additional spatial heterogeneity between and within the treatment and control region that correlates with aircraft noise and rents. For example, areas heavily exposed to noise tend to be more urbanized and thus may have a higher population density and a higher crime rate. In a *second step*, we therefore include zipcode fixed effects to control for unobserved spatial heterogeneity. As the classification of zipcodes did not change in the considered time frame, there is a unique relation for each apartment. The variable *noise region* is hence refined to the within variation of zipcodes in order to identify the noise effect.

In a *third step*, we make use of the panel information for some apartments in our sample and replace the zipcode fixed effects with apartment fixed effects. With such an estimation strategy we control for *all* time-invariant characteristics of an apartment, where time-invariant here means that the characteristics do not vary from the *pre* to the *post* treatment period, although they may well vary within the two time periods.

The results of the DID analysis are reported in Table 2. The first two columns use the overall sample, whereas columns 3 and 4 only employ the subsample of repeat-rent observations. Column 1 shows the pooled OLS results with the number of rooms, a second order polynomial in age, and the floor as controls. Column 2 additionally includes zipcode fixed effects to take spatial heterogeneity into account. Column 3 applies the same specification as in column 2 to the repeat-rent sample in order to test potential selection effects of apartments repeatedly advertised. In column 4, we show the results when using apartment fixed effects as controls. The standard errors

Table 1
Means and standard deviations by region and time.

	Period	Treatment ($\Delta Noise > 3$)	Control (ΔNoise $\in (-3,0)$)	Overall
Daytime noise $L^d_{eq}(16)$ (06:00–22:00)	*Pre*	39.4 (6.74)	43.6 (4.50)	44.8 (10.2)
	Post	44.6 (6.39)	41.3 (5.00)	43.4 (7.85)
Rental price w/o utilities	*Pre*	1618 (666.1)	1435 (731.4)	1475 (743.6)
	Post	1638 (727.2)	1628 (798.4)	1681 (817.1)
Number of rooms	*Pre*	3.33 (1.23)	3.15 (1.19)	3.14 (1.23)
	Post	3.38 (1.20)	3.42 (1.18)	3.40 (1.22)
Age	*Pre*	26.2 (17.0)	30.7 (21.0)	32.6 (37.5)
	Post	27.1 (19.2)	31.5 (37.6)	32.5 (40.9)
$\Delta L^d_{eq}(16) = L^d_{eq}(16)_{2004} - L^d_{eq}(16)_{2002}$		6.38 (2.72)	−1.14 (0.87)	
Number of observations (*Pre*/*Post*)		198/513	1690/4161	5673/14,048

Notes: $L^d_{eq}(16)$ is an equivalence metric corresponding to a steady sound level for the daytime interval 06:00–22:00 that would produce the same energy as the actual time-varying sound level. Treatment and control are defined via changes in daytime noise as indicated in the column, given daytime noise in 2002 between 30 and 50 dB(A). *Pre* captures the time period from October 2001 to December 2002, *Post* captures the period from October 2004 to December 2005. Standard deviations in parentheses. *Source: Homegate Corporation*, EMPA, own calculations.

Table 2
Difference-in-differences estimates of noise effects on rental prices.

Dependent variable: log of rental price in Swiss Francs w/o utilities.				
	(1)	(2)	(3)	(4)
Noise region	0.080	–	–	–
	(0.082)			
After policy	0.058***	0.042***	0.010	0.001
	(0.016)	(0.009)	(0.008)	(0.006)
Noise region × after policy	−0.061*	−0.047***	−0.042	−0.035**
	(0.035)	(0.017)	(0.034)	(0.015)
Number of rooms	0.256***	0.257***	0.239***	–
	(0.007)	(0.007)	(0.013)	
Age/100	−0.265**	−0.478***	−1.330***	−0.882***
	(0.131)	(0.082)	(0.146)	(0.239)
$(\text{Age}/100)^2$	0.048**	0.078***	0.987***	1.110***
	(0.018)	(0.019)	(0.177)	(0.315)
Floor	0.005	0.008***	0.008	–
	(0.006)	(0.002)	(0.007)	
Constant	6.430***	6.500***	6.660***	7.320***
	(0.035)	(0.044)	(0.052)	(0.029)
Zipcode fixed effects	No	Yes	Yes	No
Apartment fixed effects	No	No	No	Yes
Number of observations	6562	6562	436	436

Notes: For a description of the daytime noise variable, see Table 1. Noise region is defined via ΔNoise > 3, as opposed to the interval (−3, 0). After policy indicates after October 2004, as opposed to before January 2003. Covariates include the number of rooms, a second order polynomial in age, and the floor. Standard errors (reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1–3) and at the apartment level (column 4).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

(reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1–3) and at the apartment level (column 4) to consider potential correlation of error terms of observations in the same zipcode or the same apartment.

