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Section EMPIRICAL CONTRIBUTIONS

Spatial Hedonic Pricing Models for Testing the Adequacy of Acoustic Areas in Madrid, Spain

José-María Montero *, Gema Fernández-Avilés **, Román Mínguez **

ABSTRACT: Road traffic noise is one of the main concerns of large cities. Most of them have classified their territory in acoustic areas and have constructed strategic noise maps. From both sources we have elaborated seven types of acoustic neighbourhoods according to both their noise gap in regard to the legal standard and the percentage of population exposed to noise. A spatial Durbin model has been selected as the strategy that best models the impact of noise on housing prices. However, results for Madrid do not confirm the hedonic theory and indicate, as one of the possibilities, that the official acoustic areas in Madrid could be incorrectly designed.

JEL Classification: C21, Q51, Q53.

Keywords: Acoustical area, road traffic noise, strategic noise map, spatial hedonic pricing models.

Modelos espaciales de precios hedónicos para contrastar la adecuación de las áreas acústicas en Madrid, España

RESUMEN: El ruido derivado del tráfico es una de las principales preocupaciones de las grandes ciudades. La mayoría de ellas han clasificado su territorio en áreas acústicas y han elaborado mapas estratégicos de ruido. A partir de ambas fuentes hemos creado siete tipos de vecindarios acústicos según su alejamiento del estándar legal y el porcentaje de población afectada. El modelo espacial de Durbin ha demostrado ser el que mejor modeliza el impacto del ruido en Madrid, ciudad objeto de estudio. Sin embargo, los resultados obtenidos no confirman la teoría hedónica y, como una de las posibles explicaciones, sugerimos que las áreas acústicas oficiales pudieran estar mal delimitadas.

Clasificación JEL: C21, Q51, Q53.

Palabras clave: Área acústica, ruido de tráfico, mapa estratégico de ruido, modelos espaciales de precios hedónicos.

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1. Introduction

Noise has always disturbed people's lives, but the situation has worsened recently, particularly in large metropolitan areas, as a result of industrial development, night-time leisure activity and an increase in vehicular traffic. Noise is considered acoustic pollution when it implies discomfort, risk or harm to people, the carrying out of their activities or goods of any nature.

The European Commission states that the noise caused by transport and industrial activity is one of the primary environmental problems in Europe. According to the European Commission (EC, 2002) it is reducing the health and quality of life of nearly 25% of the EU's population (80 million people). In addition, some 170 million European citizens live in «grey areas», that is to say, areas where noise levels range from 55 to 65 dB(A) during the day. According to the World Health Organization (WHO), 20% of European citizens are exposed to more than 65 dBA during the day and 30% are exposed to levels of noise pressure in excess of 55 dBA at night. Furthermore, we cannot ignore the economic factor that acoustic pollution entails, as noise generates costs. Social expenditure caused by the noise of vehicular traffic in the EU is estimated to range from 30,000 to 46,000 million euro a year, approximately 0.4% of the GDP of the EU member states (Ayuntamiento de Madrid, 2010).

As regards noise at night (basically due to leisure activity), large cities no longer sleep at night and there are an increasing number of activities that take place at night: street cleaning, rubbish collection, delivery of goods and even offices (call centres). But public holidays and weekends are the main problem as a result of the number of recreational activities on offer. The noise made by nocturnal leisure undoubtedly causes the most discomfort. And this is not only due to when it occurs, but also because recreation centres are normally concentrated in areas of the city that are primarily residential.

Combating noise involves studying and analysing several perspectives (Ayuntamiento de Madrid, 2010): i) What are the sources of noise? ii) What factors influence the emission of noise? iii) What factors influence the spread of noise? iv) What is the time dimension of noise? v) Which areas are affected by noise?

Noise, especially that derived from road traffic is problematic for at least two reasons: i) increasing transportation of goods and people means higher noise levels and ii) as road traffic is related to human activity and needs, much of it occurs in areas where people live, work, go to school, etc. According to Nijland *et al.* (2003) and Andersson *et al.* (2010), the latter means that today's urban development will lead to noise being a bigger problem in the future unless efforts are made to mitigate the problem.

Noise can adversely affect both human hearing and other aspects of people's health. As regards the former, the most worrying in large cities is a temporary or permanent rise in our absolute threshold of hearing. In reference to the latter, noise can cause, among other adverse effects, the loss of privacy, degradation of suburbs affected by this problem and the depreciation of property, particularly housing. Therefore, it is no surprise that economists have developed a number of procedures that provide reasonable estimates of the monetary value of acoustic externalities and that the European Commission has developed projects to combat noise, including SILENCE, HARMONOISE-IMAGE, SMILE and QCITY.

As stated in Nelson (2008), economic valuation methods are divided into two categories: revealed preference methods such as the hedonic price method for housing values; and stated preference (SP) methods such as contingent valuation surveys. Revealed preference methods exploit the fact that there are private markets that are complementary. The main alternatives to hedonic valuation are survey methods that ask respondents to state their willingness to pay for environmental improvements, including the contingent valuation method, contingent ranking, conjoint analysis and other SP models. Notwithstanding, survey-based methods have both theoretical problems and the empirical difficulty of asking survey respondents questions concerning long term changes in noise level exposure that they have not in general experienced (Lake *et al.,* 2000). In contrast, our review of the literature suggests that the HP method is robust and appropriate for estimating values for road traffic-related noise.

We focus on the impact of acoustic pollution on the depreciation of property using spatial hedonic strategies. But our approach to the problem of noise in large cities, as far as we know, is completely new. The base of our approach is acoustic areas, which are a relatively new concept in large cities. An acoustic area is defined by the gap between the level of noise exposure and the level of noise considered acceptable given the classification of the area (residential, industrial, leisure...). This approach has the advantage of deflating the amount of noise that can be considered a consequence of living in a specific area of a large city. In this sense, this approach is different to the inclusion of noise levels (measured or perceived) in hedonic (spatial or not) pricing models. Even the objective we pursue is different: while in traditional hedonic specifications the objective is to estimate the willingness for quiet, we aim to both verify whether the acoustic areas are correctly or erroneously delimitated and also identify those areas that need urgent measures to combat noise in order to avoid a rapid depreciation of properties. Unfortunately, the results obtained suggest that the acoustic areas are not correctly delimitated.

The article is structured as follows: after this introductory section, section 2 includes the literature review. Section 3 outlines the process to delineate quiet and conflict areas in Madrid. Section 4 is devoted to spatial hedonic pricing models. Section 5 describes the case study, reports the main results of this research and ends with a policy analysis. Section 6 concludes.

2. Literature review

Gamble *et al.* (1974) is cited as the first major study to apply HP methods to road traffic noise. They studied US interstate highways in four communities in New Jersey, Virginia and Maryland. Other early work includes HP studies of traffic noise for Washington DC (Nelson, 1975, 1978), Chicago (Vaughan and Huckins, 1975) and Toronto (Taylor *et al.,* 1982). Early European studies include a 1974 study for Stockholm by Hammar and a study of Copenhagen by Hjorth-Andersen (1978).

