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# Analysis of Noise Exposure in Two Small Towns

Guillermo Rey Gozalo, J. Miguel Barrigón Morillas, Valentín Gómez Escobar
Applied Physics Department, Acoustic Laboratory, Extremadura University, 10003 Caceres, Spain.
guille@unex.es, barrigon@unex.es, valentin@unex.es

**Summary**
The categorisation method for the study of urban noise has been used with good results in cities with populations of between 50,000 and 330,000 inhabitants. However, its application in smaller towns has not been previously demonstrated. Thus, this work studies the impact of urban noise pollution in two towns of approximately 9,000 inhabitants, Olivenza (Spain) and Campo Maior (Portugal). The categorisation method was compared with the grid method. In addition, three methods for estimating the population affected by different noise levels were tested. The statistical analyses results showed that the categorisation method was applicable for small cities (of the studied size). In addition, the categorisation method was more suitable for the analysis of noise annoyance than the grid method. Conversely, because little information is available regarding the environmental problem of noise pollution in small towns, the noise exposures and the percentages of the populations annoyed by noise were compared with previous results from much larger towns.

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## 1. Introduction

The European Union Directive 2002/49/EC uses noise maps as the main tool for evaluating environmental noise exposure [1]. This directive proposes the use of either direct measurements or harmonised sound index computations for generating these maps. Independently of the advantages and drawbacks of these two methods, there is a clear interest in developing efficient sampling strategies. These measurements can be used for noise mapping or for the validation of simulation results [2].

In recent years, the generation of noise maps has transitioned from the use of measurements to the use of simulation methods. This trend can be observed by comparing the differences between the old version of ISO 1996-2 [3] and the new version [4]. One explanation for this trend is the absence of a proposed methodology for noise mapping with measurements that improve the drawbacks of the known *grid method*.

Recently, the proposed application of the categorisation method has been studied in cities with between 50,000 and 330,000 inhabitants [5, 6, 7]. In the present work, we analyse the noise pollution in two towns that have approximately 9,000 inhabitants with two sampling methodologies, the grid method (described in ISO 1996-2 [3, 4]) and the categorisation method [5, 6, 7]. In the categorisation method, the noise levels are associated with each mapped street rather than with an area (as in the grid method). The predictive capacities of the two procedures were compared in a recent publication for a city with nearly 100,000 inhabitants [8].

The two small towns selected for this study are in Spain and Portugal and have similar socioeconomic and urban-architectural characteristics. Although most noise studies have been conducted in large cities around the world, acoustic pollution is not a problem that is exclusive to large cities. A significant proportion of the population in our countries live in towns of fewer than 20,000 inhabitants (32% in the case of Spain [9]). Therefore, this study will allow us to assess the risk and extent of urban noise in small towns.

Once the noise maps for both methodologies were constructed, the population exposed to the different sound levels was estimated. Because there is currently no standardised method for estimating a population's exposure to noise [10], we analysed three different estimation methods.

Finally, the proportion of the population that would be annoyed ($\%A$) or highly annoyed ($\%HA$) by noise was calculated from the $L_{\mathrm{den}}$ (dBA) values registered at the sampling points [11].

The objectives of this study are listed below.

- To determine the influence of the sampling method (categorisation and grid) on the determination of the noise levels that affect the resident population.
- To analyse and determine the suitability of the three different methods for estimating the proportions of the population affected.
- To study the impact of noise on the populations of two similar small towns.
- To analyse and compare the proportion of the population exposed to noise and their levels of annoyance

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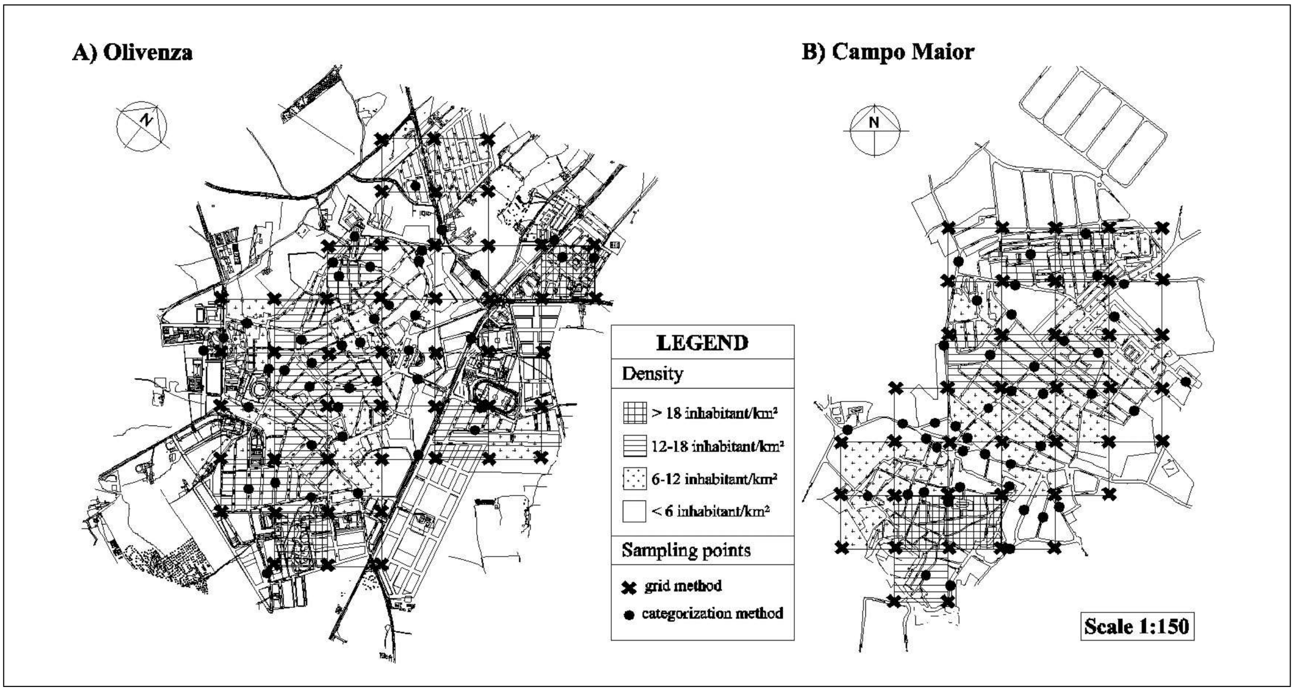