The effect of interest is the coefficient of the interaction term *noise region × after policy*. We observe that the average effect of aircraft noise caused by the new flight regime is negative in all four specifications. The magnitude of the effect ranges from about −6.1% in the pooled OLS specification to about −3.5% in the apartment fixed effects model. More precisely, the results of the apartment fixed effects model indicate that the change in average rental rates in the treatment group is about 3.5% lower than the change in the control group, holding time-invariant apartment characteristics constant. The estimates show an upward bias in the absolute magnitude of the noise effect when unobserved neighborhood and apartment heterogeneity are not taken into account. The latter result is plausible as aircraft noise tends to be negatively correlated with neighborhood amenities at the zipcode level and valuable apartment characteristics, such as nearby recreational areas and apartment quality. Hence, we conclude that cross-sectional studies tend to overstate noise discounts.

Even though the exogeneity condition of the treatment status is more likely to be met when using apartment fixed effects, repeat-rent approaches are not uncontroversial. First, apartments with panel information are typically characterized by comparatively high turnover rates. This might cause potential selection bias if the sample of repeat-rent apartments is not representative of the overall rental market. The evidence in the related literature on the generalizability of such findings is mixed (see McMillen, 2003). In order to evaluate potential bias, we estimate the noise discount with the unrestricted sample and with the restricted sample of repeat-rent observations using the same zipcode fixed effects specification. Table 2 shows that the coefficient of the interaction term is very similar in both cases (columns 2 and 3), which indicates that, regarding noise discounts, the results are stable when repeat-rent restrictions are imposed.

Second, the apartment fixed effects specification provides a consistent noise effect only if the time-variation of noise is unrelated to unobserved time trends of confounders. Aspects that may change over time are maintenance and the general depreciation of apartments, for example. Harding et al. (2007) show that the extent of depreciation and maintenance of repeat-sales houses is mainly influenced by the house age and the time between sales dates. Thus, if apartments affected by an increase in aircraft noise had a higher tenant turnover rate than unaffected apartments, the estimated noise discount might be understated due to a lower depreciation rate. In our sample, however, the tenant turnover rate in the treatment group is only slightly and insignificantly higher than in the control group. Maintenance is mainly driven by the apartment's age for which we control in our models. Thus, even though potential omitted variable bias can never be completely eliminated when using field data, we consider the assumption of exogenous noise variation as reasonable, conditional on apartment fixed effects, time, and age.

4.3. Hedonic estimates with continuous noise data

The DID approach reduces the comprehensive noise data to a binary variable *noise region* that indicates if the apartment's zipcode experienced an increase of more than three decibels between 2002 and 2004, as opposed to a change between −3 and 0 dB(A). The argument behind this procedure is that a change of three decibels is the smallest change in amplitude a human ear can perceive. The DID estimate shows an *average* difference in time trends of rental rates between treated and untreated apartments, regression adjusted for various confounding influences. The transfer of our DID estimate to other contexts hinges on homogeneity assumptions that are critical in practice (e.g., what happens if regions are affected by noise changes of different levels).

In this section, we test whether the noise discounts are confirmed if the binary treatment indicator is replaced by a continuous noise variable using the same sample as in the previous section. Subsequently, we apply the log-linear hedonic approach to the entire sample of apartments around Zurich airport to test whether the homogeneity condition also remains valid when analyzing the whole range of potential noise exposures. Based on the semi-parametric results, we expect that the homogeneity assumption is confirmed for the treatment and control sample but not for the unrestricted sample.

The log-linear hedonic model presumes that $f(noise) = \delta\ noise$ with the continuous noise measure $L_{eq}^{d}(16)$. In order to separate time effects from noise effects, we include dummies for each year. Otherwise the same specifications are used as before. The results of the pooled OLS model (column 1), the zipcode fixed effects model (column 2), the zipcode fixed effects with the repeat-rent sample (column 3), and the apartment fixed effects model (column 4) are shown in Table 3.

The first line reports the relative effect of a one-decibel increase in $L_{eq}^{d}(16)$ on apartment rents, conditional on the treatment and control sample. We observe that aircraft noise significantly decreases rents. For example, the apartment fixed effects model in column 4 shows that a one-decibel increase in the yearly average daytime noise exposure reduces the average rental rate by 0.54%. In order to test the homogeneity condition, we can multiply the noise effects in Table 3 by the difference in average noise changes between the treatment and control group shown in Table 1 ($6.38 - (-1.14) = 7.52$), and then compare the product with the DID estimate in Table 2. The measures are quite similar (e.g., −0.035 (DID) vs. −0.041 in column 4), which confirms homogeneity regarding the treatment and control sample.