Since these pioneer studies, as expected, extensive literature on HP studies for airports and road traffic noise was published (see Nelson, 2008, and the references therein). The literature on the valuation of noise declined substantially in the 1990s, but it has witnessed a renaissance over the last ten years due to the advent of GIS methods, computerised data, the popularity of spatial econometric methods and increasing concern and awareness on behalf of citizens in regard to environmental problems and quality of life.

In the last decade, without aiming to provide an extensive review, it is worth highlighting the following works: Wilhelmsson (2000), who analyses the impact of noise stemming from vehicular traffic on the value of houses in a suburb in Stockholm (Sweden). More specifically, the results obtained show that every extra decibel of noise, housing prices record an average decrease of 0.6%, while a house located in a noisy area is worth, on average, 30% less than another in a quiet area. Lake *et al.* (2000) conducted a case study based on over 3,500 property sales in Glasgow, Scotland and suggested that property prices were depressed by 0.20% per decibel increase in road noise. Bickel *et al.* (2003) estimate the resource costs, opportunity costs and disutility caused by transport noise impacts in Sweden. They review the existing literature and find that the Noise Sensitivity Depreciation Index ranges from 0.08% to 2.22%. Nelson (2008), one of the most prolific researchers on the topic, includes an extensive research outline on spatial and non-spatial hedonic pricing models including noise as a regressor. Dekkers and van der Straaten (2009) build a spatially-explicit hedonic pricing model in Amsterdam based on three sources of traffic noise (road, railway and aircraft noise), simultaneously. They conclude that a higher noise level means, *ceteris paribus,* a lower house price. In addition, air traffic has the largest price impact, followed by railway traffic and road traffic. They find a noise reduction of 1 dB leads to a decrease in price of 1.459 Euro per house, resulting in a total gain of 574 million Euros for a 1 dB decrease in noise. Montero *et al.* (2010) construct a composite (pollution and noise) index using DP2 distance and then apply kriging to match the monitoring station observations to census data, which are more numerous. The kriging process allows them to estimate the spatial dependence of the composite index and classify the neighbourhoods of Madrid according to the values of the foregoing index. Andersson *et al.* (2010) examine the effect of road and railway noise (objective measures) on property prices in the municipality of Lerum, close to Gothenburg in the west of Sweden (36,000 inhabitants and a population density of 138 inhabitants per km^2). Their results from a spatial hedonic price model (although they do not detect spatial dependencies) are in line with the evidence from the acoustic literature which has shown that individuals are more disturbed by road than railway noise, but contradicts recent results from a hedonic study on data from the United Kingdom (Day *et al.,* 2007). Baranzini *et al.* (2010) compare the use of perceived and measured noise in a hedonic housing model in Geneva, Switzerland, and confirm convergence in the perceived and measured noise variables. In their case study, a HPM using measured noise data provides turns out to be just as accurate as those that use subjective data. Finally, Nikolaos *et al.* (2011) survey the main issues in the literature on the real estate market and evaluate the effect of some externalities including noise on real estate through a detailed literature review in both Europe and the United States.

3. Acoustic areas, strategic noise maps and quiet and conflict areas

We propose an HP strategy for estimating the value of quiet, but including a new indicator as a regressor: an indicator based on the adequacy of the level of noise to the legal standard for the area. This indicator measures the gap between measured noise and the level of noise considered appropriate according to the activities that take place in a specific area. This gap is weighted with the percentage of affected population.

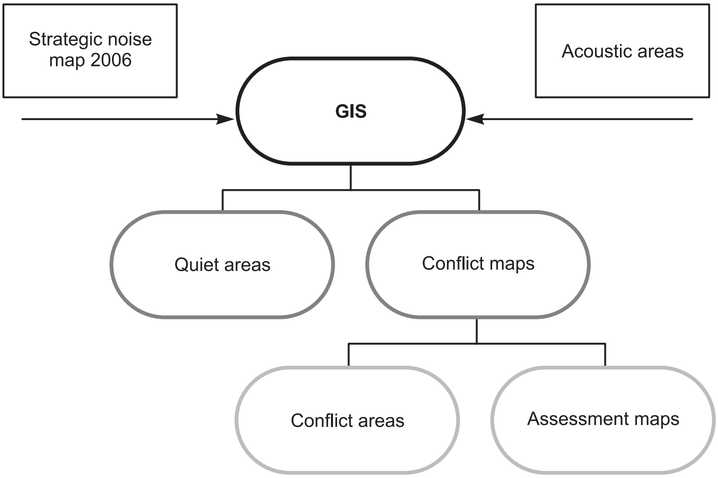
The main advantages of this type of indicator are as follows:

i) It considers the complete set of locations in a city rather than just a sample of them.
ii) It takes into account whether the area is residential, industrial, cultural, recreational, etc. Therefore, it takes into account the trade-off between the characteristics of the area, economic activity and noise.
iii) This type of indicator can be included in a spatial hedonic pricing model without provoking errors-in-variables problems.
iv) The indicator can be adapted for both the linear and non-linear effects of noise on housing prices.

Acoustic areas are a way of classifying territory according to noise. They delimitate the zones of the city with the same objectives in terms of acoustic quality. More specifically, they can be defined as parts of the city where the legislation sets specific targets according to the predominant utilisation of the land (activities that take place in that area). Seven types of acoustic areas are defined in Law 37/2003 according to the predominant use of land: residential, industrial, leisure and spectacles, services, health, schools and culture, affected by transportation infrastructures, and natural spaces. On the other hand, the Strategy Noise Map (SNM) provides comparable information about acoustic values across the city. Finally, the locations where acoustic levels exceed the quality target are known as «conflict areas».

According to art. 14.4 RD 1367/2007 a «conflict area» is a region of the city where the objective values of noise that guarantee acoustic quality are exceeded. Conflict areas have been identified by implementing the database of the SNM for Madrid, 2006 in a GIS, together with the legal standards of noise (day, evening and night) set by RD 1367/2007. In contrast, a «quiet area» is a region where the level of noise is, at least, 5 dB below the acoustic quality objective defined for such an area. Figure 1 summarises the process of evaluating acoustic quality.

Figure 1. Assessment process of acoustic quality (Madrid)



Taking the above evaluation of acoustic areas in Madrid as a starting point, and taking into account both the affected population and the degree of exposure to noise, we have classified the neighbourhoods of Madrid as follows:

Table 1. Criteria to classify neighbourhoods

	Classification	*Degree of exposure to noise*	*Percentage of affected population*
Type 1	Quiet area	Low	Under 20%
Type 2	Quiet area	Low	Above 20%
Type 3	Area not exceeding the legal standard	–	–
Type 4	Conflict area where noise only slightly exceeds the legal standard	Low	Under 20%
Type 5	Conflict area where noise greatly exceeds the legal standard	High	Above 20%
Type 6	Conflict area where noise greatly exceeds the legal standard	High	Under 20%
Type 7	Conflict area where noise greatly exceeds the legal standard	High	Above 20%

Under the assumption that homebuyers have a reasonable knowledge of the area where they intend to buy a property, that is to say, they have a reasonable idea about the main features of the neighbourhood, including noise, our objective is to estimate willingness to pay for living in a quiet area, or the noise discount for living in a conflict area.