Figure 1. Maps of Olivenza (a) and Campo Maior (b). The background of each grid represents its estimated population. Squares represent a population density of more than 18 inhabitants/km$^2$, lines represent a population density of between 12 and 18 inhabitants/km$^2$, crosses represent a population density of between 6 and 12 inhabitants/km$^2$, and no background represents a population density of below 6 inhabitants/km$^2$. Sampling points used for the grid method (crosses) and the categorisation method (discs) are also shown.

based on proposed reference values from the literature and from previously published results from larger towns.

## 2. Methods

### 2.1. The studied towns

This study was conducted in the towns of Olivenza (in the region of Extremadura, Spain) and Campo Maior (in the region of Alentejo, Portugal). These two towns each have approximately 9,000 inhabitants. In this sense, the towns are typical for the regions of Extremadura and Alentejo in which approximately 60% and 47% of the population, respectively, live in towns with less than 20,000 inhabitants [9, 11].

Geographically, these cities are located at similar distances (approximately 10 km) from the border of Spain and Portugal. The cities are each socioeconomically connected with larger towns (Badajoz, Spain and Elvas, Portugal, respectively). In addition, Olivenza belonged to Portugal from 1297 (Treaty of Alcañices) to 1801 (Treaty of Badajoz). Because of their cross-border locations and their history, Olivenza and Campo have similar architecture, art, gastronomy, and folklore. Both towns have an older walled section (better preserved in the case of Olivenza) in which most of the streets are paved with narrow U-shaped cross-section stones.

Figure 1 shows the portion of each town's population that was estimated to evaluate noise in the different cells used by the grid method. In Olivenza, the two most densely populated cells (>18 inhabitants/km$^2$) are south and east of town. This area is a residential zone that consists of apartment buildings separated by broad avenues. In Campo Maior, there are also two cells with population densities greater than 18 inhabitants/km$^2$. These cells are located south of the city, which is the old part of the town.

### 2.2. Sampling methods

#### 2.2.1. Grid method

The grid method is the most commonly used sampling method. In fact, this sampling method is part of the old [3] and the new [4] ISO 1996-2. In the grid method, a grid is superimposed over a city map, and the measurement points are located at the cell vertices or at the nearest location when the vertices are inaccessible. Thus, some points are located away from roads. In the present study, a 200-metre grid size was used. Because of the size of the towns, the number of required sampling points was comparable to that of the categorisation method. Only the cells that included residential or commercial areas were considered. The cells located in industrial areas were excluded because no one resided at these points. As shown in Figure 1, a total of 32 cells were established in Olivenza with 48 sampling points, and 27 cells were established in Campo Maior with 41 sampling points.

#### 2.2.2. Categorisation method

The categorisation method is based on the widely contrasted assumption that road traffic is (for the vast majority of town streets) the most important source of urban noise (and of the spatial and temporal variability of that noise).

The streets of the two towns were assigned to one of the six categories established in previous work [6, 7], which are the following:

Type 1 comprises those preferential streets whose function is to form a connection with other Spanish towns (national roads for the five towns studied) and to interconnect those preferential streets (in general, the indication of this latter type of street is its system of road signs).

Type 2 comprises those streets that provide access to the major distribution nodes of the town. For the purpose of this study, a distribution node is considered to exist when at least four major streets meet. This definition does not include any possible nodes of preferential streets as defined in Type 1 above. This category also includes the streets normally used as an alternative to Type 1 in case of traffic saturation.

Type 3 comprises the streets that lead to regional roads, streets that provide access from those of Types 1 and 2 to centres of interest in the town (hospitals, shopping malls, etc.), and streets that clearly allow communication between streets of Types 1 and 2.

Type 4 comprises all other streets that clearly allow communication between the three previously defined types of street, and the principal streets of the different districts of the town that were not included in the previously defined categories.

Type 5 comprises the rest of the streets of the town except pedestrian-only streets.

Type 6 comprises pedestrian-only streets.

Ten sampling points were randomly selected in each category to avoid the presence of equivalent points (two points located in the same section of the street without any intersection between them). In some categories (mainly categories 1 and 2), 10 non-equivalent points were not found. Thus, the corresponding number of sampling points was less than 10. Category 6, pedestrian streets, was not measured because it represented only a small proportion of the total street length (0% in the case of Campo Maior and 6% in the case of Olivenza).

The total number of sampling points measured by this method was 45 in Olivenza and 44 in Campo Maior (Table I). Both numbers were similar to the number of sampling points used for the grid method (48 and 41, respectively).