In order to test whether the estimated noise effects remain valid if we do not condition on the treatment/control sample, we re-estimate

Table 3
Log-linear hedonic estimates of noise effects on rental prices – treatment/control sample.

Dependent variable: log of rental price in Swiss Francs w/o utilities.				
	(1)	(2)	(3)	(4)
Daytime noise	−0.0113***	−0.0068**	−0.0069**	−0.0054***
$L_{eq}^{d}(16)$ (06:00–22:00)	(0.0026)	(0.0026)	(0.0033)	(.0015)
Number of rooms	0.251***	0.257***	0.239***	–
	(0.006)	(0.007)	(0.013)	
Age/100	−0.260*	−0.477***	−1.320***	−0.900***
	(0.130)	(0.081)	(0.146)	(0.235)
$(\text{Age}/100)^2$	0.046**	0.078***	0.982***	1.19***
	(0.018)	(0.019)	(0.172)	(0.309)
Floor	0.006	0.008***	0.008	–
	(0.005)	(0.002)	(0.007)	
Constant	6.940***	6.830***	6.830***	7.570***
	(0.110)	(0.121)	(0.131)	(0.073)
Year fixed effects	Yes	Yes	Yes	Yes
Zipcode fixed effects	No	Yes	Yes	No
Apartment fixed effects	No	No	No	Yes
Number of observations	6562	6562	436	436

Notes: For a description of the daytime noise variable, see Table 1. Standard errors (reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1–3) and at the apartment level (column 4).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table 4
Log-linear hedonic estimates of noise effects on rental prices – whole sample.

Dependent variable: log of rental price in Swiss Francs w/o utilities.				
	(1)	(2)	(3)	(4)
Daytime noise	−0.0045***	−0.0028*	−0.0029**	−0.0015*
$L_{eq}^{d}(16)$ (06:00–22:00)	(0.0015)	(0.0015)	(0.0013)	(0.0008)
Number of rooms	0.252***	0.260***	0.253***	–
	(0.007)	(0.005)	(0.009)	
Age/100	−0.102	−0.317***	−0.468***	−0.113
	(0.109)	(0.036)	(0.092)	(0.117)
$(\text{Age}/100)^2$	0.026*	0.049***	0.123***	0.022
	(0.015)	(0.007)	(0.031)	(0.023)
Floor	0.014*	0.012***	0.004	–
	(0.008)	(0.002)	(0.006)	
Constant	6.600***	6.530***	6.640***	7.420***
	(0.069)	(0.075)	(0.072)	(0.049)
Year fixed effects	Yes	Yes	Yes	Yes
Zipcode fixed effects	No	Yes	Yes	No
Apartment fixed effects	No	No	No	Yes
Number of observations	19721	19721	1374	1374

Notes: For a description of the daytime noise variable, see Table 1. Standard errors (reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1–3) and at the apartment level (column 4).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

all models using the whole sample of rental apartments, including apartments in zipcodes with very low or very high noise exposure and/or slight increases in aircraft noise. Table 4 reveals that the magnitude of the effects is substantially lower but still significantly negative in this case. The external homogeneity assumption is thus not confirmed, as supposed, due to the non-linear relationship between aircraft noise and rental rates.

5. Concluding remarks

This study has used the flight regime change at Zurich airport to estimate the effect of aircraft noise on rental rates. The results indicate that the rents of apartments that experienced an increase of more than three decibels between 2002 and 2004 decreased by about 0.5% per decibel, controlling for time-constant spatial and apartment heterogeneity. Based on the Swiss protection law, landlords are entitled to compensation for lost rents under certain conditions. So far, the *Federal Supreme Court of Switzerland* has not made a final decision on the noise depreciation index. Our study feeds in this discussion by providing a noise discount for rental apartments in the treatment region. Our results also indicate that discounts based on cross-sectional studies may be overestimated.

Even though relocation costs are much smaller for tenants than for homeowners, they are still not zero. This implies that implicit hedonic prices might not fully reflect the tenants' marginal willingness to pay. If relocation is costly, a person will only move to an apartment exposed to less noise if the quiet compensates for the higher rents *and* the costs of moving, *ceteris paribus*. Thus, the noise discounts estimated here have to be interpreted as lower bounds for the overall negative effect of noise pollution.[2] Recently, life satisfaction approaches to valuing environmental goods have evolved to enable measurement of the additional shadow costs of noise by using happiness surveys (Van Praag and Baarsma, 2005; Rehdanz and Maddison, 2008).