This approach will test the adequacy of the acoustic areas in Madrid. If acoustic areas are well delimited, there is expected to be a premium for living in a quiet area and a penalty in prices of dwellings located in conflict areas. Of course, the size of the penalty is expected to increase with the level of exposure to noise relative to the objective for the area.

In addition, a secondary but also interesting goal is to examine the relationship between densely populated areas and conflict areas, because if it is strong and positive, decision makers should adopt new measures to correct this externality.

The statistical distribution of noise is described by showing the levels of dBA that are exceeded 10%, 50% and 90% of the time: L10 (peak level), L50 (median), and L90 (background). The decibel (dB) is measured on a logarithmic scale. A ten-fold increase in sound intensity is equivalent to a 10 dB increase, or roughly double the perceived loudness. Sound levels are weighted to account for human ability to hear sounds at different frequencies, e.g., the A-weighted sound level is used to describe sounds stemming from transportation. Representative sound levels are: *a)* quiet suburban street (50 dBA); *b)* conversational speech at 3 feet (60 dBA); *c)* freight train at 100 feet (70 dBA); and d) busy city intersections (80 dBA).

4. Methods: Spatial hedonic pricing models

As mentioned in the introductory section, hedonic models are the usual strategy for estimating the impact of noise on housing prices. In case of dealing with acoustical areas (or neighbourhoods), this specification corresponds to the equation:

$$y_i = \alpha + \sum_{i=1}^{n} \lambda_j N_j^{(i)} + z_i^T \delta + \varepsilon_i \qquad i = 1,\ldots,n, \qquad j = 1,2,4,5,6,7 \tag{1}$$

where y_i represents the log of the price of the i-th dwelling, $N_j^{(i)}$ are binary variables the value of which is one when such a dwelling is sited in the j-th type area (the third category of noise is eliminated to prevent multicollinearity), $z_i^T = (z_{1i}, z_{2i},\ldots,z_{ki})^T$ includes the k individual and areal characteristics of the i-th dwelling, α is the intercept of the equation and ε_i is a random disturbance that is assumed to distribute as $N(0,\sigma_\varepsilon^2)$.

The difference of impacts on housing prices between a type of acoustic area and the reference area is given by $\frac{\partial y_i}{\partial N_j^{(i)}} = \lambda_j$.

The way N_j is included in the model goes beyond linearity and allows for more flexible modelling.

It is a well-known fact that under the assumptions of homoskedasticity, non-autocorrelation and multivariate normal distribution of the vector of random disturbances, the OLS estimation method provides both BLUE estimates of the model parameters and the estimated variance of such parameters.

However, model (1) does not take into account the spatial argument, that is to say, the existing spatial dependencies among the prices of dwellings. As has been shown in the literature (Anselin, 1988), the omission of spatial effects can result in estimators being inefficient and, what is worse, inconsistent, regardless of the estimation method. In order to capture the existing spatial dependencies in the prices of dwellings, following Le Sage and Pace (2009), the specification we propose is the spatial Durbin model (SDM). We chose this model because it is quite general and robust. In fact, the usual spatial specifications —spatial autoregressive models (SAR) and spatial error models (SEM)—, are particular cases of the SDM. In addition, the SDM provides consistent estimates for the majority of spatially correlated data generating processes.

The SDM is given by the following matrix equation:

$$y = \rho Wy + \alpha i_n + X\beta + WX\gamma + \varepsilon \qquad \varepsilon \sim N(0,\sigma_\varepsilon^2 I_n) \tag{2}$$

where y is a $(n \times 1)$ vector including the observations of the logarithms of the house prices, X is a $(n \times k)$ matrix comprising the binary variables that indicate the type of acoustic area —according to both the gap between the legal standard and the level of noise and also the percentage of affected population— as well as the observations of the individual and areal characteristics associated to each dwelling and other spatial variables such as noise, surface, condition, mean mortgage in the neighbourhood, etc., i_n is a $(n \times 1)$ unit vector for the intercept (removed from X to avoid problems of exact multicollinearity in the estimation) and W is the $(n \times n)$ spatial weights matrix. Obviously, Wy and WX capture the spatial lags corresponding to the dependent variable and those included in X, respectively. On the other hand, ρ is a spatial parameter that measures the existing spatial dependence of the dependent variable, α is the intercept parameter, σ^2 is the variance of the disturbance under homoskedasticity and β and γ are $(k \times 1)$ vectors of parameters associated to the independent variables and their lags, respectively. Restrictions $\rho = 0$ and $\gamma = 0$ in the SMD lead to the non-spatial hedonic model (1).

As we know, the specifications that include the spatial lag of the endogenous variable, Wy, as a regressor, produce an endogeneity bias, because the spatial lagged variable is correlated to ε. However, under the assumption of multivariate normal distribution of disturbances, the parameters of the model, $\theta = (\rho,\alpha,\beta,\gamma,\sigma_\varepsilon^2)^T$, can be estimated using the maximum likelihood (ML) procedure. For this purpose, as well as for computing spillovers, following Le Sage and Pace (2009), we first re-write (2) as:

$$y = (I_n - \rho W)^{-1}[\alpha i_n + X\beta + WX\gamma] + (I_n - \rho W)^{-1}\varepsilon \qquad \varepsilon \sim N(0,\sigma_\varepsilon^2 I_n) \tag{3}$$

It is important to note that spatial spillovers (effects of changes in independent variables on the dependent variable) are not given by any vector of parameters directly in SDM. This is why —once again following Le Sage and Page (2009)— we express equation (3) as follows:

$$\begin{pmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{pmatrix} = \sum_{r=1}^{k+1} \begin{pmatrix} S_r(W)_{11} & S_r(W)_{12} & \cdots & S_r(W)_{1n} \\ S_r(W)_{21} & S_r(W)_{22} & \cdots & S_r(W)_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ S_r(W)_{n1} & S_r(W)_{n2} & \cdots & S_r(W)_{nn} \end{pmatrix} \begin{pmatrix} x_{1r} \\ x_{2r} \\ \vdots \\ x_{nr} \end{pmatrix} \begin{matrix} + V(W) i_n \alpha + V(W)\varepsilon, \\ \varepsilon \sim N(0, \sigma_\varepsilon^2 I_n) \end{matrix} \qquad (4)$$

where

$$\begin{aligned} V(W) &= (I_n - \rho W)^{-1} \\ S_r(W) &= V(W)(I_n \beta_r + W\gamma_r) \end{aligned} \qquad (5)$$

Now, we can compute both the direct and indirect effects, respectively, of a change in x_{ir} and x_{jr} on y_i as:

$$\frac{\partial y_i}{\partial x_{ir}} = S_r(W)_{ii} \qquad \text{and} \qquad \frac{\partial y_i}{\partial x_{jr}} = S_r(W)_{ij} \qquad (6)$$

Both impacts are non-linear functions of the estimated parameters and, in addition, depend on the parameters associated to the regressor X_r as well as on ρ.