### 2.3. Measurement procedure

All of the measurements were made following the ISO 1996-2 2007 guidelines [4]. Because it was impossible to make long-term measurements at all of the sampling points, short-term measurements were made during three different daytime intervals to account for possible diurnal noise level variations. In particular, these measurements were made from between 07:00 and 19:00 and were defined as "$L_{\text{day}}$" by the European Directive 2002/49/EC [1] in the different 2007 and 2008 sampling campaigns. At every sampling point, a measurement was made during each of the following time intervals on different working days: 07:00–11:00, 11:00–15:00, and 15:00–19:00. Thus, more than one measurement at each location per day was never performed, and measurements at each location were never performed in the same time interval. The duration of each short-term measurement was 15 minutes. The sound-level meter was placed at a height of 1.5 metre. In the categorisation method, the sound-level meter was placed at one metre from the curb. In the grid method, when the measurement point was less than 5 metres from a street roadway, the sound-level meter was also placed at one metre from the curb. This was performed to obtain points from the grid method that could be compared with points from the categorisation method. With this procedure, nearly 60% and 70% of the sampling points from the grid method were comparable in Olivenza and Campo Maior, respectively.

Table I. The street length $\%L$ (calculated by measuring the length of all the streets of each category and comparing this length with the total length of the streets of the town) and population percentage $\%P$ in the different categories (1–5), the number of sampling points $N$ selected in each category, and the average values (arithmetic mean) of the $L_{\text{day}}$ (dBA) and $L_{\text{den}}$ (dBA) noise indices measured in the different categories of the Olivenza and Campo Maior towns.

| | $\%L$ | $\%P$ | $N$ | $L_{\text{day}}$ | $L_{\text{den}}$ |
|---|---|---|---|---|---|
| Olivenza | | | | | |
| 1 | 11.3 | 5 | 9 | 67.7 | 70.0 |
| 2 | 6.0 | 5 | 6 | 64.9 | 67.4 |
| 3 | 13.5 | 10 | 10 | 61.9 | 64.6 |
| 4 | 12.2 | 12 | 10 | 58.5 | 61.3 |
| 5 | 57.0 | 68 | 10 | 54.1 | 57.1 |
| Campo Maior | | | | | |
| 1 | 3.3 | 1 | 8 | 65.9 | 69.0 |
| 2 | 4.9 | 5 | 6 | 64.9 | 68.0 |
| 3 | 14.9 | 10 | 10 | 62.0 | 64.9 |
| 4 | 13.4 | 12 | 10 | 57.8 | 60.3 |
| 5 | 63.5 | 72 | 10 | 53.1 | 55.1 |

Data sheets were completed for each measurement with information such as traffic flow, vehicle types, weather, street dimensions, and rolling surface. The sound levels recorded included the equivalent level ($L_{\text{day}}$), percentiles ($L_{1,\text{day}}$, $L_{10,\text{day}}$, $L_{50,\text{day}}$, $L_{90,\text{day}}$, and $L_{99,\text{day}}$) and the maximum and minimum levels ($L_{\max,\text{day}}$ and $L_{\min,\text{day}}$). The fast (F) time weighting was applied to the measurements with a weight of A.

Along with the short-term measurements for each of the categories described above, at least one long-term measurement was made. These measurements were obtained by mounting a sound-level meter on a rigid structure that was 1.5 metres from the façade on different balconies. Special care was taken when selecting these points to assure the security of the monitoring equipment against adverse weather conditions and vandalism. The duration of each long-term measurement was approximately one week. These measurements enabled us to analyse the variation of sound levels in the various time periods not covered by the short-term measurements.

### 2.4. Estimating the population exposed to noise

The procedure used to estimate the proportion of the population exposed to noise is described here. First, the noise levels in both towns were sampled through the grid and category methods. Once the data were obtained, the noise levels in each category and grid cell and the populations living in each category and grid cell were estimated.

To make these estimates, the town councils provided us with demographic data that included total population ($P_i$) and the population for each street. With this information, the number of inhabitants living in each category and grid cell was estimated in three different ways.

- Method A: For each town, the linear population density ($D_i$) was determined, as follows from the total population ($P_i$) and total length of the streets ($L_i$),

$$D_i = \frac{P_i}{L_i}. \tag{1}$$

  When the length of the streets in each grid cell or category ($LZ_{ij}$) is known, the population of each cell or category ($F_{ij}$) is given by $F_{ij} = D_i \cdot LZ_{ij}$. Here, the subscript $i$ indicates the town, and the subscript $j$ indicates the grid cell or category.
- Method B: The method described in "*Good Practice for Strategic Noise Mapping and Production of Associated Data on Noise Exposure*" [2] was used to calculate the population of a particular area. Thus, the total population ($P_i$) was divided by the total inhabited area ($A_i$) for each town to give the population density ($H_i$). This value gave the population of each cell or category when multiplied by the inhabited area of each cell or category. The inhabited area of each category was given by the area of the inhabited building with its main door in this category.
- Method C (only for the categorisation method): In the categorisation method (as noted above) a noise value is assigned to each street. Therefore, we used the population of the street that was provided by the town councils. This was the reference procedure for the categorisation method, although the Method A and B results were also calculated.

### 2.5. Calculation of the population annoyed by noise

Once the noise levels for which the population was exposed were calculated, the percentages of annoyed ($\%A$) and highly annoyed ($\%HA$) population were estimated with the expressions [11, 12]

$$\begin{aligned} \%A = {} & 0.0001795\left(L_\mathrm{den} - 37\right)^3 \\ & + 0.0211\left(L_\mathrm{den} - 37\right)^2 \\ & + 0.5353\left(L_\mathrm{den} - 37\right), \end{aligned} \tag{2}$$

$$\begin{aligned} \%HA = {} & 0.0009868\left(L_\mathrm{den} - 42\right)^3 \\ & - 0.01436\left(L_\mathrm{den} - 42\right)^2 \\ & + 0.5118\left(L_\mathrm{den} - 42\right). \end{aligned} \tag{3}$$

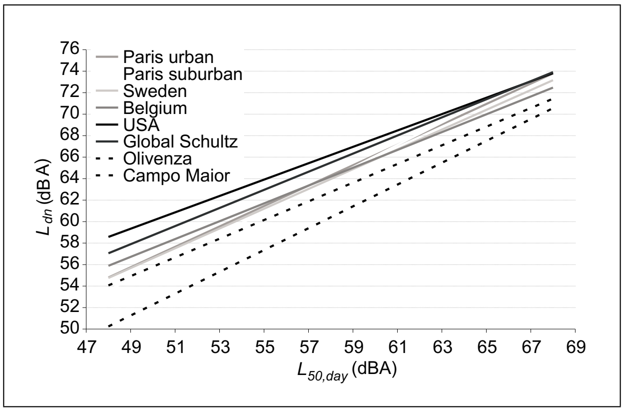

Figure 2. The relationship between $L_\mathrm{dn}$ and $L_\mathrm{50,day}$ for the studies conducted in different cities.