Regarding future research, two main conclusions can be drawn from our analysis. First, the combination of quasi-experiments with apartment-level panel data offers a powerful tool for evaluating the value of environmental and other nonmarket goods. The traditional method of reducing omitted-variable bias is multiple regression. However, even "kitchen-sink regressions"—hedonic studies that include a great deal of housing attributes—are not able to incorporate all relevant characteristics (Gibbons and Machin, 2008). This paper uses a policy change as a quasi-random experiment and draws inferences from unequal price trends between treatment and control. The potential non-randomness of the treatment assignment can be reduced by including several housing attributes, spatial fixed effects, or even better, apartment fixed effects. Our results suggest that simple cross-sectional studies tend to overestimate the effect of the considered environmental good.

Second, our semi-parametric analysis reveals that the relationship between aircraft noise and rental rates does not satisfy prominent functional forms, such as linear, log-linear, double log, or Box–Cox over the entire noise distribution. We find that in the rental market around Zurich airport a constant noise discount is justified only for medium noise levels. Since hedonic models usually do not yield nice closed-from expressions (Ekeland et al., 2004), flexible semi-parametric regression is a promising approach. We encourage further efforts in this direction.

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[2] The considerably higher monetary and psychic relocation costs for homeowners than for tenants might explain why we find only small and insignificant noise discounts for property houses (see Table A1 in the appendix).

Appendix A

See Tables A1 and A2.

Table A1
Log-linear hedonic estimates of noise effects on sales offer prices – treatment/control sample.

Dependent variable: log of sales offer price in Swiss Francs.	(1)	(2)	(3)	(4)
Daytime noise	−0.0012	−0.0010	−0.0008	−0.0008
$L_{eq}^{d}(16)(06{:}00\text{–}22{:}00)$	(0.0020)	(0.0045)	(0.0033)	(0.0032)
Number of rooms	0.236***	0.249***	0.249***	–
	(0.013)	(0.018)	(0.019)	
Age/100	−0.587**	−0.981***	−1.010***	−0.921***
	(0.260)	(0.207)	(0.190)	(0.225)
$(\text{Age}/100)^2$	0.202***	0.456***	0.426***	0.437***
	(0.071)	(0.080)	(0.172)	(0.309)
Floor	0.021*	0.031***	0.032***	–
	(0.011)	(0.012)	(0.012)	
Constant	13.0***	12.6***	12.0***	14.0***
	(0.148)	(0.411)	(0.240)	(0.489)
Year fixed effects	Yes	Yes	Yes	Yes
Zipcode fixed effects	No	Yes	Yes	No
Apartment fixed effects	No	No	No	Yes
Number of observations	1098	1098	16	16

Notes: For a description of the daytime noise variable, see Table 1. Standard errors (reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1–3) and at the apartment level (column 4).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

Table A2
DID estimates of the noise effects with alternative cut-off values.

	(1)	(2)	(3)
Treatment region defined with $\Delta Leq^d(16) > 2$ dB(A), control region in $(-3,0)$			
Noise region	0.0758	–	–
	(0.0763)		
After policy	0.0592***	0.0424***	0.0014
	(0.0167)	(0.0094)	(0.0062)
Noise region × after policy	−0.0423	−0.0308*	−0.0297**
	(0.0360)	(0.0223)	(0.0142)
Number of observations	6766	6766	442
Treatment region defined with $\Delta Leq^d(16) > 4$ dB(A), control region in $(-3,0)$			
Noise region	0.0813	–	–
	(0.0877)		
After policy	0.0587***	0.0421***	0.0013
	(0.0165)	(0.0097)	(0.0061)
Noise region × after policy	−0.0570	−0.0458**	−0.0361**
	(0.0409)	(0.0191)	(0.0155)
Number of observations	6423	6423	432
Treatment region defined with $\Delta\ Leq^d(16) > 3$ dB(A), control region in $(-2,0)$			
Noise region	0.0582		
	(0.0790)		
After policy	0.0592***	0.0385***	−0.0088
	(0.0169)	(0.0096)	(0.0066)
Noise region × after policy	−0.0627*	−0.0436**	−0.0311**
	(0.0362)	(0.0175)	(0.0148)
Number of observations	5693	5693	370
Year fixed effects	Yes	Yes	Yes
Zipcode fixed effects	No	Yes	No
Apartment fixed effects	No	No	Yes

Notes: Dependent variable: Log of rental price in Swiss Francs w/o utilities. Noise effects are measured for the $Leq^d(16)$ equivalence metric. Noise region is defined as indicated in the table. After policy indicates after October 2004, as opposed to before January 2003. Covariates include the number of rooms (columns 1 and 2), a second order polynomial in age (all columns), and the floor (columns 1 and 2). Standard errors (reported in parentheses) are robust to heteroscedasticity and clustered at the zipcode level (columns 1 and 2) and at the apartment level (column 3).
* $p < 0.1$.
** $p < 0.05$.
*** $p < 0.01$.

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