As the magnitude of the impact of a variable X_r generally differs across regions, Pace and Le Sage (2006) define the Average Direct Impact (ADI), Average Total Impact (ATI) and Average Indirect Impact (AII) of regressor X_r as follows:

$$\begin{aligned} ADI &= n^{-1} \text{ trace } \left(S_r(W)\right) \\ ATI &= n^{-1} i_n^T \left(S_r(W)\right) i_n \\ AII &= ADI - ATI \end{aligned} \qquad (7)$$

Finally, one of the main advantages of the SDM is that if we set some restrictions in this model, it is possible to obtain other well-known spatial models. Setting $\gamma = 0$ leads to the SAR model, and by setting $\gamma = \rho\beta$ we obtain the SEM. As the SDM framework nests those models, it is robust under different specifications. Another advantage is that once the SDM, SAR and SEM have been estimated by ML, we can perform LR tests to select the appropriate specification.

In summary, for comparative purposes, we will estimate the hedonic house prices model using OLS and ML, depending on whether or not the spatial argument is included in the analysis.

5. Case study: Madrid

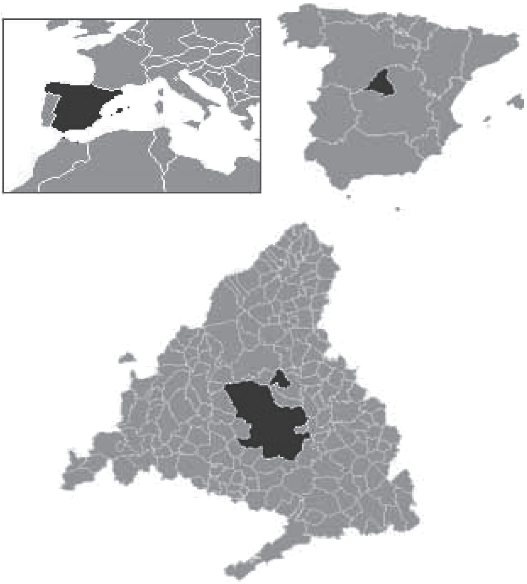
5.1. Housing market and noise

Madrid (the capital of Spain) is the third most populous city in the European Union (pop. 6,271,638 in 2009, 3,213,271 of which live in the city). Like other capitals in the world, Madrid is the city where Government institutions, the Parliament, embassies, main museums, central offices of the most relevant companies, etc., are located. This has made Madrid a large city covering 60,430.76 ha, together with a large peripheral metropolitan area with more than five million inhabitants that it is closely related to. Obviously, these relations imply movement and a large number of trips and regular flows of both population and also goods, etc., which has led to a complex transportation system.

More specifically, Madrid has both a dense ring road network (M-30, M-40, M-45 and M-50) and a dense radial highway network. Both networks have enormously improved accessibility to emerging industrial and high economic activity areas, resulting in competitiveness and dynamism. However, as a negative consequence of the above positive factors, road traffic has become the main source of noise.

In addition, Madrid has the fourth largest European airport and is the centre for train communications (half a thousand trains enter Madrid from the 10 most important Spanish cities, as well as from Paris and Lisbon). Freight transportation by train is also really important in Madrid. Every day 400 trains enter and leave the city, transporting 150,000 tons of commodities. In fact, Madrid has the largest inland maritime customs centre in Europe.

Figure 2. Location of Madrid



It is therefore no surprise that the number of vehicles in Madrid has increased by 5.6% over the last decade, amounting in 2010 to a total of 1,917,382. This implies 1,202.5 vehicles per km and 683.5 vehicles per 1,000 inhabitants. Two million drivers enter and leave the city on a daily basis. So, car pressure is increasing as well as its negative impacts on noise.

As a result of the economic development of Madrid and the increase in population, construction (especially residential construction) has become an extremely important industry for the economy of Madrid as a whole. According to the Spanish Regional Accounts, 2009, this sector contributes 8.6% of total GDP. Madrid is the city with the largest housing stock in Spain —11.5% of the total, with a percentage of home ownership of 78.7% (2,275,188 out of 2,890,229)— and is also the main housing market: in 2009 some 53,513 housing transactions were completed in Madrid (Spanish Housing Office). The highest housing prices in the country are also registered in Madrid.

As for noise, Madrid was the first city to establish regulations aimed at combating noise. The first Spanish law to specifically combat acoustic pollution was enacted in 1969. However, only the noise generated by industry and citizen activities and behaviour were considered up to the 1990s, environmental noise being omitted[1]. This shortfall was overcome through Appendix I of the Integrated Pollution Prevention and Control Act 16/2002, of July 1st. But it was not until the enactment of the Noise Act 37/2003 of November 17th that a nationwide law regulating this problem existed. This law was later completed by the Royal Decrees 1513/2005 and 1367/2007, which expound on it.

Acoustic quality objectives and immission limits are established in accordance with acoustic areas. The Noise Act defines an acoustic area as a territorial area, delimited accordingly by the competent authority, which has the same acoustic quality objective.

Finally, the Action Plan for Acoustic Pollution in Madrid was drawn up in 2009 with the objective of complying with the demands established in EU legislation and the Noise Act. This plan expressly recognises that the main source of noise in the city is vehicular traffic.

The SNM for Madrid provides both the levels of noise across the city and the amount of people affected by the different intervals of noise. The latter is core information to assess how serious the problem is and to give priority to areas where a large number of citizens are affected. As can be seen in Table 2, the percentage of population exposed to an L_{den} above 65 dBA is 14.9%. In the night time, the percentage of population affected by L_n levels above 55 dBA is 41.7%.

Table 3 reports the percentage of population exposed to more than 65 dBA (L_{den}) in some of the largest European cities and the corresponding percentage in the night time when the threshold is $L_n > 55$ dB. The data come from the Communication

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[1] Environmental noise is defined as undesirable or harmful exterior noise caused by human activity, including the noise made by vehicular, rail and air traffic and industrial dispatches.

Table 2. Population exposed to noise according to noise intervals

L_{den} *intervals*					
55-60	60-65	65-70	70-75	> 75	Total population affected
482,800	623,600	389,200	85,400	9,100	1,590,300
L_{n} *intervals*					
50-55	55-60	60-65	65-70	> 70	Total population affected
636,100	462,400	169,400	32,200	1,400	1,301,500

Table 3. Percentage of population exposed to $L_{den} > 65$ dB and $L_n > 55$ dB

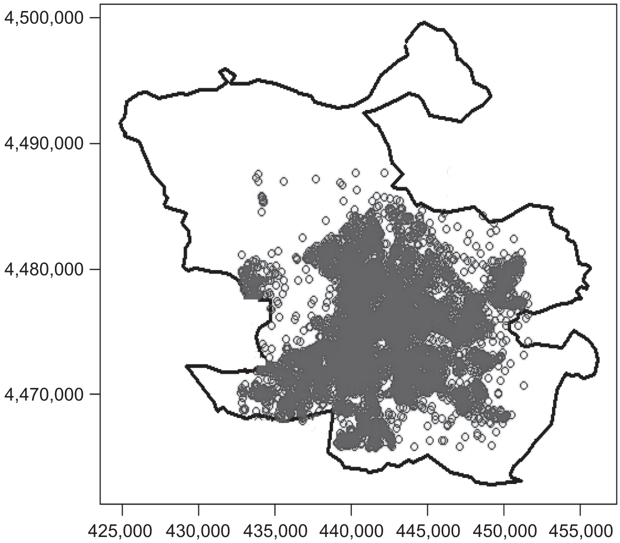
	Population	$L_{\text{den}} > 65\ dB$	$L_{\text{n}} > 55\ dB$
		% pop. > 65 dB	*% pop. > 65 dB*
Warsaw	1,704,717	42.8%	47.5%
Budapest	2,650,230	25.7%	29.9%
Bucharest	2,082,000	24.0%	28.0%
Hamburg	2,040,000	18.1%	24.7%
Greater London Urban Area	8,278,251	15.6%	19.9%
Madrid	3,238,208	14.9%	10.2%
Greater Manchester Urban Area	2,240,230	14.5%	7.1%
Berlin	3,331,249	8.2%	6.6%
West Midlands Urban Area	2,284,093	5.6%	6.5%
Rome	2,546,804	5.3%	5.2%