Thus, as written in the EU Directive, the $L_\mathrm{den}$ noise indicator was used to evaluate the noise annoyance (one of the objectives of this work). Because the short-term measurements were made during the daytime (as noted above), we needed to determine a relationship to connect $L_\mathrm{den}$ with a diurnal index. To do so, we first considered the relationships reported by Shultz for certain countries and cities between $L_\mathrm{dn}$ and $L_\mathrm{50,day}$ [13]. Next, the $L_\mathrm{den}$ index was obtained using the relationship between $L_\mathrm{den}$ and $L_\mathrm{dn}$ that was proposed by Miedema and Oudshoorn [11].

When the relationships between $L_\mathrm{dn}$ and $L_\mathrm{50,day}$ were compared with those proposed by Shultz (see Figure 2), they appeared to have different behaviour. Thus, an analysis of covariance (ANCOVA) showed that the slopes of these models were significantly different ($p$-value $< 2.2 \cdot 10^{-16}$). Therefore, we decided to identify our own relationship. However, instead of applying the $L_\mathrm{50,day}$ index as Schultz did, we studied the correlations of the different sound indices to select the one that was most strongly correlated with $L_\mathrm{den}$. Finally, this index was found to be $L_\mathrm{day}$ in both towns. Therefore, the final expressions used to obtain the $L_\mathrm{den}$ values from the *in situ* diurnal measurements were as

Olivenza :

$$L_\mathrm{den} = 0.95 L_\mathrm{day} + 5.60 \quad (r = 0.93, S_y = 1.70\,\mathrm{dBA}), \tag{4}$$

Campo Maior :

$$L_\mathrm{den} = 1.08 L_\mathrm{day} - 2.32 \quad (r = 0.98, S_y = 0.97\mathrm{dBA}). \tag{5}$$

### 2.6. Statistical analysis

As noted above, three sound level measurements were made at each sampling point for both methods. The sound level assigned for each sampling point was the energy average of these three measurements. To study the population's noise exposure, the measured sound levels were extrapolated to the nearest façade and normalised to a height of 4 metres [1]. For these calculations, the normalisation effects of geometric divergence for open profile streets (considering streets as a source of line noise) were considered. In contrast, the French Standard "Guide du Bruit" corrected the data from streets with a U-shape [14]. In the grid method, the noise level assigned to each cell ($S_{ij}$) was the arithmetic mean of the sound levels measured at the points ($G_{ijk}$) of the grid cell (the subscript $k$ refers to the sampling point code). The noise level assigned to each cell was assumed to be the expected value for the points located within the cell.

In the categorisation method, the value assigned to each category ($R_{ij}$) was the arithmetic mean of the sound levels measured at the sampling points ($C_{ijk}$). This value was the expected value for all of the other points located in the same category.

## 3. Results and discussion

### 3.1. Overall analysis of the sound levels

For the categorisation method, the mean values of $L_{\text{day}}$ obtained from the measurements and the calculated values of $L_{\text{den}}$ for both cities and for each category are shown in Table I. In Category 1 (the noisiest category) and in categories 4 and 5 (the categories with a higher percentage of resident population), the sound values obtained in Olivenza are higher than those obtained in Campo Maior. However, the sound values obtained in categories 2 and 3 were similar in both towns.

For the grid method, Figure 3 shows a bar chart of the calculated $L_{\text{day}}$ and $L_{\text{den}}$ noise values for the different cells. The highest $L_{\text{day}}$ index grid value percentages corresponded to the 55–60 dBA intervals in both towns. However, the highest percentage of the grid values for the $L_{\text{den}}$ index corresponded to the 60–65 dBA interval in Olivenza and to the 55–60 dBA interval in Campo Maior. Thus, these results suggest that Campo Maior had lower noise levels than Olivenza.

To calculate a global noise value for these towns from the grid method, the arithmetic mean of the values assigned to the points ($G_{ijk}$) that form the cells could be taken. Similarly, from the categorisation method, the mean value of the categories could be used, and each category could be weighted by the ratio between its length and the total length of the town streets (given in Table I). Thus, the following are obtained:

- Olivenza: $L_{\text{day}}$ values of 58.0 dBA and 57.9 dBA, and $L_{\text{den}}$ values of 60.8 dBA and 60.7 dBA for the grid and categorisation methods, respectively.
- Campo Maior: $L_{\text{day}}$ values of 55.3 dBA and 56.0 dBA, and $L_{\text{den}}$ values of 57.6 dBA and 58.4 dBA for the grid and categorisation methods, respectively.

Therefore, no differences were observed between the two sampling methods for the overall estimated $L_{\text{day}}$ and $L_{\text{den}}$ values in either town. However, there were major differences between the average noise levels in the two towns.

It is important to consider that the grid method is adequate for the assessment of a towns mean noise value (taking into account the systematic selection of sampling points). Thus, this method is considered as a reference or control method in this study. Consequently, the values obtained by other sampling methods should be similar to those obtained from the grid sampling method. This hypothesis is considered later for the categorisation method.