Information Resource Center Administrator (CIRCA) *http://circa.europa.eu/Public/irc/env/d_2002_49/library*, a collaborative platform between European Administrations and member states on acoustic cartography required by Directive 49/2002/EC.

5.2. Data sets

The issue of housing prices remains unresolved in Spain. This is the reason we have constructed our own database for Madrid. The final database we have created contains information about the price and 33 characteristics of 11,796 owner-occupied single family homes. Figure 3 shows the location of the observed dwellings. The database was created from the sales that took place in Madrid in the first quarter of 2010. As far as we know, it is the largest database ever used to analyse the Madrid housing market. It is important to note that the sample accounts for 90% of the sales in that quarter. The list of variables we have used mirrors the usual set used in the literature (see Table A in the appendix). Most of them have been codified as categorical to allow for more flexibility in the specification of the model. This allows for non-linearities between the different levels of each variable.

Figure 3. Location of observed houses



Source: Own elaboration based on a proprietary data base.

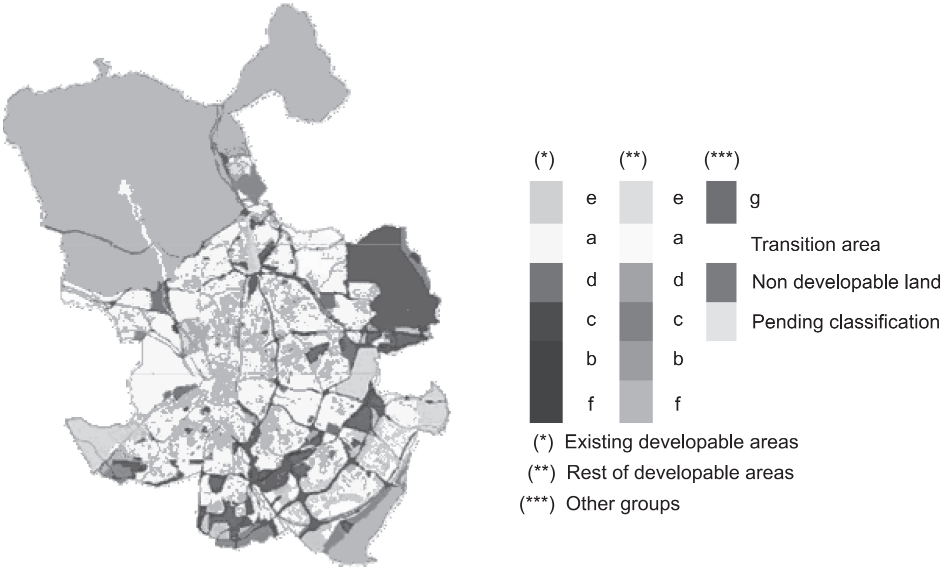
As for the data relative to noise, they were provided by the Department of Quality, Control and Environmental Assessment at the Madrid Council. As stated in section 3, conflict areas are obtained by implementing the data from the SNM (2006) in a GIS together with the daytime, evening and night-time legal standards set by the RD 1367/2007. Quiet areas are the zones where the level of noise is at least 5 dB below the legal standard for such an area. Figure 4 shows the acoustic areas of the city and Figure 5 contains the SNM for Madrid, while Figure 6 reports the classification of neighbourhoods according to noise exposure and population affected that we use in this article.

5.3. Results and policy analysis

Of course, the simplest (or better direct) expectation one could have is that the noise level reduces housing prices. But one could also assume some other more complex possibilities, depending on the urban model of the area under study, which would lead to examine the expected 'net effects' of noise and other core variables that influences housing prices.

In our case, as our starting point is official acoustic areas, and they are supposed to have been defined according to the activities that take place in a specific area, our

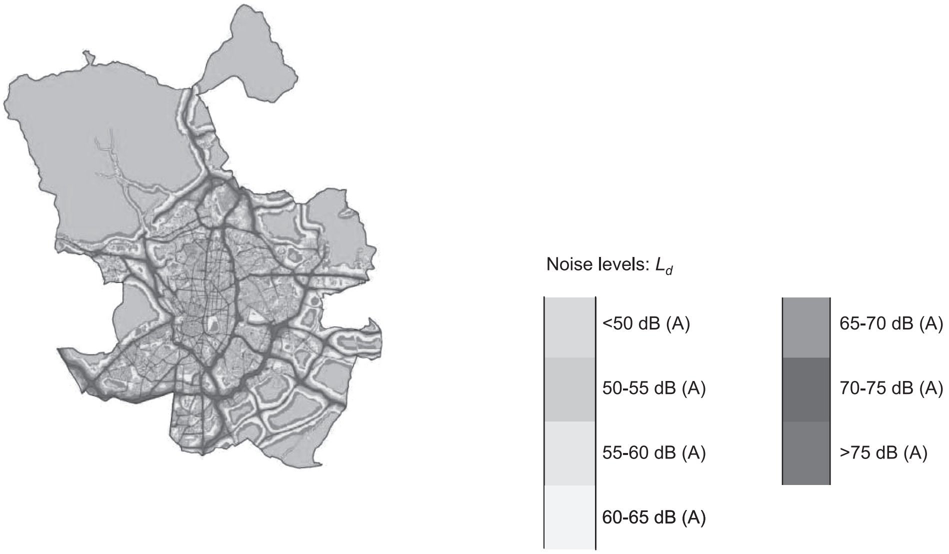
Figure 4. Acoustic areas (RD 1367/2007)



Type	*Characteristics*
a	Residential use
b	Industrial use
c	Recreational use and shows
d	Predominance of tertiary use, different to type C
e	Predominance of health, educational and cultural use that require special protection from acoustic pollution
f	Sectors of the territory affected by the general network of transport infrastructures
g	Natural landscapes that require special protection from acoustic pollution

Source: Ayuntamiento de Madrid (2010), pp. 28 and 29.

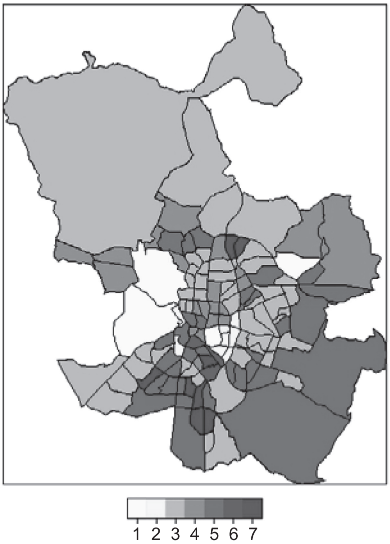
Figure 5. Strategic Noise Map (2006)



Type of area	*Indexes of noise (Target)*		
	L_d *(7:00 am-7:00 pm)*	L_d *(7:00 pm-11:00 pm)*	L_d *(11:00 pm-7:00 am)*
e	60	60	50
a	65	65	55
d	70	70	65
c	73	73	63
b	75	75	65
f	Indeterminate	Indeterminate	Indeterminate
g	Indeterminate	Indeterminate	Indeterminate

Source: Ayuntamiento de Madrid (2010), p. 9.

Figure 6. Type 1 to Type 7 neighbourhoods in Madrid



Source: Own elaboration based on Department of Quality, Control and Environmental Assessment at the Madrid Council.

prior expectations are a relative premium for quietude in Type 1 and Type 2 neighbourhoods (with respect to the Type 3 one), and a relative penalty for noise in Type 4 to Type 7 zones (again with respect to the reference neighbourhoods).

As for results, we first obtain ordinary least squares (OLS) estimates for a non-spatial hedonic model (Table 7, first column) and test for the presence of spatial autocorrelation in the residuals using the usual Lagrange Multiplier test statistics for error and lag dependence (Table 4). This and the rest of econometric models have been computed using the Spatial Econometrics Toolbox written in Matlab by Le Sage (1999) and the spdep library written in *R* by Bivand (2010).

Table 4. Lagrange multiplier diagnostics for spatial dependence

	LM-Lag	*LM-Lag Rob.*	*LM-Err*	*LM-Err Rob.*
OLS	438,477 (0.00)	73,886 (0.00)	400,977 (0.00)	36,387 (0.00)

* LM-lags test a non-spatial hedonic model (null hypothesis) versus a SAR model (alternative hypothesis). LM-Err test a non-spatial hedonic model (null hypothesis) versus a SEM (alternative hypothesis). In both cases, we display the test statistic, the asymptotic distribution under H_0 being a $\chi^2_{(1)}$, together with the associated *p*-value.

From the first column of Table 7 we can deduce that low noise has a substantial impact on prices in a Type 1 quiet neighbourhood compared to the reference ones where noise matches the legal target (Type 3). Moving from a Type 3 to a Type 1 neighbourhood implies an increase in price of dwellings of 6.5% due to quietude. However, this is not the case of a Type 2 neighbourhood. Despite quietude, a Type 2 neighbourhood unexpectedly penalises housing prices for quietude (1.7%) with respect to the reference neighbourhoods. Also unexpectedly, housing prices in conflict neighbourhoods where noise only slightly exceeds the legal standard have a premium for noise, irrespective of whether the population affected by an excess of noise over the legal standard for the zone is more or less than 20% of their total population. The premium for noise is even higher in a Type 6 neighbourhood (South and South-Eastern parts of the city and highly affected by road traffic noise). Finally, a Type 7 neighbourhood —a conflict area where noise greatly exceeds the legal standard and with a high percentage of their population affected by noise—, records a slight depreciation for noise with respect to the reference neighbourhoods, but not significant. Obviously, when interpreting the above results it must be taken into account that in the OLS model the spatial dependencies of dwelling prices are not considered. The rest of the coefficients of the model display the signs initially expected.

As indicated in Table 4, there is strong evidence of spatial dependence in the hedonic model. This suggests the specification of a spatial Durbin model (SDM) to capture this dependence (eq. 2). The reasons to choose the SMD are both, theoretical and statistical. From the theoretical point of view, it can be argued that the SDM is a quite general model that includes spatial lags both of the dependent variable and also the regressors. Given that home buyers are not atomistic agents (as decision makers) acting in isolation, but they interacts (its preferences, utility, etc.) with other heterogeneous agents in the system in the form of social norms, neighborhood effects, copy-catting and other peer group effects, SDM can be considered an optimal specification to take into account the above mentioned interactions (see Anselin, 1999, p. 2, and the references therein, and Anselin and Lozano-Gracia, 2008, pp. 14-15, for details). In addition, the inclusion of spatial lags both of the dependent variable and also the regressors makes SDM especially suitable to compute the spillovers; what is more, the SDM allows for a functional form of spillovers quite more flexible than other strategies based on a distance decay criterion.

It is possible to specify a more general model, as the spatial autoregressive model with autoregressive disturbances (SARAR model), by incorporating spatial dependence in the disturbance term, but: *a)* the spillovers would be the same (for the same vector of parameter values) and, *b)* the results of Moran's I and Geary' C tests obtained with the SDM residuals ($I = -1.2323$, p-value = 0.2178, and $C = -1.2126$, p-value = 0.2253) do not suggest the existence of spatial autocorrelation in the disturbance term. This is why, for the sake of simplicity, we have selected the SDM. In addition, as SDM nests other well known particular spatial specifications as SAR and SEM, this allows for testing whether those parsimonious specifications are preferred to SDM or not. It must be taken into account that the estimates of the SDM are consistent even in the case that the data generating process were the corresponding to the above more parsimonious models. From the statistical point of view, on the one hand we reject the specification of a SARAR model on the basis of the above results of Moran's I and Geary's C tests, and on the other hand, as the SAR and SEM spatial models are individual cases of the general SDM, we can proceed performing likelihood-ratio (LR) tests, the null hypothesis being the suitability of the restricted model (SAR or SEM) in comparison to the general SDM. Table 5 shows the result of those tests, which reject the null hypothesis in both cases, indicating the preference for the SDM model ahead of the rest. Table 6 displays other statistical information justifying our choice of the SDM.

Table 5. LR tests for selecting models

LR TESTS (ML estimation)		
SAR(H_0) - SDM(H_1)	220.63	(0.00)
SEM(H_0) - SDM(H_1)	255.47	(0.00)

* Likelihood ratio tests: The nested (SAR or SEM) model vs. the more general model (SDM). The asymptotic distribution of the test statistic is a χ^2 with degrees of freedom equal to the number of restrictions imposed by the corresponding nested model. The values in parentheses are the p-values associated to each test statistic.

Table 6. Estimated Hedonic House Price Models

	Non-spatial Models	*Spatial Models*		
	OLS	*SDM*	*SAR*	*SEM*
n	11,796	11,796	11,796	11,796
σ	21.27%	20.62%	20.83%	20.83%
$p(M)$	40	80	41	41
AIC	–3.09	–3.14	–3.13	–3.13
Log Likelihood		5,916.56	5,806.24	5,788.82
ρ		0.231 (67.10)	0.214 (61.49)	0.239 (27.98)

$p(M)$ represents the number of parameters in the model.