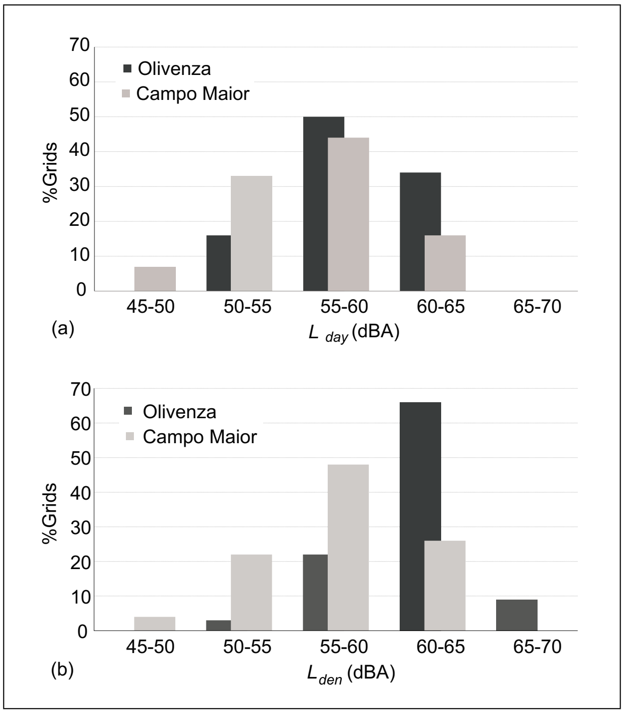

Figure 3. Bar charts of the noise levels obtained with the grid method in Olivenza and Campo Maior. (a) $L_{\text{day}}$ (dBA); (b) $L_{\text{den}}$ (dBA).

### 3.2. The population's noise exposure

The population exposed to the different ranges of $L_{\text{day}}$ and $L_{\text{den}}$ noise levels was estimated for both towns using three methods to estimate the citizens that live in a certain region or on a certain street (A, B, and C). These results are given in Table II. For the A and B estimation methods, the estimated population percentages that were exposed to the various noise level ranges did not differ by more than 1% in the grid case for either town or in the categorisation case for Campo Maior (Table II). However, in the categorisation case for Olivenza, the estimated percentages differed by approximately 3% in some sound level ranges. Considering method C for the categorisation method, we observed that the percentages differed more significantly and reached absolute values near 5% with clearly appreciable relative values in some cases. The selection of the exposed population evaluation method could be important depending on the sampling procedure and the urban structure. Here, we used methods B (a method based on the surface population density) and C as the reference estimation methods for the grid and the categorisation methods, respectively.

The results of the reference estimation methods are shown in the bold data in Table II. In these cells, the distribution of the affected population differs appreciably depending on the sampling method. Thus, the categorisation method in both towns is shifted to the left (lower levels of noise) relative to the grid method. For example, the high-

Table II. The percentage of the population exposed to the different $L_{\text{day}}$ (dBA) and $L_{\text{den}}$ (dBA) sound index intervals for each town (Olivenza and Campo Maior), sampling method (categorisation and grid methods), and estimation method (A, B, or C). Bold data correspond to the reference estimation methods.

| | Cat. | | | Grid | |
|---|---|---|---|---|---|
| Range | A | B | C | A | B |
| | Olivenza, $L_{\text{day}}$ | | | | |
| 45–50 dB | - | - | - | - | - |
| 50–55 dB | 60.3 | 63.1 | **67.5** | 21.8 | **22.1** |
| 55–60 dB | 13.1 | 12.4 | **12.1** | 40.2 | **39.1** |
| 60–65 dB | 20.3 | 20.1 | **15.6** | 38.0 | **38.8** |
| 65–70 dB | 6.3 | 4.4 | **4.8** | - | - |
| 70–75 dB | - | - | - | - | - |
| | Olivenza, $L_{\text{den}}$ | | | | |
| 45–50 dB | - | - | - | - | - |
| 50–55 dB | - | - | - | 4.8 | **3.8** |
| 55–60 dB | 60.3 | 63.1 | **67.6** | 24.9 | **6.4** |
| 60–65 dB | 27.0 | 25.1 | **22.3** | 59.4 | **58.0** |
| 65–70 dB | 6.4 | 4.4 | **4.8** | 10.9 | **11.8** |
| 70–75 dB | 6.3 | 7.4 | **5.3** | - | - |
| | Campo Maior, $L_{\text{day}}$ | | | | |
| 45–50 dB | - | - | - | 7.5 | **7.2** |
| 50–55 dB | 70.4 | 71.3 | **72.1** | 38.3 | **38.6** |
| 55–60 dB | 13.4 | 13.2 | **11.9** | 41.7 | **42.3** |
| 60–65 dB | 15.1 | 14.5 | **15.0** | 12.5 | **11.9** |
| 65–70 dB | 1.1 | 1.0 | **1.0** | - | - |
| 70–75 dB | - | - | - | - | - |
| | Campo Maior, $L_{\text{den}}$ | | | | |
| 45–50 dB | - | - | - | 3.3 | **3.2** |
| 50–55 dB | - | - | - | 20.0 | **20.1** |
| 55–60 dB | 70.4 | 71.3 | **72.1** | 57.8 | **58.6** |
| 60–65 dB | 23.6 | 23.3 | **22.0** | 18.9 | **18.1** |
| 65–70 dB | 6.0 | 5.4 | **5.9** | - | - |
| 70–75 dB | - | - | - | - | - |

est percentage of exposed population for $L_{\text{den}}$ was in the 55–60 dBA interval for the categorisation method but was in the 55–60 dBA and 60–65 dBA intervals for the grid method in Campo Maior and Olivenza, respectively.

Therefore, from these results the following conclusions were drawn.

a) The three proposed estimation methods for calculating the population exposed to the different $L_{\text{day}}$ and $L_{\text{den}}$ noise levels generally provided similar results. However, in certain cases, the differences are relevant, which suggests the importance of conducting noise impact studies with an adequate sampling strategy, in addition to using an adequate procedure for calculating the affected population.

b) The two sampling methods produced very different estimations for the population's exposure to noise. Thus, a comparative study was performed to characterise the quality of each method and to decide which method gave the most appropriate result for the two towns. The results of this study are presented in the following subsection.

Table III. The average prediction error absolute values ($|\overline{E_{ij}}|$) of the $L_{\text{day}}$ (dBA) values measured in the different categories at Olivenza and Campo Maior.

| Town | Category | Grid | Cat. |
|---|---|---|---|
| Olivenza | 1 | 7.2 | 1.2 |
| | 2 | 5.2 | 1.6 |
| | 3 | 5.9 | 2.7 |
| | 4 | 3.3 | 2.3 |
| | 5 | 5.4 | 1.8 |
| Campo Maior | 1 | 7.8 | 0.5 |
| | 2 | 7.4 | - |
| | 3 | 6.2 | 1.2 |
| | 4 | 3.9 | 1.0 |
| | 5 | 4.0 | 3.4 |

### 3.3. Comparative study of the two sampling methods

Because the estimations of the population's exposure to noise for each sampling method were clearly independent, we decide to make a comparative study of both procedures. For this comparative study, we analysed the predictive capacity of each method using the measurements of the other method as controls [8]. The parameter used for this comparison was the prediction error ($E_{ij}$), which is the difference between the measured value and the predicted value.

- For the categorisation method: $E_{ij} = G_{ijk} - R_{ij}$,
- For the grid method: $E_{ij} = C_{ijk} - S_{ij}$,

where $G_{ijk}$ and $C_{ijk}$ are the sound level values ($L_{\text{day}}$) measured at a point of the grid cell or category, respectively (*control values*), and $R_{ij}$ and $S_{ij}$ are the sound level values ($L_{\text{day}}$) predicted by the category or grid method, respectively, for the point where the sound level value ($G_{ijk}$ or $C_{ijk}$) is located (*expected values*).

First, grid sampling points were assigned to one of the categories (this was possible for 60% of the cases in Olivenza and 70% of the cases in Campo Maior), and the noise level value of the sampling point was compared with the expected value of that category. Secondly, the noise level values of the sampling points from the categorisation methods were compared with the expected values of the grid cell in which they were located.

The percentages of the $L_{\text{day}}$ prediction errors that were higher than 3 dBA in the first descriptive analysis for the grid method were 83% and 69% in Olivenza and Campo Maior, respectively. For the categorisation method, these percentages were 15% and 22% in Olivenza and Campo Maior, respectively. From these results, the categorisation method appears to have a more accurate predictive capacity than the grid method.

Furthermore, if we consider the average absolute prediction error ($|\overline{E_{ij}}|$) of $L_{\text{day}}$ in each category (Table III), the errors are considerably larger in the grid method than in the categorisation method.

Table IV. The p-values of the Shapiro-Wilk's normality test for the $L_{\text{day}}$ (dBA) measured values. $M$: Selected points. A p-value below 0.05 (*) indicates a significant difference from a normal distribution.

| | Grid study | | Cat. study | |
|---|---|---|---|---|
| Category | $M$ | $L_{\text{day}}$ | $M$ | $L_{\text{day}}$ |
| Olivenza | | | | |
| 1 | 8 | 0.163 | 4 | 0.023(*) |
| 2 | 6 | 0.172 | 2 | - |
| 3 | 9 | 0.297 | 4 | 0.228 |
| 4 | 9 | 0.683 | 5 | 0.938 |
| 5 | 9 | 0.991 | 12 | 0.846 |
| Campo Maior | | | | |
| 1 | 7 | 0.330 | 1 | - |
| 2 | 6 | 0.405 | - | - |
| 3 | 10 | 0.537 | 7 | 0.403 |
| 4 | 10 | 0.330 | 6 | 0.354 |
| 5 | 9 | 0.501 | 14 | 0.189 |

Table V. The p-value of the non-parametric Wilcoxon signed ranks test for the $L_{\text{day}}$ (dBA) measured in the different categories of Olivenza and Campo Maior. The *p*-values below 0.05 (*) or 0.01 (**) indicate that the median differs or very significantly differs from zero, respectively.

| Town | Category | Grid study | Cat. study |
|---|---|---|---|
| Olivenza | 1 | 0.008 (**) | 0.625 |
| | 2 | 0.031 (*) | 0.500 |
| | 3 | 0.004 (**) | 0.250 |
| | 4 | 0.910 | 0.813 |
| | 5 | 0.004 (**) | 0.519 |
| Campo Maior | 1 | 0.016 (*) | - |
| | 2 | 0.031 (*) | - |
| | 3 | 0.004 (**) | 0.375 |
| | 4 | 0.014 (*) | 0.063 |
| | 5 | 0.301 | 0.426 |

The differences that were observed from the descriptive analysis were analysed with inferential analysis. To determine the most convenient statistical tests to use, we began the inferential analysis of the prediction errors ($E_{ij}$) with a noise level distribution study of the sampling points. The Shapiro-Wilk test [15] was used to determine which noise level value data sets were normally distributed. The results of this test (Table IV) showed that the $L_{\text{day}}$ distribution in Category 1 of Olivenza was different from a normal distribution at a significance level of 0.05(*). Because of this significant difference and the small sample size, a non-parametric test was used [16]. Thus, the non-parametric Wilcoxon signed-rank test [17, 18] was applied. This test determines if the median prediction error does not significantly differ from zero. If there is no significant difference, the sampling method is assumed to significantly predict the sound level value.