In order to specify the spatial econometric model we deal with, we have used a spatial weights matrix that takes into account the six closest neighbours. As usual, the weights matrices are used in row-standardised form. Nevertheless, we have checked that results do not vary significantly when other weights matrices are used (matrices with a different number of neighbours, Delaunay triangles from a Voronoi tessellation, etc.). As SDM includes the spatial lagged variables, we focus on spillovers (Table 7) instead of the coefficients of the regressors.

We must underline that the spillover measures the effect of a change in the regressor x_j on the dependent variable, this effect being divisible into changes due to the observation itself (direct effects) and those caused by neighbouring observations (indirect effects). As such spillovers are generally different for each observation $i = 1,\ldots,n,$ our results refer to the average values of the spillovers for all observations. In order to take into account the uncertainty regarding the parameters estimated when calculating the spillovers, 1,000 simulations are performed using different values for parameters each time. These values are obtained from the asymptotic distribution of the estimators, that is, in each simulation the values $\gamma = (\rho,\beta^T,\theta^T)^T$ are obtained by extracting a value from the distribution $N\left(\widehat{\gamma};\widehat{VAR}(\widehat{\gamma})\right)$ where $\widehat{\gamma}$ represents the vector of parameters estimated in the SDM model and the matrix $\widehat{VAR}(\widehat{\gamma})$ is the corresponding estimated variance-covariance matrix (Le Sage and Pace, 2009).

Note that ρ, which measures spatial dependence in this specification, is significant and positive. The absolute value of ρ (0.231) is in line with other research on noise and air pollution. With respect to the impact of the types of neighbourhood considered (according to the level of noise relative to the legal standard for the site) on the price of dwellings, results are similar to those obtained in the above non-spatial regression. Nevertheless, some differences can be appreciated. Results reported in Table 7 confirm that low noise has a substantial impact on price in Type 1 quiet neighbourhoods compared to the reference neighbourhoods where noise matches the legal target (Type 3). Moving from a Type 3 to a Type 1 neighbourhood implies an increase in the price of dwellings of 10% due to quietude. However, there is no significantly different impact on price for quietude when Type 2 and Type 3 neighbourhoods are considered. Unexpectedly, conflict neighbourhoods where noise only slightly exceeds the legal standard have an extra price for noise irrespective of whether the population affected by an excess of noise over the legal standard for the area is above or below 20% of their total population. These Type 4 and 5 neighbourhoods are next to the main ring road of the city (M30), a very busy road, and in relation to a Type 3 neighbourhoods, the extra price for exposure to noise is certainly similar in both types of areas. That ’premium for noise’ is higher in Type 6 neighbourhoods (high level of noise with respect to the legal standard and low percentage of people exposed to noise): 5.9%. Finally, in Type 7 neighbourhoods, conflict areas where noise greatly exceeds the legal standard and a high percentage of their population is affected by noise, do not record a significant impact for noise with respect to the reference neighbourhood (Type 3). As in the non-spatial case, the rest of the coefficients of the model display the signs initially expected.

The unexpected results for neighbourhoods with noise levels over the legal standard are a consequence of large indirect spillovers, which in Type 6 neighbourhoods largely compensate the direct externalities (with the opposite sign) and in Type 7 zones are certainly similar to direct spillovers. In Type 4 and Type 5 areas indirect spillovers practically coincides with total ones (albeit they are not significant).

The direct spillovers show the expected sign for non quiet areas (a penalty for noise deviating from the legal standard that increases with the percentage of population affected), but are not significant in all Types of neighbourhood.

The reason of the low magnitude of direct effects, irrespective of the type of neighbourhood, could be attributed to the use of both, lags in the dependent variable and lags in the regressors. As is known, a consequence of the inclusion of a large number of lagged reggresors is more room for indirect effects.

The reason why the indirect effects only display the expected pattern in quiet areas could be that noisy neighbourhoods are surrounded by quiet ones and areas with a small gap between the legal standard and the level of noise are next to areas where there is a large gap and areas where the level of noise is at least 5 db(A) below the legal standard.

Results do not change substantially when the SAR or SEM specifications are implemented (Table 7). The main differences in regard to the SDM estimates are: i) the willingness to pay for quietude in a Type 1 neighbourhood decreases from 10% to 5-6%; ii) the impact of moving from the reference neighbourhoods to a quiet Type 2 neighbourhood is a reduction in price of approximately 2.5%; iii) the extra price for moving from the reference neighbourhoods to a Type 6 neighbourhood (where noise greatly exceeds the legal standard) drops from 5.9% to 2.4% with SAR model and 3.5% with the SEM; and iv) the extra price for moving from a Type 3 to a Type 7 neighbourhood turns into a slight penalty.

Table 7. Total, direct and indirect spillovers according to type areas

	OLS	*SDM*			*SAR*			*SEM*
		Total	*Direct*	*Indirect*	*Total*	*Direct*	*Indirect*	
	Coeff. *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*	*Coeff.* *(t-stat)*
Type 1 Area	0.0653 (5.07)	0.1003 (5.08)	–0.0278 (–0.90)	0.1281 (3.51)	0.0602 (3.84)	0.0476 (3.82)	0.0126 (3.78)	0.0487 (3.14)
Type 2 Area	–0.0169 (–1.77)	0.0009 (0.07)	–0.0344 (–0.96)	0.0353 (0.92)	–0.0250 (–2.05)	–0.0198 (–2.06)	–0.0053 (–2.02)	–0.0250 (–2.13)
Type 4 Area	0.0275 (3.78)	0.0278 (2.68)	0.0083 (0.37)	0.0195 (0.79)	0.0151 (1.66)	0.0119 (1.66)	0.0031 (1.66)	0.0249 (2.79)
Type 5 Area	0.0213 (4.09)	0.0287 (4.02)	0.0015 (0.09)	0.0272 (1.51)	0.0204 (3.08)	0.0161 (3.08)	0.0043 (3.02)	0.0170 (2.65)
Type 6 Area	0.0464 (3.78)	0.0594 (3.38)	–0.0244 (–0.64)	0.0837 (1.96)	0.0237 (1.53)	0.0187 (1.53)	0.0049 (1.52)	0.0349 (2.34)
Type 7 Area	–0.0034 (–0.36)	0.0068 (0.52)	–0.0400 (–1.44)	0.0468 (1.54)	–0.0054 (–0.45)	–0.0043 (–0.45)	–0.0011 (–0.45)	–0.0113 (–0.98)

* Direct and total spillovers for the non-spatial and SEM models coincide with the β_i coefficients of the corresponding models. There are no indirect spillovers in these models. For the SDM and SAR models the spillovers (direct, indirect and total) are computed using equation (10). The values in brackets are the *t*-statistics of the coefficients.

On a note apart, it is no surprise that indirect effects on SDM are larger than in SAR. The reason is that in the SAR specification $\gamma_r = 0$ and, since the indirect effects are located off-diagonal terms of $S_r(W)$, they are multiplied by ρ and powers of ρ. As the estimated value of ρ is 0.21, the indirect effects are small. However, in SDM γ_r is not null and the spillovers are expanded in the form:

$$\begin{aligned} S_r(W) &= \left[I_n + \rho W + \rho^2 W^2 + \ldots\right]\left(I_n\beta_r + W\gamma_r\right) \\ &= I_n\beta_r + W\gamma_r + \rho W\beta_r + \rho W^2\gamma_r + \rho^2 W^2\beta_r + \rho^2 W^3\gamma_r + \ldots \end{aligned} \tag{8}$$

Note that in the above equation the term $W\gamma_r$ specifically affects to the off-diagonal values of $S_r(W)$. Note also that such values are not weighted by ρ. As a consequence, the indirect effects tend to be much larger in SDM than in SAR.