Table V lists the p-values from the Wilcoxon signed-rank test for $L_{\text{day}}$ for the two towns and distinguishes the street category that corresponds to each sampling point. Based on these results, none of the expected categorisation method values in either town significantly differed from the sound level of the control. This finding contrasts the grid method results in which only Category 4 in Olivenza and Category 5 in Campo Maior had expected values that did not differ significantly from the control values.

These conclusions confirm those resulting from the descriptive analysis. Both indicate that the sound levels predicted by the categorisation method have a lower error than those predicted by the grid method. In addition, the median prediction errors of the categorisation method are generally not significantly different than zero. However, this finding only occurs in certain categories for the grid method. One particularly important finding is that the grid method has greater prediction errors in the noisier categories (for which the impact of noise on the population is most relevant).

In summary, the present results show that the categorisation method is better suited for noise annoyance analysis than the grid method. In addition, the categorisation method is a powerful method for predicting sound levels that were not significantly different from the control values in the analysed categories.

### 3.4. Analysis and comparison of the proportions of the population annoyed by noise

Based on the previous considerations, the sound levels that were determined from the categorisation sampling method and estimation method C were used to calculate the population's exposure to noise. The results for the two towns are presented in Table II. These results lead to the following conclusions.

1. With respect to $L_{\text{day}}$:
   - 32% and 28% of the Olivenza and Campo Maior inhabitants, respectively, are exposed to noise levels that (according to the WHO) can cause serious annoyance ($L_{\text{day}}$ >55 dBA [19]). Furthermore, all (100%) of the inhabitants of both towns are exposed to noise levels that exceed 50 dBA, which can cause moderate annoyance (according to the WHO) [19].
   - Exposure to noise levels above 65 dBA (limit value for daytime noise according to the OECD [20]) affects 5% and 1% of the inhabitants of Olivenza and Campo Maior, respectively.
2. With respect to $L_{\text{den}}$:
   - Based on the OECD terminological criteria, 10% and 6% of the population live in "*black acoustic zones*" ($L_{\text{den}}$>65 dBA), 90% and 94% live in "*grey acoustic zones*" (65 dBA>$L_{\text{den}}$>55 dBA), respectively [21]. This values were compared with the percentage obtained from road traffic in larger European cities [22, 23], (Table V). We can see, for example, that the percentage of the population that was affected by high noise levels was greater in Paris, Berlin, London, and Florence (38%, 42%, 24%, and 54%, respectively, for population that live in in "*black acoustic zones*". However, in Paris and Florence a

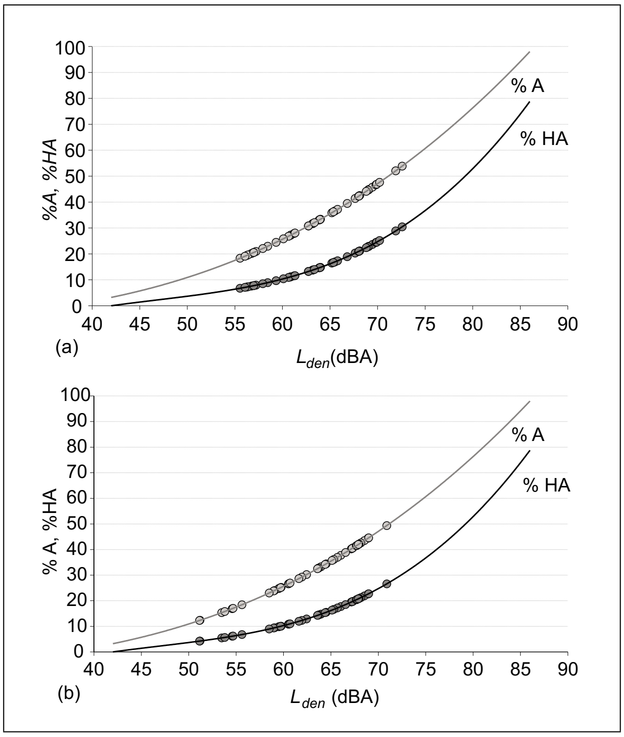

Figure 4. Estimation of the annoyance caused by road traffic noise based on the noise exposure $L_{\text{den}}$ (dBA). Solid lines are plots of equations (2) and (3). Points lying on the curves are estimates corresponding to the $L_{\text{den}}$ (dBA) values measured at the sampling points of the categorisation method. (a) Olivenza; (b) Campo Maior.

34% and a 6%, respectively, live in "*white acoustic zones*" ($L_{\text{den}}$<55 dBA), whilst in the towns of Olivenza and Campo Maior this percentage was 0%.

- The percentages of annoyed (%*A*) and highly annoyed (%*HA*) people were calculated from the $L_{\text{den}}$ values (equations 2 and 3). These results are shown in Figure 4. In both towns, the distribution of the obtained values from the different sampling points is similar for the %*A* and %*HA* curves. The biggest difference between both towns occurs in the lowest %*A* and %*HA* curve ranges. Thus, 9% and 16% of the sampling points in Olivenza and Campo Maior are in the 10–20% range of the %*A* curve, and 24% and 30% are in the 0–10% range of the %*HA* curve, respectively. Equations (2) and (3) were only calibrated for road traffic noise sources, which were the predominant sources of sound measured in this study.
- We also compared the %*A* and %*HA* population estimates for the different Olivenza and Campo Maior categories to the estimates obtained in two much larger Spanish towns in which the categorisation method was previously applied (Salamanca and Cáceres with 160,000 and 90,000 inhabitants, respectively) [6]. As expected, Salamanca and Cáceres (17 and 10 times more populated than Olivenza and Campo Maior, respectively) have greater %*A* and %*HA* values than Olivenza and Campo Maior for all of the categories. These differences are not very large (approximately 9–13 for %*A* and less than 9 for %*HA*). In contrast, when comparing the estimated %*A* and %*HA* populations for the different categories (Table VI), we observed that the A% and %*HA* values from Olivenza and Campo Maior were lower than those of Madrid and Munich and higher than those of Amsterdam (with populations of 768,000, 1,330,000, and 3,256,000 inhabitants, respectively) [24].