The main findings that derive from the above estimated models lead firstly to the question of whether the acoustic areas defined by the RD 1367/2007 are well defined, because a premium for noise is not in agreement with the hedonic theory.

The second possibility assumes that the acoustic areas are well defined but, as there is no discussion regarding the spatial dependence of dwelling prices and such dependence immediately leads to spatial hedonic pricing specifications, indirect effects are the cause of the unexpected result. Indeed, including spatial lags in the hedonic pricing model implies taking into account adjacent locations to that where the impact of a specific amenity is estimated. That usually results in substantial indirect impacts and, as the different acoustic areas defined in the RD 1367/2007 spread right across the city, indirect impacts are large and could display the opposite sign to direct effects and, as a consequence, more than offset the direct spillovers. As a result, the sign and sometimes the magnitude of total impacts do not agree with the hedonic theory. If this second possibility is the right one, the following question arises: the acoustic areas that home buyers include in their utility function coincide with the acoustic areas defined in the RD 1367/2007? In the case of a negative response, subjective areas should be considered in the analysis to explain the impact of noise on the price of dwellings. But in that case a serious problem looms in future. As a set of measures is going to be implemented to reduce noise in the areas where legal standards are exceeded and to maintain quietude in quiet areas, if official acoustic areas do not match home buyers' perceptions, indirect impacts will lead to high prices of dwellings in locations where noise exceeds the legal standard due to their proximity to quiet areas or areas where the level of noise matches the legal standard. As the Plan designed for Madrid Council to improve the level of acoustic pollution insists, the opinion of citizens is core information. As such, we recommend redesigning the acoustic areas according to citizens' perception of noise.

The third and last possibility is that the proposed spatial strategies are not appropriate for estimating the impact of noise on housing prices. The weakest point of the model is probably the contiguity matrix. Some anisotropic patterns of contiguity could be considered for noise impact estimation purposes, and that pattern should probably be different depending on the area of the city. In this way, the indirect effects will be more realistic and will not so clearly shadow the direct spillovers.

In any case, irrespective of the adequacy of the acoustical areas, in light of the magnitude of the indirect effects it is clear the importance of the noise conditions of adjacent neighbourhoods in the willingness to pay for quietude.

6. Conclusions

One of the consequences of noise, especially road traffic noise, is the depreciation of houses located in neighbourhoods exposed to levels of noise that exceed the legal standard for such areas.

As road traffic is related to human activity and needs, much of it occurs in areas where people live, work, go to school, etc. And these kinds of activities can be expected to increase in the future, making noise an even greater problem in the future unless steps are taken to mitigate it. It is important to bear in mind that the impact of noise on housing prices can result in the degradation of the neighbourhood and the city being divided by housing prices.

The construction of acoustic areas and strategic noise maps, as well as the estimation of the noise depreciation index, are core instruments for addressing future efforts to mitigate the noise problem and avoid the degradation of the most affected neighbourhoods. That is one of the reasons why economists have developed a number of procedures that provide reasonable estimates of the monetary value of acoustic externalities and that the European Commission has developed projects to combat noise, including SILENCE, HARMONOISE-IMAGE, SMILE and QCITY, among others.

However, in Madrid the neighbourhoods that exceed the legal standard for noise, regardless of the percentage of population exposed to excessive noise, have a «premium for noise» that could be concealing the degradation of the neighbourhood. This premium for noise is due to the indirect effects that arise from the proximity between noisy areas and quiet areas in the city. In most aspects, Madrid could be considered a concentric city and indirect effects, which have been shown to be certainly relevant, are very difficult to interpret.

Three possible explanations for our unexpected finding are proposed. The first refers to the inadequacy of the acoustic areas defined in the RD 1367/2007. The second is that the acoustic areas that home buyers include in their utility function do not coincide with the acoustic areas defined in the RD 1367/2007. And the third, closely related to the above mentioned concentric disposition of the city, focuses on the pattern of the contiguity matrices included in the spatial hedonic specifications. In our opinion, an anisotropic pattern of contiguity could be considered for noise impact estimation purposes and should probably be different depending on the area. Of course, this is a promising and challenging avenue of research.

In spite of the above possibilities, we should not forget that, as stated in Chay and Greenstone (2005) for air quality, exogenous differences in noise gaps with respect to the legal standard are extremely difficult to isolate because the «true» relationship between the type of area (according to the above mentioned gap) and the price of properties may be obscured in cross-sectional analysis by unobserved determinants of housing prices that co-vary with such a gap. This question remains unanswered.

Finally, special attention should be paid to citizen perception of noise, because to the extent that legal and perceived acoustic areas do not match, the policy measures proposed in the Plan designed for Madrid Council to mitigate acoustic pollution will fail to avoid the degradation of the South-East peripheral areas of the city, which have a high percentage of population exposed to levels of noise clearly above the legal standard for such areas.

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Appendix

Table A. Variable names and descriptions

Variable name	*Description*
Dependent variable	
Price	House price
Variable of interest	
Type 1 Area	Quiet area (% of affected pop. under 20%)
Type 2 Area	Quiet area (% of affected pop. above 20%)
Type 4 Area	Conflict area where noise slightly exceeds the legal standard
Type 5 Area	Conflict area where noise greatly exceeds the legal standard
Type 6 Area	Conflict area where noise greatly exceeds the legal standard
Type 7 Area	Conflict area where noise greatly exceeds the legal standard

Table A. *(Continue)*

Variable name	*Description*
House characteristics	
Pollution	Census based pollution perception
Crime	Rate of crime
Good condition	Indicator variable for good condition
Flat	Indicator variable for flats
Studio-apartment	Indicator variable for studios
Top-floor flat	Indicator variable for top-floor flats
House	Indicator variable for houses
Age	Age of the housing
Ground level	Indicator variable for ground level
Floor 1st	Indicator variable for floor 1st
Floor 2nd - 3rd	Indicator variable for floor 2nd and floor 3rd
Floor 4th - 5th	Indicator variable for floor 4th - 5th
Floor 6th or more	Indicator variable for floor 6th or more
Baths	Number of bathrooms
Garage	Indicator variable for parking space
Lift	Indicator variable for lift
Air conditioning	Indicator variable for central air conditioning
Swimming pool	Indicator variable for swimming pool
Monthly mortgage	Monthly mortgage
Areal characteristics	
.30	Indicator for housing which are inside of M-30
M.30.2	Indicator for housing which are close to the M-30
Shopping area	Indicator for houses in the shopping area
Historical quarter	Indicator for houses in the historical quarter
Built up area	Number of square meters of built up area
Density pop. distr.	Population density in the district
Children (% distr.)	Percentage of children below 14 years
Immigrants (% distr.)	Percentage of immigrants in the district
Mortgage reference area	Mean mortgage in the area