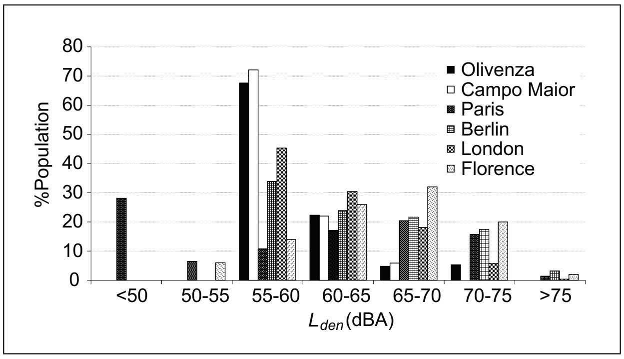

Figure 5. The percentage of the population exposed to the different $L_{\text{den}}$ (dBA) ranges in the two studied towns and in some larger European cities.

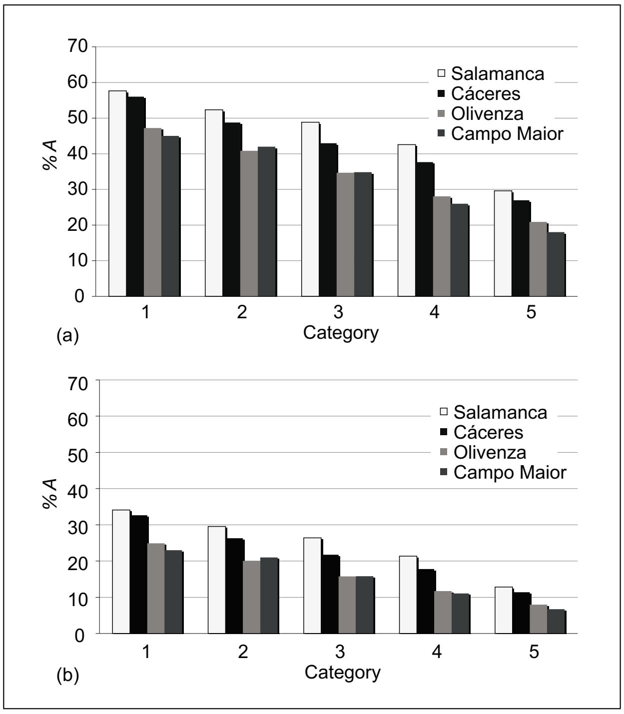

Figure 6. The estimated percentage of the population that is annoyed by road traffic noise in the Salamanca, Cáceres, Olivenza, and Campo Maior categories. (a) Annoyed (%*A*); (b) highly annoyed (%*HA*).

In summary, noise pollution is a problem that affects both small and large towns. Although the noise levels in small towns are somewhat lower than those in large towns, they

Table VI. The $\%A$ and $\%HA$ population values for the studied towns and three European cities [24].

| Town | $\%A$ | $\%HA$ |
|---|---|---|
| Olivenza | 27.0 | 11.0 |
| Campo Maior | 22.8 | 8.9 |
| Amsterdam | 17.0 | 7.0 |
| Munich | 32.5 | 15.4 |
| Madrid | 34.7 | 17.1 |

are comparable (in some aspects) to those of much larger towns.

## 4. Conclusions

The following conclusions were drawn from this study.

- The two sampling methods resulted in similar overall $L_{\text{day}}$ and $L_{\text{den}}$ values for the two studied cities. Nevertheless, important differences were found between the calculated noise exposures.
- The studied estimation methods for calculating the population exposed to noise levels ($L_{\text{day}}$ and $L_{\text{den}}$ indices) gave similar results. However, relevant differences were found in certain cases, which indicated that the method for calculating the population noise exposure is important, regardless of the noise assessment method.
- These results confirm the applicability of the categorisation method to towns that are five times smaller than those previously studied.
- The $L_{\text{day}}$ noise value prediction errors (based on the descriptive and inferential statistical analyses) were lower for the categorisation method than for the grid method. In addition, the inferential analysis showed that the categorisation method generally gave expected values that did not differ significantly from the corresponding control. In contrast, significant differences were generally observed for the grid method between the expected values and the control. Furthermore, the grid method had greater prediction errors for the noisier street categories in which the impact of noise on the population is more important. In summary, the categorisation method seemed better suited than the grid method for evaluating the level of noise annoyance for town inhabitants.
- Noise pollution is not only a problem in cities and large towns but also in small towns and villages. Thus, 32% and 28% of the inhabitants of Olivenza and Campo Maior, respectively, are exposed to sound levels that can cause serious annoyance. Furthermore, all of the Olivenza and Campo Maior inhabitants are exposed to sound levels that can cause moderate annoyance. In these two small towns, the proportion of the population that lives in a "*grey acoustic zones*" was higher than the proportions reported in Paris, Berlin, London, and Florence. However, the proportion of citizens that live in a "*black acoustic zones*" was lower in Olivenza and Campo Maior than in Paris, Berlin, London, and Florence. The A% and $\%HA$ values were higher than in Amsterdam.

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